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Thermal Properties of Hempcrete, a Case Study

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This Bachelor's thesis introduced a thermal insulation material with a low environmental impact called hemp concrete or hempcrete. The thesis focused on spray type hempcrete and its thermal properties. The thermal properties were studied from literature and with practical tests.

The thesis was a part of School of Management and Engineering Vaud's (HEIG-VD) and a local Swiss construction company's co-operation project called "Shot- bio-based insulation mix design and technology". The goal of the project was to develop a spray type hempcrete that fulfils the Swiss national norms and standards, in order to become an official construction material.

The tests performed in this Bachelor's thesis were preliminary tests to launch the material's thermal property testing phase. The thesis studied spray type hempcrete's thermal properties in thermal conductivity in laboratory and in-situ. A thermal transmittance measurements and thermal camera investigation was done in conventional houses insulated with spray type hempcrete.

Based on the studies the spray-type hempcrete performs well as an insulation material in a residential house. Furthermore, the study showed that simply by looking into the values of laboratory measurements, the whole truth behind the thermal performance of hempcrete is not revealed. When the features of the hempcrete are observed together, the thermal performance of the material is good.

Keywords	hempcrete, bio-based insulation, thermal properties

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Tämä opinnäytetyö tutustuttaa lukijansa ekologiseen rakennusmateriaaliin. Opinnäytetyössä käsiteltiin lämpöeristeenä toimivaa materiaalia nimeltä hamppubetoni. Työssä syvennyttiin erityisesti ruiskutettavaan hamppubetoniin ja sen lämpöteknisiin ominaisuuksiin. Lämpöteknisiä ominaisuuksia tutkittiin kirjallisuuden ja käytännön kokeiden avulla.

Työ tehtiin osana Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud (HEIG-VD) ja paikallisen sveitsiläisen rakennusliikkeen yhteistyöprojektia nimeltä Shot- bio-based insulation mix design and technology. Korkeakoulun ja rakennusliikkeen yhteisprojektin tavoite oli kehittää kansalliset standardit ja normit täyttävä ruiskutettava eristemateriaali. Opinnäytetyön osa projektista oli aloittaa lämpöteknisten tutkimusten mittaamisvaihe.

Opinnäytetyön testeissä tutkittiin ruiskutettavan hamppubetonin lämpöteknisiä ominaisuuksia laboratoriokokein koekappaleille ja kenttäolosuhteissa olemassa oleville hampulla eristetyille omakotitaloille, jotka sijaitsivat Länsi-Sveitsissä. Mittaukset koostuivat kolmesta toisiaan täydentävistä testeistä. Testit olivat koekappaleiden lämmönjohtavuuskokeista, hamppubetoni seinän lämmönläpäisykerroinkokeesta ja omakotitalojen lämpökuvaksista. Materiaalin lämmönjohtavuutta tutkittiin laboratoriokokein ja kentällä tehtyjen mittauksien avulla. Lämmönläpäisykerroin- ja lämpökameratutkimukset tehtiin olemassa olevissa ruiskutettavalla hamppubetonilla eristetyissä asuinrakennuksissa.

Opinnäytetyössä tehtyjen tutkimusten ja kirjallisuudesta löytyneiden tulosten perusteella voidaan todeta ruiskutettavan hamppubetonin toimivan hyvin ja tasaisesti lämmöneristeenä asuinrakennuksissa. Opinnäytetyössä havaittiin myös, että materiaalin suorituskykyä tulisi tarkastella laajemmin kuin pelkästään laboratoriomittauksissa ilmenneiden tulosten pohjalta. Tutkimuksissa selvisi, että hamppubetonin ominaisuudet kokonaisvaltaisesti kompensoivat sen lämpöteknistä suorituskykyä heikentäviä ominaisuuksia ja nostavat sen suorituskyvyn hyvälle tasolle.

Avainsanat	hamppubetoni, ekologinen lämmöneriste, lämpötekniset ominaisuudet

Contents

1 Introduction

Climate change is a serious threat to the modern society. The rising greenhouse gas emissions are increasing the average temperature of the planet which leads to predictable and unpredictable catastrophes of a huge magnitude. The emissions are caused by continuous use of natural resources over the regeneration capacity of globe. [1.] If the current trend continues, the result is the depletion of the natural resources [2,3].

The buildings in Europe are responsible for 40-45 % of the total energy use and they are a large contributor to the carbon dioxide emissions [3,1]. The total energy consumption during the whole lifecycle of a building includes the energy in the use phase, the energy embodied in the materials, maintenance, the construction of the building and its demolition. The biggest factors to the total energy consumption are the energy embodied in the construction materials and the energy consumed in the use phase. The chart (figure 1) shows that the length of the lifespan of a conventional house has a significant impact on the ratio between the energy embodied in materials or that used for space heating. In the future, buildings will be more energy efficient, thus the energy used and the emissions caused by the materials will play a major role in the total energy use. The change towards energy efficient buildings will raise the rate of energy used during the constructing and the demolition. [4,29-31]

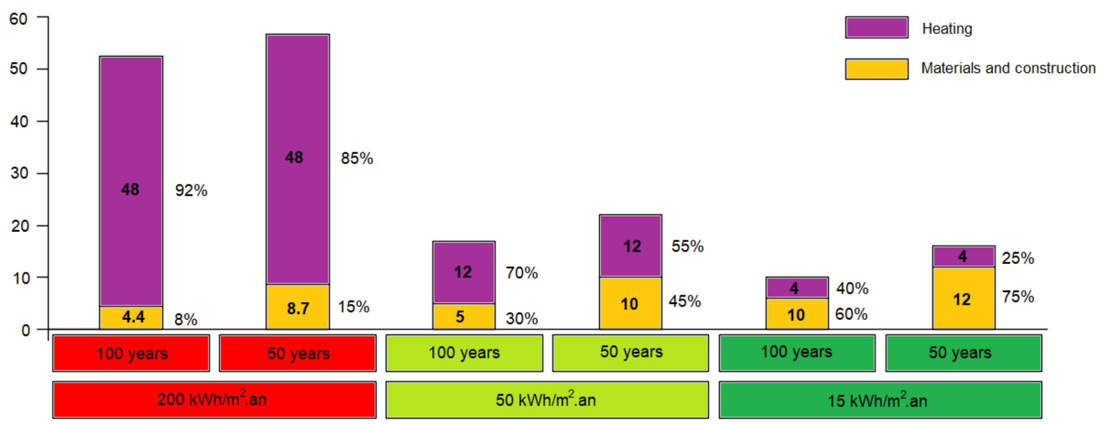

Figure 1. The deviation between the energy used in the construction phase and the energy embodied in construction materials, and the energy used in heating a conventional house. [4,31]

The construction sector uses a significant proportion of the natural resources of the world. The materials used in the construction sector often have very high embodied energy. Embodied energy includes all energy used to produce a ready-to-use material, throughout the materials lifecycle. Usually, the more production stages the material has, the higher the embodied energy is. High embodied energy is often proportional to high emissions. In the construction sector, the materials with the highest embodied energy are concrete and metals, such as aluminum and steel. [3,7.] In a global scale, concrete is responsible for up to five percent of the whole carbon dioxide emissions caused by man [4,32].

As buildings become more energy efficient, the choice of building materials will have a greater effect on the total energy used and emissions caused by a building. To reduce the embodied energy in the materials, the building sector has to react and create new designs and materials to reduce the emissions. This Bachelor's thesis introduces a thermal insulation material with a low environmental impact called the hemp concrete or hempcrete. The thesis took part in a project called "Shot- bio-based insulation mix design and technology" of the School of Management and Engineering Vaud's (HEIG-VD) and a local Swiss construction company. The goal of the project was to develop a spray type hempcrete, which fulfils the Swiss national norms and standards, in order for it to become an official construction material. The Bachelor's thesis focuses on the thermal abilities of the material. The thermal ability tests done in laboratory and in-situ are preliminary tests to launch the testing phase. The tests are done in HEIG-VD's civil engineering laboratories and in the field in conventional houses located in Western Switzerland.

2 Hempcrete

The idea of modern hemp-based concrete was first born in the mid-1980's in France. The material was originally designed to be a repair material for old straw composite buildings which needed a breathable render material. The idea evolved into a hemp-lime insulation material, hempcrete. Unlike concrete, hempcrete is not a load bearing material. It needs an additional framework to withstand strain. Hempcrete has three main ingredients: hemp hurds, a binder and water (figure 2). The aggregate of hempcrete is hemp hurd which is woodchip from the stem of a hemp plant (cannabis sativa). Typically, hemp composites use a mineral based binder substance as a binder. The water mixed with the binder creates an adhesion between the hemp hurds. [5,37-43.]

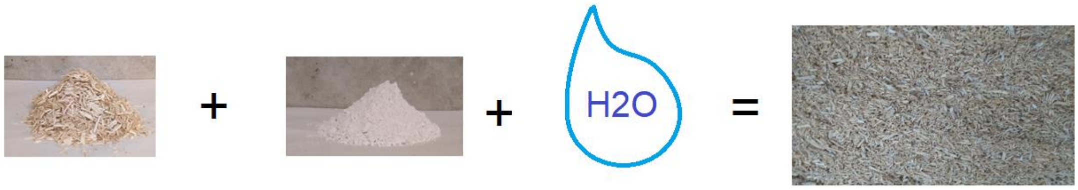

Figure 2. The elements of hempcrete and the result (sprayed hemp-lime wall)

The ingredients, the environmental impacts, the production and some technical features are presented below.

2.1 Ingredients

Of the ingredients in hempcrete, hemp plant (cannabis sativa) is cultivated across the globe. It is an ancient crop, cultivated for its fibers and seeds. Parts of hemp plant are used for food, textiles, paper, construction material, fuel oil and many more. [5,16-25.] According to Magniont, a hemp plant comprises, approximately, 32% of fibers, 42% of shives, 18% of powder and pitch and 8% of seed, and all parts of the plant can be used [3,122]. The stem of hemp, which is a vital ingredient for hempcrete, is often a byproduct from a hemp plant cultivated for fibers or seeds. The cultivation of hemp for hemp hurds alone is not profitable, neither economically nor ecologically. [2,27.] The cultivation of the hemp plant can be very beneficial, as an annual plant it produces yield relatively fast, and it has various soil improving attributes. The plant requires very little care, and it does not need any chemical fertilizers nor pesticides. The plant is excellent in crop rotation due to its fast growth. [2,23-27.]

