DT175 BSc (Hons) Architectural Technology

TECH4200 - Thesis

TDS_T6.2_Final Presentation of Research Work

By: Killian Markey

Student Number: C19422132

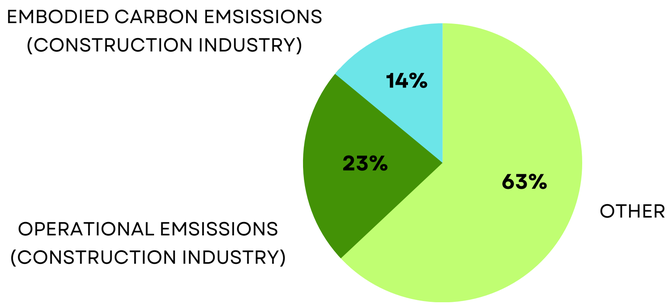
An Investigation of the physical and thermal properties of Irish Hemp Fibres as a loose-fill insulation product

1. INTRODUCTION

INTRODUCTION

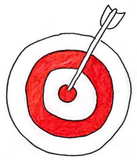
This study focuses on the encouragement of the use of biodegradable and low embodied carbon materials, hemp-based insulation in particular. This stems from the need to lower carbon emissions. This study will investigate the possibility of having a lower embodied carbon insulation which is fully biodegradable by potentially improving existing hemp fibre batt insulation by removing the polyester (plastic) binder. Plastic is a non-biodegradable non-renewable resource which requires high energy to manufacture increasing carbon emissions.

GLOBAL CARBON DIOXIDE EMISSIONS (2022)



AIM

The main aim of the study is to develop the information available on the thermal and physical properties of hemp fibres and how they can be best used as a loose-fill insulation material.



SCOPE

To achieve the aim of this study, both primary and secondary research will be conducted.

Primary - Hot box testing will be conducted to assess the thermal performance of various hemp fibre specimens.

Secondary - Existing literature will aid in the assessment of what obstacles hemp fibre as a loose-fill insulation will face.

A limitation of this research was the quantity of hemp fibre obtained for testing. This is due to the lack of hemp processing infrastructure in Ireland.

HEMP PLANT USED

The Irish Hemp Farmers Association was contacted and a farmer named Willie Annett located in Banbridge, Co. Down supplied this research with the Finola variant of Hemp plants.

The hemp plants obtained were processed to isolate the hemp fibres which were required for testing.

DUAL HEMP VARIANT

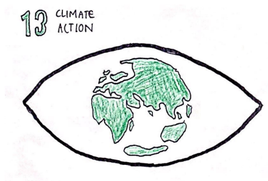
1.5 m HIEGHT

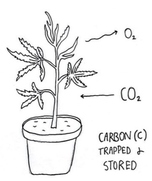
OBJECTIVES

1. Review literature and conduct desktop research to assess the effects of using polyester (plastic) binders within construction, and within hemp fibre based insulations.
2. Investigate the processing of hemp fibres, to better understand the process, and conduct hemp processing to obtain fibres for testing.
3. Identify the optimum density of Irish hemp fibres in a mixed orientation for thermal conductivity as an insulation material.
4. Determine the influence fibre orientation and fibre length has on hemp fibres thermal conductivity, as an insulating material.

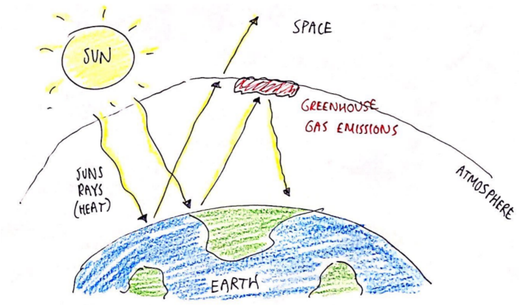
MOTIVATION

Hemp-based materials have a lower embodied energy due to their lower energy intensive manufacturing process, largely largely because of carbon sequestration during their growth phase. This helps to create lwer embodied carbon construction materials.



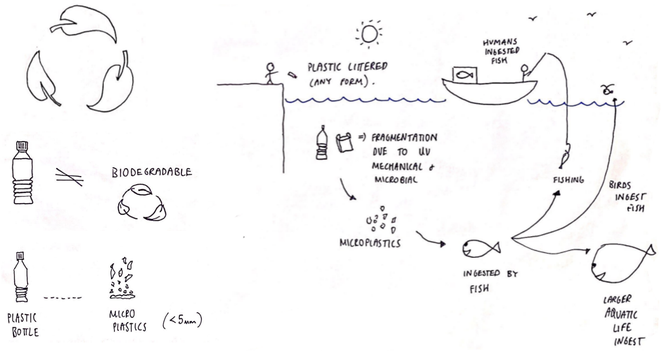


MOTIVATION

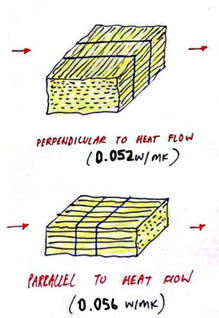


Hemp-based insulations exist in the form of insulation batts composing of hemp fibres and a polyester/synthetic binder.

The use of **plastics are harmful to the environment as they can develop into microplastics** which are not biodegradable and can cause health problems when ingested. Plastics also have an energy intensive manufacturing process which can increase the embodied carbon value also.



MOTIVATION OF TESTING



Study by Costes et al. (2017) investigated the **orientation of fibres in a straw bale had an effect on thermal conductivity**. They also found that **an increase in density led to an increase in thermal conductivity in the straw bale insulation material** (worse performing thermally).

A study on construction professionals done by Gieskam et al. (2015) found that the **top "Barrier to use of" "Lower embodied carbon" materials is the "lack of technical knowledge or training"**.

AN INVESTIGATION OF THE PHYSICAL AND THERMAL PROPERTIES OF IRISH HEMP FIBRES AS A LOOSE-FILL INSULATION PRODUCT