Various binders can be used as an adhesive in hemp composites. Some common binders are Portland cement and lime, more specifically hydrated lime ($Ca(OH)_2$). Typically, the binder is a mix of lime or Portland cement with substances such as gypsum or pozzolanic substances for example as fly ash or metakaolin. Different mixes of binders are used to gain different material properties such as thermal or mechanical properties.

[2,75-78.] Portland cement and hydrated lime are produced by burning limestone (calcium carbonate, $CaOH_3$) in high temperatures. For Portland cement, clinker is burnt with limestone at 1200 to 1280 degrees in Celsius. Hydrated lime is burnt at 900 to 1100 degrees. The burning of $CaCO_3$ results in carbon dioxide (CO_2) and calcium oxide (CaO), also known as quick lime. Quick lime is extinguished with water (H_2O), resulting in hydrated lime ($Ca(OH)_2$), the binder for hempcrete. The manufacturing process of hydrated lime creates more carbon dioxide compared to the manufacturing of Portland cement. However, the emission rate turns favorable to lime binder. Lime binder in a hempcrete wall starts to carbonate, meaning that in a chemical reaction the lime re-absorbs carbon dioxide from the atmosphere, turning back to calcium carbonate ($CaCO_3$). Lime re-absorbs up to 60 per cent carbon dioxide during a period of one hundred years. [5, 37-43.]

2.2 Environmental impacts

Hempcrete is seen as a low impact construction material [2]. The study "Life cycle assessment of a hemp concrete wall: Impact of thickness and coating", carried out at the European University of Brittany, studied the environmental impacts of a hempcrete wall. The study shows how wide the range of the emission sources for hempcrete are. Transportation is a large factor, but the biggest contributor to the total emissions is the binder and the emissions related to it. This is seen in figure 3, which illustrates the carbon dioxide emissions of a hempcrete wall per functional unit. The total value (figure 3) is negative due to the decarbonation process and the photosynthesis of hemp plant, as explained above in the chapter 2.1. Thus, the thickness of the hempcrete is proportional to the carbon dioxide bound to it. The lifespan of the calculated wall was set to one hundred years, and in the end of its lifecycle the hempcrete was disposed to a landfilling purpose, creating nearly no emissions at all. [6,223-231.]

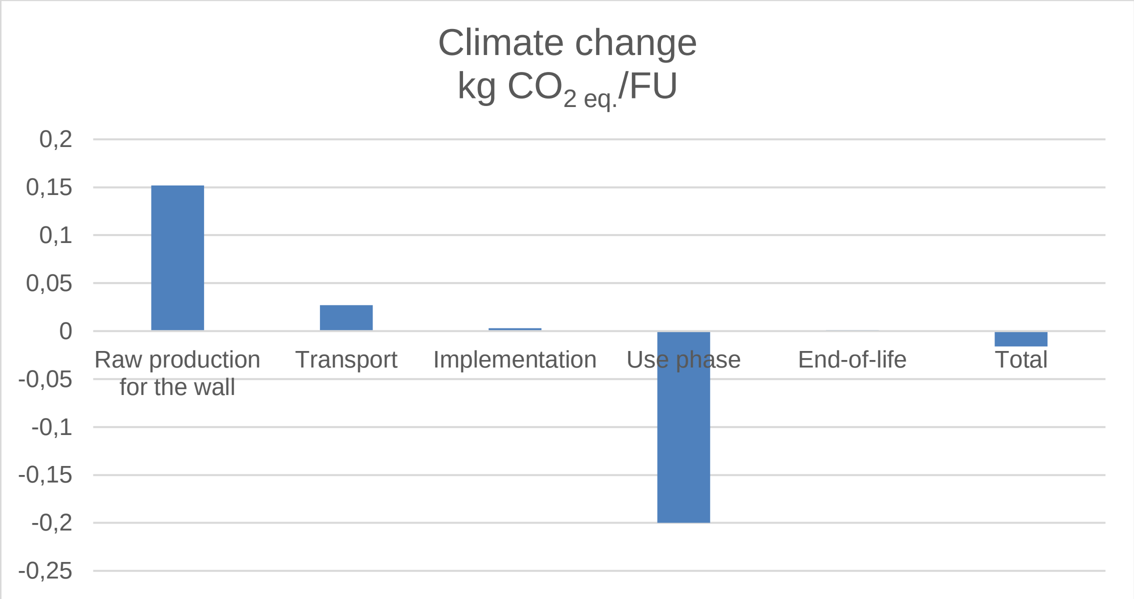

Figure 3. The distribution of CO_2 emissions in hemp-lime wall [6,228].

Although the thickness of a hempcrete insulation has an influence on how much carbon dioxide is bound to the building, there are other emissions related to the material. As any other material flows of a lifecycle of a product, much wider scale of harmful impacts to environment is related to the lifecycle of a material, than just the carbon dioxide emissions. For hempcrete the raw production phase, which creates most of the CO_2 emissions, create alongside with the transportation, most of the environmental impacts. As an example, transportation and the raw production phase consume non-renewable energy and destroy the ozone layer. However, the destruction of the ozone layer caused by the material flows of hempcrete is marginal. Hempcrete also creates pollution to water and air, mostly caused by the cultivating and the processes of the hemp plant. [2 ,290-310.]

2.3 Production

Although the thickness of a hempcrete insulation has an influence on how much carbon dioxide is bound to the building, there are other emissions related to the material. As any other material flows of a lifecycle of a product, much wider scale of harmful impacts to environment is related to it, than just the carbon dioxide emissions. For hempcrete the raw production phase, which creates most of the CO2 emissions, alongside with the transportation, create most of the environment impacts, in general. Just to name a few, transportation and the raw production phase they consume non-renewable energy and they destroy the ozone layer. The destruction of the ozone layer caused by the material flows of hempcrete is marginal. Hempcrete creates pollution to water and air, mostly caused by the cultivating and the processes of the hemp plant. [2 ,290-310.]

Hempcrete is manufactured in several different forms and ways. In every case, all the ingredients are mixed together regardless the manner of production. Only the proportions of the ingredients and the order or the manner of mixing vary. The proportion of the ingredients or additives to the mix alters the purpose of use. For example, the amount of binder defines the density and, therefore, the thermal abilities and strength of the material. The material can be used as an insulation in floors, walls and roofs. [5.]

There are bricks, cubes, panels and spray type hempcrete currently in the market. Hempcrete requires a load bearing framework regardless of the type of product. The hemp bricks and blocks are laid with hemp plaster, and the panels are lifted and attached to the frame. According to Allin, the spraying of hempcrete is the most advanced way to produce it. The spray-type hempcrete is produced by spraying a mix of hemp hurds and a binder with rized air through a pipe. At the end of the pipe the mixture of hemp hurds and the binder is sprayed with water. Normally, the hempcrete is sprayed into a backboard or into a mold. The molds and boards can be removed afterwards. [5,48-51,151,160-162.]

2.4 Technical features

As any construction material, hempcrete has to meet up with national standards that vary from country to country. An excerpt from the Finnish Ministry of the Environment Land Use and Building Act, paragraph § 117 defines the requirements construction must fulfill with following words “A building must meet the essential requirements for structural strength and stability, fire safety, hygiene, health and environment, safety in use, noise abatement, and energy economy and insulation, as set by its intended use (essential technical requirements).” [7,34.]

Table 1 below presents some technical abilities of the Limecrete company’s Tradical Hempcrete.

Table 1. Technical features of hempcrete [8].

The hempcrete's technical abilities (The Limecrete company 2012):		
Density	275	kg/m3
Flexural Strength	0.3-0.4	N/mm2
Thermal conductivity	0.06	W/mK
Heat Capacity	1500-1700	J/kg
Mean Asoustic Absorption Coefficient	0.69	NRC
Air Permeability	0.75	gm/m2/mm hg
μ Vapour Diffusion Resistance	4.84	
Fire Rating	1hr	BS EN 1365-1:1999
Carbon capture	130	kg CO2/m3
Airtightness	<2	m3/m2 .hr@50pa

When comparing the technical values (table 1) with the values of some common insulation materials, hempcrete may not seem to perform too well. However, hempcrete provides several beneficial features that increase its performance beyond the values imply. The material has an advantage of making the living clean and healthy. Due to being natural, as well as hydroscopic materials, hemp and lime support clean and healthy life. As a hydroscopic material, the envelope of a hempcrete house balances the relative humidity level of the indoor air. A higher humidity level transfers the humidity to the space with a lower relative humidity. Hempcrete has a high thermal inertia, which means that the material heats up slowly and also gives out the heat energy slowly. When the thickness of a hempcrete layer is designed correctly, the wall stabilizes the thermal conditions of the indoor air. At the day time it stores heat from the sun and during the night time it gives out the stored warmth to the indoor air. [5, 60-67.] A high thermal inertia of the material reduces the heating demand by five to ten per cent [9, 513].

The thermal conductivity value (lambda) of hempcrete is not as good as many other commonly used thermal insulation materials have. More important value for a thermal performance of a building is the total thermal transmittance, the U-value. It is possible to build hempcrete houses without cold bridges, which are large contributors to the heat losses in buildings. Therefore, a hempcrete building's total U-value with the recommended thickness can be very competitive with the houses that have the more commonly used insulation materials. [5, 59]

3 Theory

The second law of thermodynamics states the direction of thermal flow, from warm to cold. Heat always transfers trough material and space always when there is a temperature difference. [10,1-4.] The heat energy has three commonly known mechanisms for heat transfer: convection, conduction and radiation. The thermal convection is a primary form of heat movement in gasses or liquids. A temperature difference in a fluid creates flows that are caused by the different densities. The colder and more dense substance moves down in the field of gravity. Thermal conductance occurs when two molecules with different kinetic energy interact with each other. The warmer molecule with the higher kinetic energy collides with a molecule with the lower kinetic energy transferring kinetic energy (heat). Every surface with a temperature higher than the absolute zero emits thermal radiation in the form of electromagnetic waves through material and space. [11,10-26; 12,21-28.]

A thermal insulation is a material or combination of materials that retards heat transfer in all three heat transfer mechanisms. There are different types of thermal insulation materials available. Typically, the function of a thermal insulation is based on the low thermal conductivity of gasses. Most thermal insulation materials are filled with tiny air bubbles which are isolated from each other by the porous structure of the material. The air bubbles must be small enough so that the gases inside them cannot move freely and transfer heat by convection. Porous materials often have good thermal insulation abilities. [13, 335.]

The national building code of Finland, part C4 Thermal insulation guideline (2003), defines thermal insulation in building applications as “[b]uilding material used primarily or in addition to other uses essentially for thermal insulation” [14,3]. A thermal insulation material retards heat flow through a building’s envelope, reducing the need of heating and cooling, which is a cost-effective way to save energy. Usually, a thermal insulation also has other properties in addition to the thermal properties. The material can, for example, improve strength, acoustic or hydrothermal performance in a building and its structures. A thermal insulation in a building has an enormous impact on the thermal comfort of a building. [12.]

Thermal comfort reveals how the inhabitants experience the indoor air of a building. Factors such as the indoor air temperature, relative humidity and air currents have an effect on how the habitants sense the indoor air. Air currents create an uncomfortable sensation of coldness. The sensation of a thermally comfortable space is very individual. A person’s metabolism has a significant impact on how he or she experiences the indoor air. The human body produces heat and humidity all the time. When the humidity and the heat transfers to the ambient air at the same rate as the human body creates it, the inside air feels comfortable. The amount of humidity and temperature are significant factors to the transfer speed of heat and moisture from a person’s skin. Deficient humidity and temperature levels of indoor air lead to excessive transfer of moisture from the skin, and vice versa, causing an uncomfortable sensation of the indoor air. Comfortable indoor air has relative humidity levels between 30 to 60 per cent. [12,13-16]

3.1 Thermal conductivity

The national building code of Finland, part C4 Thermal insulation guideline (2003), defines thermal conductivity with the following words: “[t]hermal conductivity indicates the density of heat flow in steady-state through a layer of homogenous material with a thickness of a unit of length when the temperature difference between the surfaces of the material layer is a unit of temperature.” [14,3]. In the metric system, thermal conductivity is known as lambda value (λ). The unit lambda in the metric system is Watts per meter Kelvins (W/m*K). [10,3.] The higher the thermal conductivity of a material, the faster the heat transfers through it. On average, substances such as metals have a high thermal conductivity, liquids a mediocre and gasses have low thermal conductivities. Therefore, even a slight increase in humidity, or amount of liquid, in insulation creates an unwanted increase in thermal conductivity. [15,9.]

The lambda value for construction materials is an important value when evaluating the thermal performance of insulation materials and calculating heat losses [14]. Thermal insulation materials are compared with the lambda value [13,354-355]. Figure 4 shows some lambda values of common thermal insulation materials.

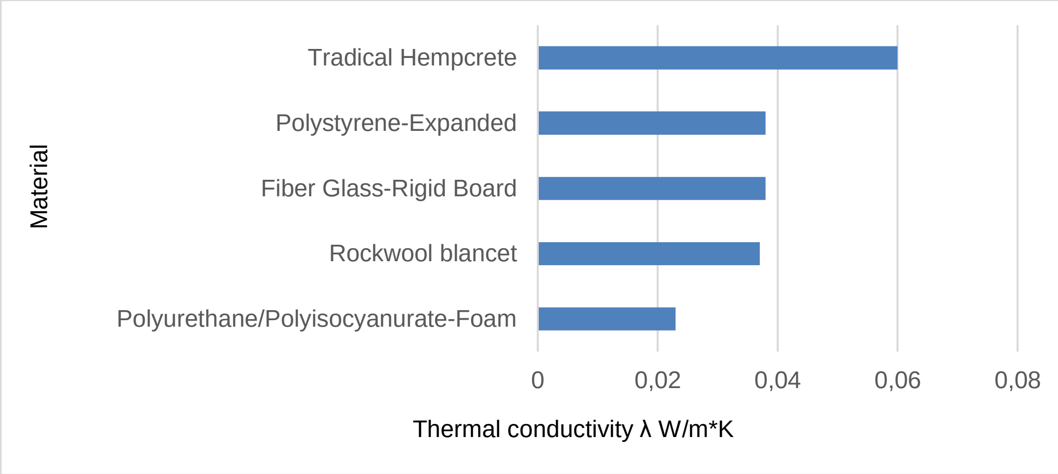

Figure 4. Thermal conductivity values for some common building materials [13,362-363; 8].

The lambda values the construction material manufacturing companies state are laboratory tested values. The materials are tested with standardized testing methods and equipment. The lambda value is calculated using formula (1) from the standards ISO 8302 “Thermal insulation – Determination of steady-state thermal resistance and related properties – Guarded hot plate apparatus” and from ISO 8990 “Thermal insulation. Determination of steady-state thermal transmission properties. Calibrated and guarded hot box”. [16; 17.] One of the lambda values that the manufacturing companies state, is the lambda-10 value (λ_{10}). The mean conductivity, lambda 10, explained by the national building code of Finland: “indicates an arithmetic mean value of individual measurement results for thermal conductivity of a material when measurements are taken at the mean temperature of 10 °C” [12,3].

$$\lambda = \frac{\Phi * d}{A * (T_1 - T_2)} \tag{1}$$

λ is thermal conductivity

Φ is the total heat flow rate

d average thickness of a specimen

A is metering area measured on a selected isothermal surface

T_1 is temperature of the warm surface of the specimen

T_2 is temperature of the cold surface of the specimen.

3.2 Thermal transmittance

Thermal transmittance measures the density of a heat flux through an area with temperature difference of one unit between two surfaces. In the metric system the units for thermal transmittance is Watts per square meter Kelvin (W/m^2*K). [12,23-25.] In the building sector, the thermal transmittance is called the U-value [13,3]. The U-value is used to calculate heat losses or gains in buildings. The lower the thermal transmittance value of a material, the better an insulator it is. [12,24.] The national building code of Finland, part C4 defines how the heat losses of a building are. The U-value for a building wall is calculated with formula (2). [14]

$$U = \frac{1}{R_T} \tag{2}$$

U is the total thermal transmittance

R_T is total thermal resistance of a building component from one environment to another.

Normally, the walls of a building are a mix of many different material layers. The total thermal resistance is the sum of all the material layer thermal resistance values. When the different layers of a wall are of uniform thickness the total thermal resistance is calculated with formula (3) [14,6].

$$R_T = R_{si} + R_1 + R_2 + \ldots + Rm + R_{se} \tag{3}$$

$R_{si} + R_{se}$ is the sum of the internal and external surface resistances

$R_1, R_2, \ldots R_m$ is the thermal resistance of a single layer with an uniform thickness.

The single thermal resistance of a layer is calculated by using formula (4) [14,6].

$$R_1, R_2, \ldots R_m = \frac{d_1}{\lambda_1}, \frac{d_2}{\lambda_2}, \ldots \frac{d_m}{\lambda_m} \tag{4}$$

$d_1, d_2, \ldots d_m$ is the thickness of a material layer

$\lambda_1, \lambda_2, \ldots \lambda_m$ is the design thermal conductivity of a material layer.

Some building structures are designed in a way that the material layers are not homogenous and there are, for example, vertical or horizontal beams in the insulation layer. The thermal resistance of such layers are calculated with formula (4) [14,6].

$$\frac{1}{R_j} = \frac{f_a}{R_{aj}} + \frac{f_b}{R_{bj}} + \ldots + \frac{f_n}{R_{nj}} \quad (5)$$

$f_1, f_2, \ldots f_n$ is a proportional part of the total area of a material layer of the homogeneous sub-area a,b, … n in the inhomogeneous material layer j.
$R_{aj}, R_{bj}, \ldots R_{nj}$ is the thermal resistance of the homogeneous sub-area a,b, … n in the inhomogeneous material layer.

Therefore, the total thermal transmittance value for a multilayer wall where a layer might have different materials in it is calculated with formula (5) [14,6].

$$U = \frac{1}{R_{si} + \frac{d_1}{\lambda_1} + \frac{f_a}{\frac{d_j}{\lambda_{aj}}} + \frac{f_b}{\frac{d_j}{\lambda_{bj}}} + \frac{d_3}{\lambda_3} + R_{se}} \quad (6)$$

Thermal lag

A phenomenon that affects the speed of the thermal flow is the thermal inertia or thermal mass. The heat flow transfers slowly through a material with a high thermal mass. The duration which the heat flow uses to travel from one side to another of the material layer is called the thermal lag. [18.]

3.3 Thermal imaging

All surfaces emit thermal radiation which is type of electromagnetic radiation, mostly infrared radiation. The volume of thermal radiation the surfaces emit depends on the temperature and the emissivity rate of a surface. The wavelength of infrared radiation is between eight to twelve nanometers. This wavelength is out of the wavelength of visual light’s. It can be monitored with an infrared camera, also known as a thermal camera. [19.]

A thermal camera is a tool which measures the total radiation emitted from the surface of a material. The total thermal radiation is a sum of thermal radiation from an object plus thermal radiation reflected from the object's surface coming from the ambient space. A thermal camera measures the total thermal radiation from surfaces in real time. Through the lenses each measurement spot converts into an image where each pixel represents the temperature value of the measured area with a color. A longer distance between the camera and the measured surface mean a larger area for each measurement spot. Thus, in a situation where the object is measured further away, a smaller point with a radiation level difference is impossible to detect. [19, 15-18.]

Emissivity (ε) is a ratio which indicates how much thermal energy a surface emits compared to a theoretical black surface at the same temperature. The theoretical black surface absorbs all ambient radiation and emits only the radiation it possesses. The emissivity ratio is from zero to one, where zero is a perfect reflector, meaning that all thermal radiation form ambient space is reflected. The ratio one is a theoretical black surface. Common construction materials have an emissivity ratio of 0.9. That means their surface emits 90 per cent of the thermal radiation compared to the theoretical black surface with the same temperature. [19, 16-19.]

When performing a measurement with a thermal camera, the emissivity rate must be defined from the settings of a camera to match the measured surface. If the setting is not correct, the measured values are not correct. In thermal imaging the measurement angle influences the accuracy of the results. As the imaging angle changes, the emissivity rate changes. The camera is designed to be used at a 90-degrees angle. If the angle is changed, the emissivity setting should be changed as well. [19, 16-20.]

Thermal imaging in the construction sector is a quick, simple and accurate way to evaluate the conditions and the quality of a building, whether it is a building under construction or an older one. The thermal imaging is done remotely, without a physical contact to the surfaces nor a need of demolishing structures blocking the access to the measured layers. The thermal performance and comfort of a building can be studied diversely. For example, with a thermal camera it is possible to study the condition of the building's envelope, HVAC systems or the electrical systems. Normally, the thermal images are taken to determine flaws. The flaws often manifest as irregularities in the surface temperature levels. The irregularities might expose a lacking thermal insulation layer, air leakage or even in some cases a problem with dampness. However, a variation in the surface temperatures is not always an indication of a flaw. The surface temperature levels are not uniform. A lot of factors influence the surface temperatures and they should all be taken in to account when performing a study. Some major factors are the heating, cooling and ventilating systems. [20.]

The thermal imaging aims at locating surface temperatures that vary from the ambient temperature levels. The reasons for the differences are analyzed on the basis the observations done in the field and previously gathered background information. Typical points of interest in thermal imaging are thermal and air leaks. A thermal leak or an air leak can be detected when the temperature of an area is significantly different than that of the ambient surfaces. Thermal leaks or cold bridges are caused by flaws in the insulation layer, or by weaker insulator materials, such as the load bearing structures. An air leak is the air leaking through the envelope of the building. It is caused by the pressure difference between the inside and outside spaces. When searching for air leaks, the pressure difference over the envelope of the building should be measured. The air leaks are always imaged from the space with the lower pressure levels. [119, 9-10, 19-27.]

The weather conditions have a significant impact on thermal imaging, especially influential are sunshine and outside air temperature. The standard conditions during the imaging are minus five degrees Celsius and no sunshine. Twelve hours before the investigation, no contact with sun rays should occur with the measured object. The outside temperature should not vary more than by five degrees, and the inside temperature not more than by two degrees. If the object has massive structures, the time required without sunshine contact to the surfaces is 24 hours. If the conditions are not fulfilled, it has to be stated in the thermography report. If the conditions are not standard weather conditions, the thermal performance of the building's envelope can be analyzed using the formula (7). The formula (7) converts the values to meet the values when measured with the standard weather conditions. [18, 49-50.]

$$T_I = \frac{T_{sp}-T_o}{T_i-T_o} * 100[\%] \qquad (7)$$

T_I is temperature index

T_{sp} is inside surface temperature

T_i is indoor air temperature

T_o is outdoor air temperature.

The measured surface temperatures are calculated with formula (7) and the solved temperature indexes are compared with the reference values of table 2 below.

Table 2. The reference values and the category of the surface temperature values [21].

	Weak	Good
Wall temperature index	81 %	87%
Floor temperature index	87 %	97 %
Envelopes junctions and point temperature indexes	61 %	65 %

The reference values, from the publication Asumisterveysohje (housing health instructions) by the Finnish Ministry of Social Affairs and Health (table 2), define the level of thermal performance of interior surfaces of a building [21].

4 The measurements

The measurements for spray-type hempcrete were performed in the laboratory and in-situ. Thermal conductivity laboratory tests were carried out in HEIG-VD's civil engineering laboratory for spray-type hempcrete samples. The in-situ measurements studied the thermal performance of the envelope of residential houses isolated with sprayed hempcrete. The thermal performance studies included a thermal transmittance measurement and thermal imaging.

4.1 Thermal conductivity

The laboratory measurements in this final year project, measured mean thermal conductivity for hempcrete, the lambda 10, 25 and 40 values (λ_{10}, λ_{25} and λ_{40}). The thermal conductivity measurements in the thesis followed the standard ISO 8302 (1991)" Thermal insulation - Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus" [16]. The testing was carried out in HEIG-VD's laboratories, and five hempcrete samples made by a local Swiss construction company were tested.

The samples (figure 5) were a spray-type hemp-lime-gypsum mix, sprayed in molds (width times length, 500 x 500 millimeters and thickness 100 or 200 millimeters). The samples were done with three different mixes of hemp hurds, lime and gypsum. After spraying the test specimens, they were stored in laboratory conditions, at a temperature of 21 °C ±2 and relative humidity 50% ±10, in HEIG-VD’s GC2 laboratory. After that the samples remained in the molds for three days and then the mold was removed. The samples were left to dry for couple of months before the testing. The drying period was monitored and recorded by weighing the samples once a day.

Figure 5. A sample of hemp-lime-gypsum block in the opened testing box, before testing.

In the steady state thermal conductivity measurements, heating and cooling units create temperature differences between two surfaces of a test specimen. The whole system is isolated from the ambient air (figure 6) by an insulating box made of expanded polyester. During the testing, two surface temperatures are measured with temperature sensors, and a heat flow through the sample is measured by a heat flow sensor. A data logger registers and saves the measurement data at regular intervals. Once the thermal flow has reached an equilibrium, the measuring is continued with ten more data captures.

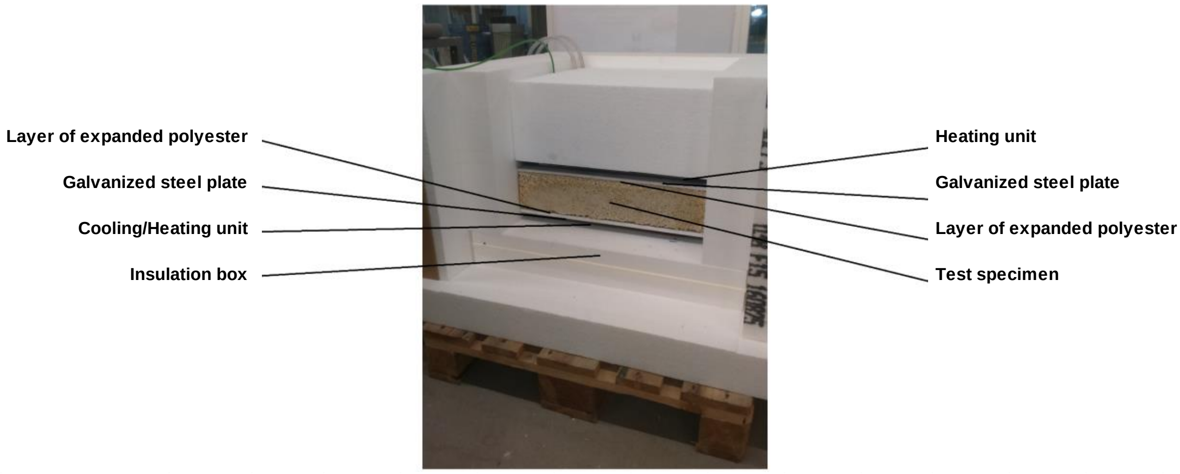

Figure 6. The testing apparatus opened from one side with explained layers.

The apparatus used in the measurements:

- A data logger
- Three surface temperature sensors
- A heat flow sensor
- Two thin galvanized steel plates (500x500 millimeters, thickness ~0.2mm)
- Heating and cooling units
- Five pieces of hempcrete test specimens, (500x500 millimeters varying thickness of 100 and 200 millimeters)
- A thin layer of insulant
- An isolation membrane to isolate the system from ambient air

As mentioned above, lambda 10, 25 and 40 tests were performed for the samples. The mean temperatures between the two surfaces of the sample are different according to the lambda value of the test. The surface temperatures for each lambda measurement are: for λ_{10}: 2.5 and 17.5 Celsius; for λ_{25}: 17.5 and 32.5 Celsius and for λ_{40}: 32.5 and 47.5 Celsius. Once the surface temperatures and the heat flux had reached a steady state, the thermal conductivity was calculated with formula (1). Each of the three mean thermal conductivity values were inserted in a graph and an average line was drawn with a spreadsheet calculation program. The linear function of the line was determined with the spreadsheet and the accurate λ_{10} was solved from the function.

4.2 Thermal transmittance

An in-situ measurement of the U-value of a wall was carried out in a residential dwelling, in Western Switzerland. The measured wall is part of an extension of a house. The extension is made from sprayed hempcrete with concrete framework (figure 7). The U-value measurements were done by measuring the temperatures and heat flow through the outer wall. The measurements were carried out with three temperature sensors (two outside and one inside) and with a heat flow sensor (inside). The measured data was recorded with a datalogger at regular intervals. The data was processed with an in-situ thermal conductance calculation software. The software calculates an average thermal transmittance from the recorded data and filters the scattering.

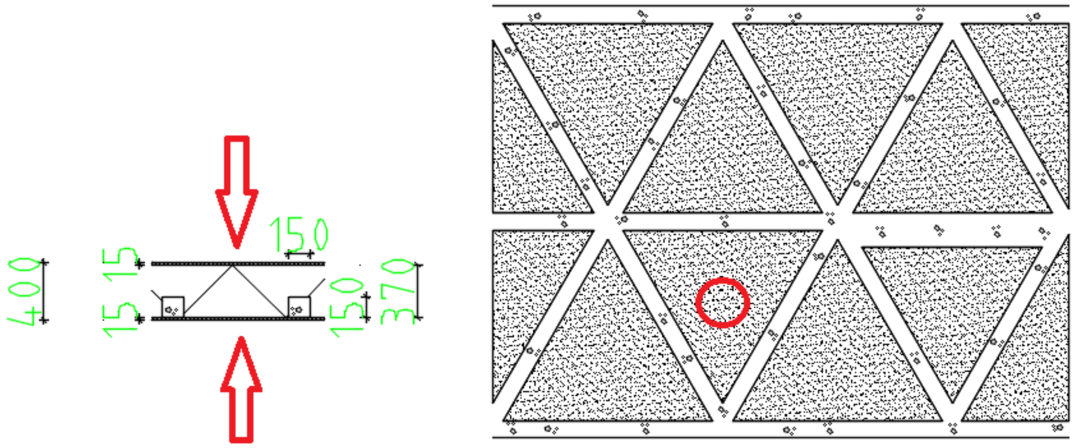

Figure 7 A sketch of the measured wall, with the sensor positions. The wall is hempcrete with lightweight concrete framework and lime render.

When performing in-situ measurements, the thermal conditions are constantly changing. Hempcrete has a high thermal inertia, therefore a high thermal lag. The measured inside and the outside temperatures create fluctuating graphs at different phases. The high or low peaks of the outside temperature have a delayed effect on the inside surface temperature. To be able to analyze the measured data correctly, the duration of the thermal lag needs to be fed in the calculation software. In this thesis, the thermal lag value for the measured wall was determined with a simple method which is not completely accurate. From the recorded data, the high temperature peaks in the outside and inside temperature graphs were highlighted and the time between them was calculated (figure 8).

Then the rough estimation of the thermal lag value was inserted in the calculation software, with margins.

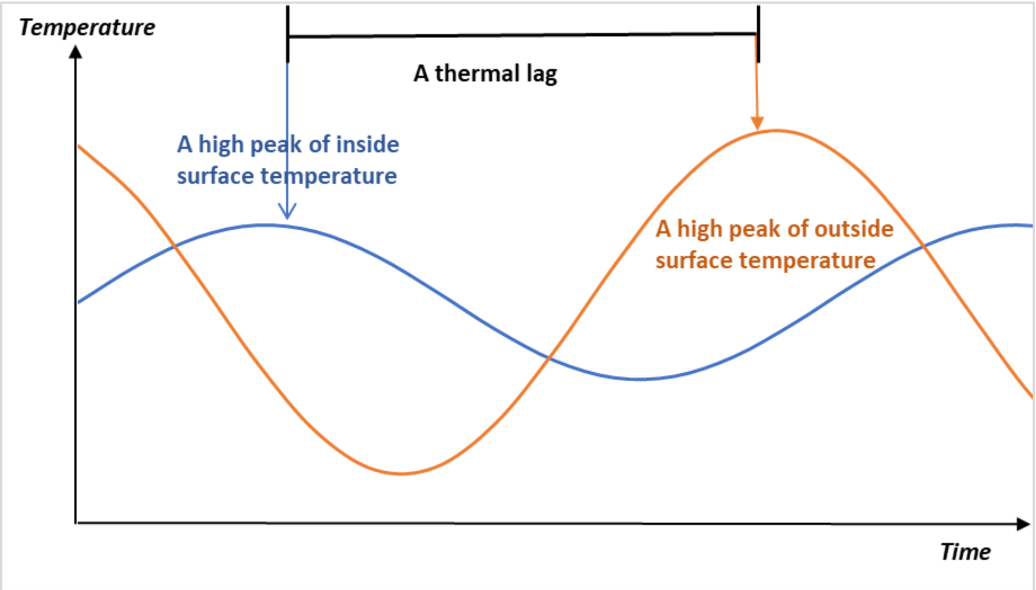

Figure 8 A simplified case of determination of thermal lag

The in-situ thermal conductance calculation software calculates the total U-value for the hempcrete wall. The wall consists of a light concrete framework, hempcrete and two inner and outer lime render layers. The single lambda value for the hempcrete layer is solved using the formula (5).

4.3 Thermal imaging

The thermal imaging in this thesis was done for four residential dwellings, in Western Switzerland. Three of the houses had been insulated with spray-type hempcrete as a thermal upgrade. The houses did not have insulation at all before. Fourth house had an extension done with sprayed hempcrete. The thermal imaging was done following the Finnish Building Information guide 1213-S Rakennuksen lämpökuvaus (Thermography in building) [22]. All the dwellings were thermographed from the outside and one of the four from the inside as well.

The thermal camera imaging process proceeds with the following steps after the object is defined. In the first step, it is crucial to gather as much background information as possible of the measured building. The more the background information the thermal camera investigator has the better outlook for success he or she has. Depending on the objective of the measurements, different information on the object is needed. Normally, plan drawings of a building provide sufficient amounts of data. The second step, based on the objective and the background information, an implementation plan is created. The plan should state the objective and all the important information related to it clearly. The plan also defines the date when the thermal camera inspection is done, which is influenced highly by the weather conditions. Since the weather cannot be perfectly predicted, an alternative date should be decided as well. In the third step the implementation plan is supplemented when performing the thermal imaging. [22.]

The actual measurements begin with a calibration of the measurement instruments and by filling in the current weather information. The calibration time for an instrument depends on the instrument. For some instruments, the calibration might take only a few minutes when moving from one temperature zone to another, and with some instruments it may take more than 30 minutes. The thermal imaging is done at a parallel angle to the measured object (+/- 30 degrees). The distance from the camera to the object when measuring from the inside is 2-4 meter and outside 10 meters or less. After the measuring, the images are processed and analyzed. [22.] The temperature values of the measurements performed from the inside are calculated with formula (7).

5 Results

The performed measurements for spray-type hempcrete were thermal conductivity laboratory measurements, in-situ thermal transmittance measurements and thermal imaging. The results for each measurement are presented below.

Thermal conductivity

The thermal conductivity measurement results are presented in table 3 below. The measurements were taken of five samples, made with one of three recipes. The first number in the sample ID tells in what order the sample was sprayed in the molds. The second numbers after the slash tell the date of the manufacturing and the recipe.

Table 3 Mean thermal conductivity (λ_{10}) test results

Sample ID	Bulk density	Thermal conductivity	Thickness
	kg / m³	λ_{10} (W / m * K)	mm
2/30.1	263.2	0.065	200
5/23.2	248.5	0.081	100
5/30.1	238.6	0.086	100
8/20.4	293.7	0.095	100
9/20.4	288.2	0.092	100

The results of the laboratory measurements for thermal conductivity laboratory measurements were similar to the values found in the literature. Therefore, it can be stated that the measurements were successful.

More thorough measurement reports can be found in appendix 1.

Thermal transmittance

The in-situ thermal transmittance measurements in this thesis was done to exterior wall in an extension of a residential house. The extension walls were made from hempcrete with a light concrete framework. The walls were rendered both from the inside and outside with a lime render. The measured data analysis was done with a calculation software which calculates the total thermal transmittance for the measured wall. The total thermal transmittance value for the multi-layer wall was *0.178 W / m*^{2} ** K*. The result was better than expected. The lambda laboratory tests did not indicate that the hempcrete wall would perform as well as it did in-situ.

From the total thermal transmittance, the thermal conductivity of the hempcrete layer was solved from the equation (3). The result was *0.065 W / K * m*. It was similar to the lambda 10 value that was tested in laboratory. The lambda laboratory measurement results are given in the Thermal conductivity section above.

The calculation software's thermal transmittance report can be found in appendix 2.

Thermal imaging

Thermal imaging in this thesis aimed at locating weaknesses in a hemp insulation layer, by locating higher temperatures on the exterior surface of the measured buildings. Overall the insulation layer had quite steady surface temperatures. Weaker spots (higher thermal conductance) were obviously the areas without an insulation layer and the areas, such as the joints, corners and the structures, penetrating the insulation layer had warmer surface temperatures. In other words, those areas create more heat losses through the envelope. On average, the sprayed hempcrete performs well as a thermal insulant. In one of the houses thermal imaging was done both from the inside and outside. The measurements from the inside investigated the indoor thermal comfort. The measured temperatures were inserted in formula (7) and the calculation results were compared with the reference values in Asumisterveysohje (table 2). The thermography study located two air leaks which had lower temperatures than recommended. Other than that, no significant deviation was found from the surface temperatures. It can be said that the interior of the house is thermally comfortable.

6 Analysis

The analysis of the measurements performed in this thesis and the results of the measurements is presented in this chapter. The measurements performed were: the thermal conductivity measurements for spray-type hempcrete samples in laboratory and the thermal transmittance in-situ measurements and the thermal done to existing hemp houses. The analysis focuses on how the measurement procedure went, how successful the measurements were and how accurate the results were. Each subtitle presents suggestions to improve the measurements in the future.

6.1 Thermal conductivity

The laboratory tests for thermal conductivity were carried out to define the lambda-10 value for samples of sprayed lime-gypsum-hemp insulation. The test specimens were made with different mixes of hemp, lime, gypsum and water; thus, the results were expected to cover a wide scale expected.

The laboratory measurements followed the standard ISO 8302. The standardized measurement is meant for a homogenous insulation material. However, in this thesis the samples were heterogenous. When measuring a heterogenous test specimen by following the standard ISO 8302 the results may be unreliable. The heterogenous materials, with great porosity, might allow heat transfer by convection. The insulation materials are manufactured in a way that the heat transfer by convection is reduced to minimum, which is possible due to the tiny air bubbles, as explained above in chapter 3.

The results indicated that the thick sample (20/30.1) had superior thermal conductivity value compared to the thin ones, although the thermal conductivity value is not proportional to the thickness of a material. The difference was notable. The difference can be explained with the theory above. The thin samples are more likely less air tight than the thick one. Therefore, the effect of heat transfer by convection is less. In the regular use hempcrete has a render on both sides, making it airtight.

The sample 2/30.1 was measured only in mean temperature difference of 10 degrees (λ_{10}) so the other two lambdas (25 and 40) were left outside. In fact, it is hard to draw any conclusions between the thickness and the possible heat transfer by convection in the samples with this low and vague of a measurement procedure.

The recommended follow up is to increase the sampling. Each recipe and thickness should be a unique set for testing. Additionally, tests done with rendered samples could provide information of the heat transfer by convection. After these procedures, the tests could be proven valid or invalid.

6.2 Thermal transmittance

The thermal transmittance in-situ measurements studied the performance of sprayed hempcrete performance in its real environment. The in-situ measurement gives important and realistic data on the thermal performance of sprayed hempcrete. When calculating the energy losses in buildings, the in-situ values can be used in order to get realistic values of the energy transmitted through the envelope.

The hydroscopicity of hempcrete and lime render makes the in-situ measurements interesting. The study wanted to investigate how the changing humidity levels influence the heat conduction when comparing the results with the laboratory test results presented in this thesis. The measured wall performed surprisingly well, usually the performance of the thermal insulation material in the field is weaker than the performance in laboratory tests. In this case the lambda calculated from the total U-value was even lower than the lowest lambda-10 value tested in laboratory in this thesis. The in-situ lambda value for the hempcrete layer was close to the values found in literature. The exceptionally good value could be explained with the theory explained in in the chapter 6.1: the thicker hempcrete layer and the layer without render could transfer heat with convection.

A lot of uncertainties have an influence on the outcome of in-situ thermal transmittance measurements. Some of the uncertainties are the constantly changing weather circumstances and changing circumstances of the indoor air; the weather changes the temperature and the humidity levels. The indoor air is influenced by the habitants. For example, a showering person increases the humidity level. The changes occur rapidly. The calculation software for thermal transmittance calculates an average of the measured data and it filters the biggest deviation, making the result reliable. In the best-case scenario, the same wall could be tested both in-situ and in a laboratory.

6.3 Thermal imaging

The thermal imaging study investigated the thermal performance of the residential dwellings insulated with spray-type hempcrete. The study attempted to discover temperature differences in the surface temperatures. There were hardly any significant temperature differences in the parts with the sprayed hempcrete layer. One part of the thermographic inspection was to investigate if the dwellings have thermal bridging. Based on the thermal images it can be stated that at the least the effect of thermal bridging is reduced by the insulation layer although the phenomena are relatively difficult to locate in the dwellings with the supplement insulation. One of the dwellings was inspected from the inside, to study the material’s effect on thermal comfort. Although two air leaks were found the temperature of the surfaces was sufficient to ensure the thermal comfort to the inhabitants. The source of the air leaks is most possibly the base floor and inner wall joint, in contact with to the cold basement. Therefore, the air leaks do not concern the hemp insulation layer.

The resolution of thermal camera was quite low. In the field the thermal camera screen was hard to read, and the temperature variations were hard to locate. Because of that, no close-ups of the high temperature spots were taken. The resolution influences the quality of the analyses. Three of the four houses were photographed only from the outside and no information about the inside thermal conditions is known. The knowledge of the inner conditions would have helped in the analysis. It is recommended to perform thermal camera measurements again with a thermal camera with a better resolution and with a larger temperature difference between the outside and inside temperature. Also, the three houses which were photographed only from the outside should be imaged from the inside.

7 Conclusions

The building and construction sectors cause a significant deal of the greenhouse gas emissions globally. The potential of reducing the emissions of the construction sector is substantial. After climate agreements, countries have set regulations aiming at reducing energy use in buildings. [2, 1-6.] It seems like, the trend of increasingly rising energy regulations is leading to the point where in the future the new buildings are going to be either, extremely low-energy buildings or passive houses. Some of the passive houses in present day have had problems with the indoor air quality. Problems such as improper humidity levels, indoor air pollutants and high CO_2 and temperature levels. [23.] A natural and hydrothermal insulation material such as hempcrete could provide a part of the solution to the indoor air quality problems. In the United States a passive hemp house has been built. The result has been good, clean indoor air and low energy house with thermally comfortable indoor air. [24.]

Without trivializing the impact or the proportion of new buildings in the total energy consumed by the buildings, concern was the not so energy efficient older buildings. The old building stock possesses a great potential of reducing energy use. There are several approaches when considering options to improve the energy performance of a building. Some old, and even fairly new buildings, in areas that require heating or cooling systems, might have no thermal insulation at all. When performing a thermal update to a building, thermal insulation is the easiest way to make a thermal update. Adding or improving thermal insulation to a building with inferior or no insulation is an extremely cost-efficient way to improve the thermal performance. A good design and calculations must be done to evade some risks, for example an unwanted dew point in the structures creates a lot of harm.

The focus of this thesis was to study a low-environmental impact construction material hempcrete. The material itself creates very little emissions and, with its thermal insulation abilities, lowers a building’s energy use in heating and cooling. The thesis focused on the thermal characteristics of the material by performing laboratory and in-situ tests. The tests were planned to fill each other’s gaps. The thermal conductivity test performed in a laboratory measured a single ability of a material in steady state. The value is commercially important. In real life it only tells a little about the real thermal performance. That is why the thesis wanted to introduce in-situ tests as well. The thermal transmittance test studied the same phenomena as the thermal conductivity test. The in-situ thermal transmittance results were compared to the thermal conductivity values measured in the laboratory. The in-situ thermal transmittance test was done only in one measuring spot. Thus, a thermal camera study concentrated on establishing how the whole envelope of a building performs. The thermal camera study also aimed to prove that the results of the thermal transmittance measurements can be trusted. If the thermal performance of the envelope is uniform, then the transmittance is uniform as well. With thermography research, the aim was also to study how the abilities claimed in literature function in real life.

Based on the studies performed for this thesis, it can be stated that hempcrete works well as a thermal insulant. If only its lambda value was discussed, it would not seem to perform exceptionally well as an insulant. When taking into account the whole package, hempcrete can provide high thermal inertia, no thermal bridges and the overall thermal transmittance with the recommended thickness. It cannot be denied that it has a great potential as a thermal insulation material. Designers and installers should be trained in the design and the method of construction to fulfill the material’s potential. For example, the direction of the windows, or perhaps a thicker and higher thermal inertia wall should be directed in a manner that the thermal inertia would benefit the most from the sun rays. At its best, hempcrete is done as near production by local craftmanship, and the result is houses that are thermally comfortable, healthy to live in, ecological and low on energy consumption.

The paper concentrates almost only on the good abilities the material possesses. In the literature it was difficult to find disadvantages of the material. The major argument for hempcrete is perhaps its carbon negativity. It can be seen as a bit misleading. The total emissions, during the lifecycle of hempcrete, are much more than the carbon dioxide emissions. However, since the CO_2 emissions are in the spotlight, they suggest material that has no emissions at all or has a negative effect on the global warming. That said, hempcrete creates less emissions compared to the more commonly used materials. I believe that with materials like hempcrete the future looks brighter. Not all buildings can nor should they be constructed with hemp, but the material has its place and could be exploited more widely.

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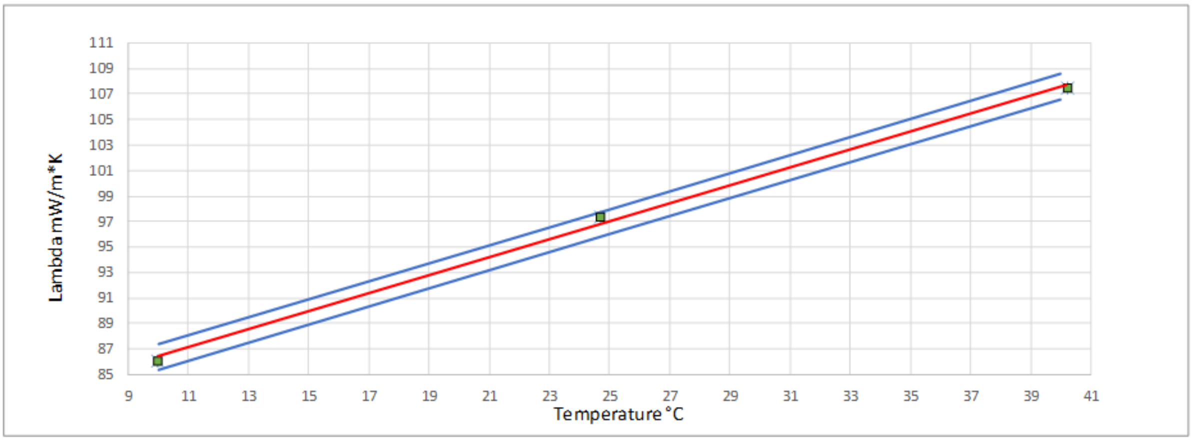
THERMAL CONDUCTIVITY MEASUREMENT REPORT

Date	1.7.2017
Report n°	1
Institution	HEIG-VD
Testing equipment	LSI-Lastem's M-Log (ELO009), Heatflow sensor (ESR240), Surface temperature sensor (EST124)
Configuration of the equipment	
Operator	Jere Komsi

Reference of the specimen	Hempcrete 5/30.1	**Dimension of the test specimen**	
Origin	HEIG-VD	**Cross section**	500 mm x 500 mm
Fabrication date	30.1.2017	**Measured thickness**	100 mm
Definition of product	Hemp lime gypsum	**Nominal thickness**	100 mm
Description of product	Thremal insulation	**Mass**	5965 g
		Density	238.6 kg / m³

Preparation and storage T 21 +/- 2 C RH 50 +/- 10

Evaluation of mass
The drying cycle
The measuring cycle
Humidity rate before measurement
Pressure on the specimen during the measurement



	Measurement 1	Measurement 2	Measurement 3
Test number	Hempcrete	Hempcrete	Hempcrete
Testing temperature °C	10.0	24.7	40.2
Temperature difference. K	14.7	14.7	15.6
Lambda in mW/m*K	86.11	97.36	107.5
R in m^2K/W	1.161	1.027	0.931

Polynome of regression Lambda f(T):
*y = f(T) = 0.705 * T + 79.36*

lambda-10	86.41mW/(m*K)
R-10	1.157 m^2K/W
TC	0.705 mW/(m*K)

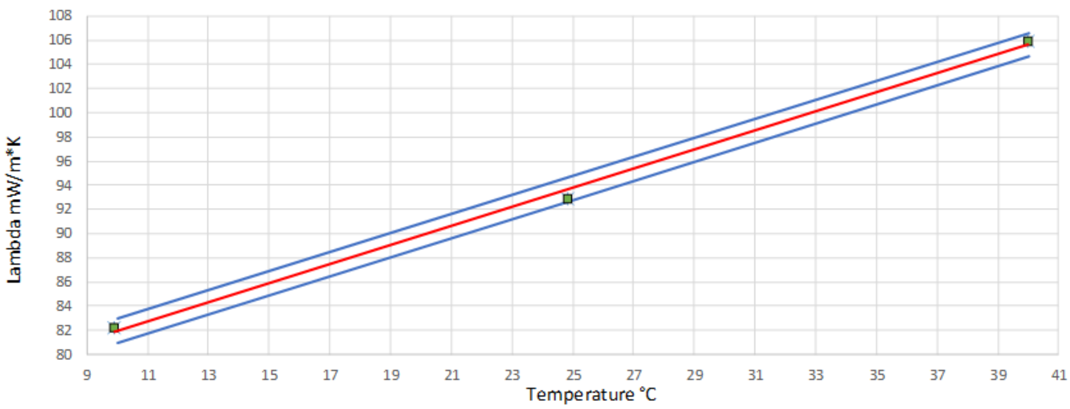
THERMAL CONDUCTIVITY MEASUREMENT REPORT

Date	6.7.2017
Report n°	2
Institution	HEIG-VD
Testing equipment	LSI-Lastem's M-Log (ELO009), Heatflow sensor (ESR240), Surface temperature sensor (EST124)
Configuration of the equipment	
Operator	Jere Komsi

Reference of the specimen	Hempcrete 5/23.2	**Dimension of the test specimen**	
Origin	HEIG-VD	**Cross section**	500 mm x 500 mm
Fabrication date	23.2.2017	**Measured thickness**	100 mm
Definition of product	Hemp lime	**Nominal thickness**	100 mm
Description of product	Thremal insulation	**Mass**	6226 g
		Density	248.5 kg / m³

Preparation and storage T 21 +/- 2 C RH 50 +/- 10

Evaluation of mass
The drying cycle
The measuring cycle
Humidity rate before measurement
Pressure on the specimen during the measurement



	Measurement 1	Measurement 2	Measurement 3
Test number	Hempcrete	Hempcrete	Hempcrete
Testing temperature °C	9.9	24.8	40.0
Temperature difference. K	14.9	15.0	15.1
Lambda in mW/m*K	82.22	92.29	106.01
R in m²K/W	1.216	1.084	0.9433

Polynome of regression Lambda f(T):
*y = f(T) = 0.7892 * T + 74.05*

lambda-10	81.19 mW/(m*K)
R-10	1.232 m²K/W
TC	0.7892 mW/(m*K)

THERMAL CONDUCTIVITY MEASUREMENT REPORT

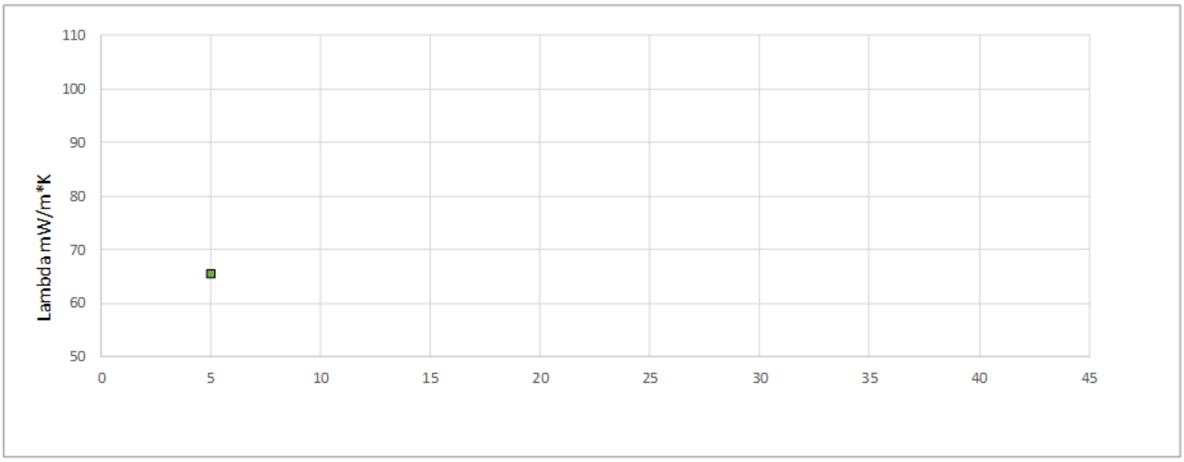
Date	11.7.2017
Report n°	3
Institution	HEIG-VD
Testing equipment	LSI-Lastem's M-Log (ELO009), Heatflow sensor (ESR240), Surface temperature sensor (EST124)
Configuration of the equipment	
Operator	Jere Komsi

Reference of the specimen	Hempcrete 2/30.1	**Dimension of the test specimen**	
Origin	HEIG-VD	**Cross section**	500 mm x 500 mm
Fabrication date	30.1.2017	**Measured thickness**	200 mm
Definition of product	Hemp lime gypsum	**Nominal thickness**	200 mm
Description of product	Thremal insulation	**Mass**	13159.0 g
		Density	263.2 kg / m³

Preparation and storage T 21 +/- 2 C RH 50 +/- 10

Evaluation of mass
- **The drying cycle**
- **The measure cycle**

Humidity rate before measurement
Pressure on the specimen during the measurement



	Measurement 1	Measurement 2	Measurement 3
Test number			
Testing temperature °C	9.9		
Temperature difference. K	15.2		
Lambda in mW/m*K	65.48		
R in m^2K/W	3.054		

Polynome of regression Lambda f(T):
*y = f(T) = 0 * T +*

lambda	65.48 mW/(m*K)
R	3.054 m^2K/W
TC	mW/(m*K)

heig-vd

RAPPORT D´ ESSAIS THERMIQUES

selon EN 12667 et EN 12664

Date	20.07.2017
Rapport n°	BetonChanvre_8-BetonChanvreEssai3
Institution d´ essai	HEIG-VD
Equipment d´ essai	appareil de mesure de conductivité thermique 'lambda-Meter EP500e' selon EN 1946-2, constructeur Lambda-Messtechnik GmbH Dresden
Configuration d´ équipement	Plaques horizontales, face chaude en partie supérieure Mesure avec compensateurs de ... mm d'épaisseur et film équipé de capteur pour mesure de température
Références normatives	Mesure de l´épaisseur selon norme EN 823 Mesure de la cond. therm. réalisée selon normes ISO 8302 et EN
Opérateur	Morgane Giorgi

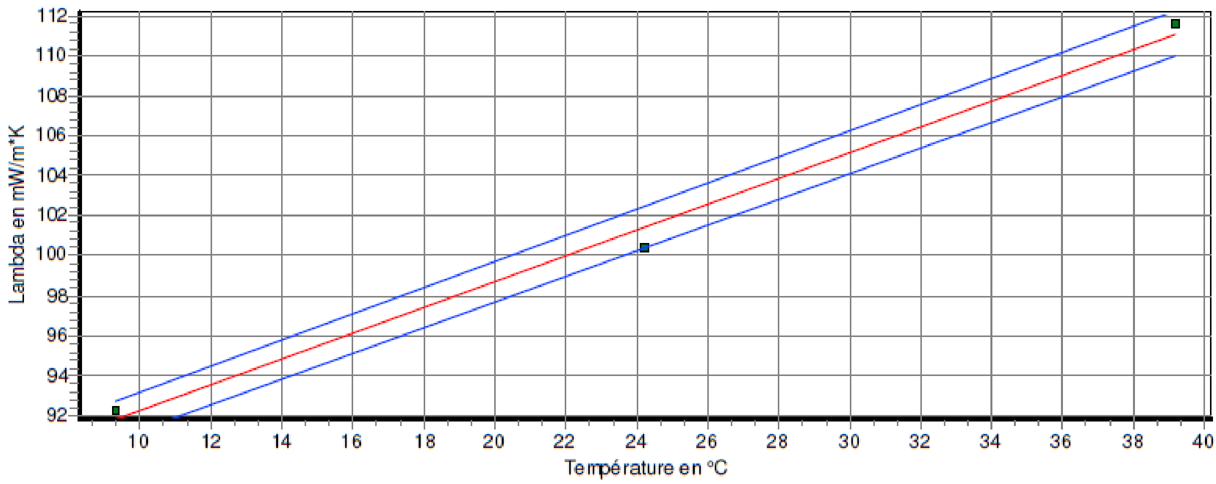
Référence de l´ éprouvette	BetonChanvre_8	**Dimensions de l´ éprouvette**	
Origine	HEIG-VD	**Section**	496 mm x 497 mm
Date de fabrication		**Epaisseur mesurée**	107.17 mm
Produit - Définition	Béton de chanvre	**Epaisseur nominale**	100 mm
Produit - Description	Béton de chanvre avec fibres apparentes	**Masse**	7613.2 g
		Masse volumique	288.2 kg/m

Préparation et stocké ... jours avant la mesure, à ...% d'humidité atmosphérique et ...°C.

Evolution de la masse durant:
le cycle de séchage
le cycle de mesure

Taux d´ humidité avant la mesure

Pression sur l´ éprouvette lors de la me: 1000 Pa



	Mesure 1	Mesure 2	Mesure 3
Numéro d´ essai	BetonChanvreE	BetonChanvre	BetonChanvre
Temp. d´ essai °C	9.3	24.2	39.2
Diff. de temp. K	15	15	15
Lambda en mW/m*K	92.28	100.43	111.6
R en m²K/W	1.1614	1.0671	0.9603

Polynôme de régression Lambda f(T):

y = ƒ(T) = 0.6463 * T + 85.78

lambda-10	92.24	mW/(m*K)
R-10	1.1619	m?*K/
TC	0.6463	mW/(m*K?

20.07.2017

signature

RAPPORT D´ ESSAIS THERMIQUES

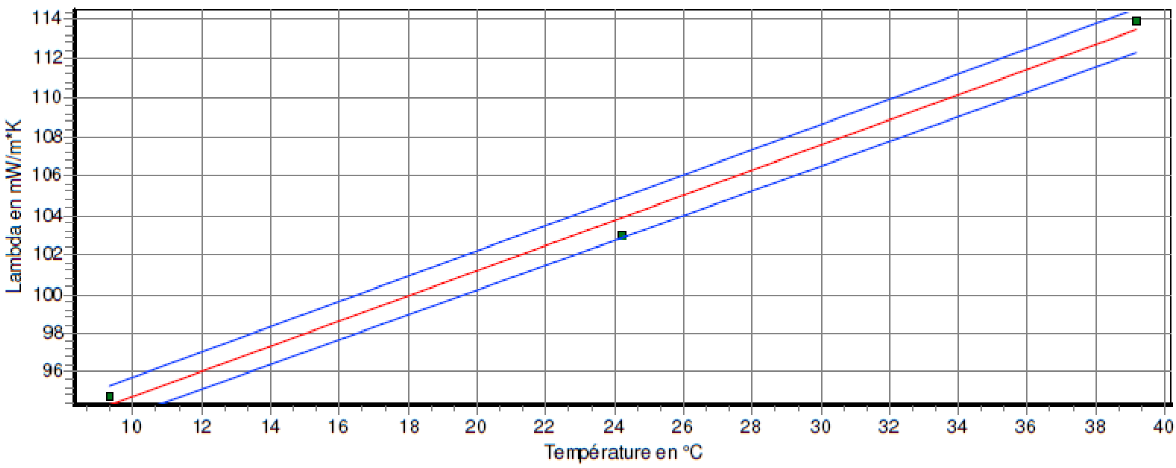
selon EN 12667 et EN 12664

Date	17.07.2017
Rapport n°	BetonChanvre_9-BetonChanvreEssai3
Institution d´ essai	HEIG-VD
Equipment d´ essai	appareil de mesure de conductivité thermique 'lambda-Meter EP500e' selon EN 1946-2, constructeur Lambda-Messtechnik GmbH Dresden
Configuration d´ équipement	Plaques horizontales, face chaude en partie supérieure Mesure avec compensateurs de ... mm d'épaisseur et film équipé de capteur pour mesure de température
Références normatives	Mesure de l´épaisseur selon norme EN 823 Mesure de la cond. therm. réalisée selon normes ISO 8302 et EN
Opérateur	Morgane Giorgi

Référence de l´ éprouvette	BetonChanvre_9	**Dimensions de l´ éprouvette**	
Origine	HEIG-VD	**Section**	498 mm x 494 mm
Date de fabrication		**Epaisseur mesurée**	105.95 mm
Produit - Définition	Béton de chanvre	**Epaisseur nominale**	100 mm
Produit - Description	Béton de chanvre avec fibres apparentes	**Masse**	7639 g
		Masse volumique	293.7 kg/m

Préparation et stocké ... jours avant la mesure, à ...% d'humidité atmosphérique et ...°C.

Evolution de la masse durant:
le cycle de séchage
le cycle de mesure
Taux d´ humidité avant la mesure
Pression sur l´éprouvette lors de la me: 1000 Pa



	Mesure 1	Mesure 2	Mesure 3
Numéro d´ essai	BetonChanvreE	BetonChanvre	BetonChanvre
Temp. d´ essai °C	9.3	24.2	39.2
Diff. de temp. K	15	15	15
Lambda en mW/m*K	94.81	103	113.85
R en m²K/W	1.1175	1.0286	0.9306

Polynôme de régression Lambda f(T):
y = ƒ(T) = 0.6369 * T + 88.45

lambda-10	94.82	mW/(m*K)
R-10	1.1174	m?*K/
TC	0.6369	mW/(m*K?

20.07.2017

signature

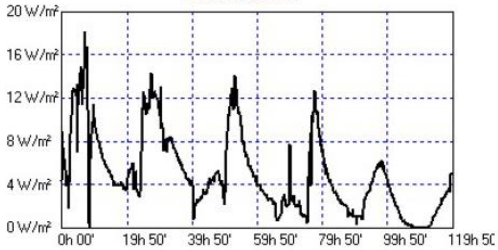
IN SITU CALCULATION OF THERMAL TRASMITTANCE

Measurement carried out by:	Jere Komsi
Building:	Domestic dwelling
Located in:	Western Switzerland

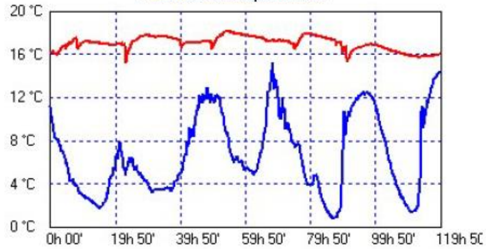
DATA

File	
Measurement start	Data: 30.04.2016, hour: 15.10.00
Measurement end	Data: 05.05.2016, hour: 15.00.00
Measurement number	720
Sampling rate	10'

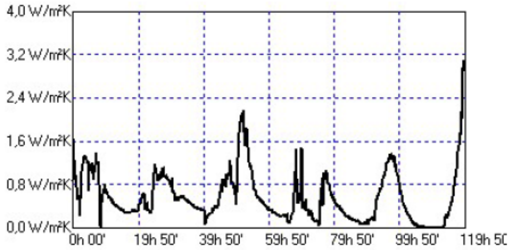
Measured flux



Measured temperatures



Instantaneous conductance



BLACK-BOX METHOD

Setup parameters	
na	0 - 10
nb1	1 - 10
nb2	40 - 56
Tolerance	0.05

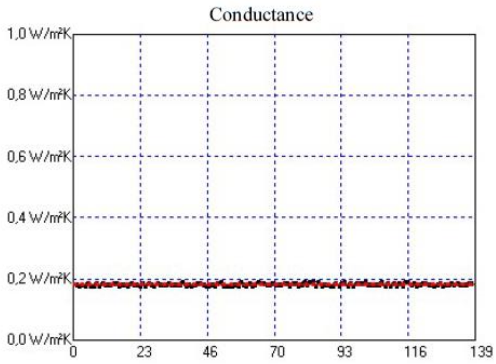
Valid models						
	na	nb1	nb2	Flux error	Conductance error	Conductance [W/m²K]
1	1	3	43	0,7911	0,0155	0,1841
2	1	3	47	0,7848	0,0011	0,1794
3	1	4	43	0,7909	0,0049	0,1824
4	1	4	47	0,7846	0,0166	0,1768
5	1	5	43	0,7905	0,0275	0,1861
6	1	5	47	0,7842	0,0052	0,1804
7	1	6	43	0,7891	0,0270	0,1767
8	1	6	46	0,7842	0,0268	0,1881
9	1	7	43	0,7890	0,0218	0,1775
10	1	8	43	0,7879	0,0217	0,1848
11	1	8	47	0,7810	0,0158	0,1819
12	1	9	43	0,7879	0,0191	0,1844
13	1	9	47	0,7810	0,0125	0,1814
14	2	2	56	0,5764	0,0456	0,1855
15	2	3	43	0,7908	0,0247	0,1855
16	2	3	47	0,7847	0,0013	0,1797
17	2	3	56	0,5763	0,0199	0,1808
18	2	4	43	0,7906	0,0123	0,1835

19	2	4	47	0,7845	0,0139	0,1772
20	2	5	43	0,7902	0,0356	0,1873
21	2	5	47	0,7842	0,0080	0,1808
22	2	5	54	0,5708	0,0259	0,1830
23	2	6	43	0,7888	0,0195	0,1778
24	2	6	46	0,7842	0,0298	0,1886
25	2	7	43	0,7888	0,0150	0,1786
26	2	8	43	0,7876	0,0327	0,1865
27	2	8	47	0,7810	0,0200	0,1826
28	2	8	54	0,5640	0,0476	0,1769
29	2	9	43	0,7876	0,0325	0,1864
30	2	9	47	0,7810	0,0174	0,1822
31	2	10	54	0,5623	0,0076	0,1840
32	3	1	47	0,7863	0,0225	0,1831
33	3	2	43	0,7930	0,0375	0,1871
34	3	2	47	0,7863	0,0146	0,1817
35	3	3	43	0,7903	0,0106	0,1831
36	3	3	56	0,5762	0,0337	0,1835
37	3	4	43	0,7901	0,0040	0,1807
38	3	4	46	0,7852	0,0359	0,1895
39	3	4	54	0,5711	0,0487	0,1786
40	3	5	43	0,7895	0,0203	0,1846
41	3	5	47	0,7832	0,0113	0,1774
42	3	5	54	0,5708	0,0209	0,1840
43	3	6	46	0,7832	0,0100	0,1851
44	3	7	46	0,7831	0,0247	0,1876
45	3	8	43	0,7868	0,0167	0,1837
46	3	8	47	0,7799	0,0004	0,1791
47	3	8	54	0,5638	0,0348	0,1796
48	3	9	43	0,7868	0,0137	0,1832
49	3	9	47	0,7799	0,0061	0,1781
50	3	10	47	0,7789	0,0416	0,1862
51	3	10	54	0,5620	0,0185	0,1892
52	4	1	43	0,7912	0,0026	0,1805
53	4	1	56	0,5761	0,0108	0,1785
54	4	2	43	0,7910	0,0138	0,1784
55	4	2	54	0,5749	0,0431	0,1769
56	4	2	55	0,5730	0,0021	0,1825
57	4	3	43	0,7891	0,0240	0,1771

	4	3	46	0,7843	0,0292	0,1888
59	4	3	55	0,5730	0,0014	0,1818
60	4	4	43	0,7891	0,0249	0,1770
61	4	4	46	0,7843	0,0261	0,1883
62	4	5	43	0,7886	0,0029	0,1806
63	4	6	46	0,7827	0,0052	0,1846
64	4	6	52	0,5684	0,0177	0,1901
65	4	6	53	0,5674	0,0183	0,1880
66	4	7	46	0,7826	0,0201	0,1871
67	4	8	43	0,7863	0,0031	0,1813
68	4	9	43	0,7863	0,0010	0,1809
69	4	10	43	0,7852	0,0479	0,1886
70	4	10	47	0,7782	0,0214	0,1826
71	5	1	47	0,7786	0,0253	0,1824
72	5	2	47	0,7786	0,0208	0,1816
73	5	2	54	0,5746	0,0007	0,1858
74	5	2	55	0,5730	0,0173	0,1856
75	5	3	47	0,7767	0,0042	0,1790
76	5	3	54	0,5746	0,0023	0,1852
77	5	3	55	0,5730	0,0140	0,1850
78	5	4	47	0,7765	0,0053	0,1775
79	5	6	43	0,7831	0,0082	0,1830
80	5	6	46	0,7784	0,0419	0,1906
81	5	7	43	0,7830	0,0022	0,1813
82	5	7	46	0,7784	0,0415	0,1905
83	5	8	43	0,7819	0,0460	0,1893
84	5	8	47	0,7740	0,0042	0,1775
85	5	9	43	0,7819	0,0465	0,1894
86	5	9	47	0,7740	0,0059	0,1772
87	5	10	47	0,7734	0,0336	0,1839
88	6	1	43	0,7836	0,0035	0,1811
89	6	2	43	0,7834	0,0077	0,1791
90	6	3	43	0,7811	0,0162	0,1782
91	6	3	46	0,7759	0,0299	0,1886
92	6	4	43	0,7810	0,0193	0,1778
93	6	4	46	0,7758	0,0209	0,1870
94	6	4	53	0,5670	0,0086	0,1899
95	6	5	43	0,7810	0,0179	0,1779
96	6	5	46	0,7757	0,0234	0,1874
97						

	6	6	43	0,7809	0,0247	0,1768
98	6	6	46	0,7757	0,0164	0,1862
99	6	6	53	0,5662	0,0194	0,1881
100	6	7	46	0,7757	0,0115	0,1853
101	6	7	53	0,5662	0,0060	0,1907
102	6	8	43	0,7790	0,0123	0,1828
103	6	9	43	0,7790	0,0125	0,1828
104	6	10	47	0,7704	0,0214	0,1821
105	7	1	47	0,7712	0,0311	0,1834
106	7	2	47	0,7712	0,0267	0,1827
107	7	3	43	0,7783	0,0479	0,1892
108	7	3	47	0,7693	0,0098	0,1800
109	7	4	43	0,7782	0,0435	0,1886
110	7	4	47	0,7692	0,0035	0,1790
111	7	5	43	0,7782	0,0434	0,1886
112	7	5	47	0,7692	0,0004	0,1785
113	7	6	43	0,7778	0,0273	0,1859
114	7	7	43	0,7764	0,0140	0,1790
115	7	7	46	0,7704	0,0339	0,1892
116	7	8	43	0,7743	0,0466	0,1890
117	7	8	47	0,7650	0,0146	0,1809
118	7	9	43	0,7741	0,0345	0,1871
119	7	9	47	0,7648	0,0026	0,1781
120	7	10	47	0,7642	0,0345	0,1844
121	8	1	54	0,5683	0,0368	0,1871
122	8	1	55	0,5685	0,0401	0,1871
123	8	6	47	0,7663	0,0297	0,1833
124	8	7	43	0,7740	0,0179	0,1842
125	8	7	47	0,7643	0,0114	0,1767
126	8	8	47	0,7634	0,0229	0,1823
127	8	9	43	0,7731	0,0418	0,1882
128	8	9	47	0,7632	0,0092	0,1801
129	8	10	47	0,7629	0,0358	0,1846
130	9	1	54	0,5683	0,0211	0,1844
131	9	1	55	0,5684	0,0272	0,1849
132	9	7	47	0,7629	0,0252	0,1831
133	9	8	47	0,7624	0,0480	0,1868
134	9	9	47	0,7617	0,0214	0,1827
135	10	1	54	0,5683	0,0048	0,1814

	10	1	55	0,5684	0,0172	0,1831
137	10	7	47	0,7627	0,0416	0,1861
138	10	9	47	0,7614	0,0389	0,1860



Average conductance	0,1833 W/m²K
Standard deviation	0,0039 W/m²K
Average tramittance	0,1777 W/m²K

Report created by INFOFLUX software
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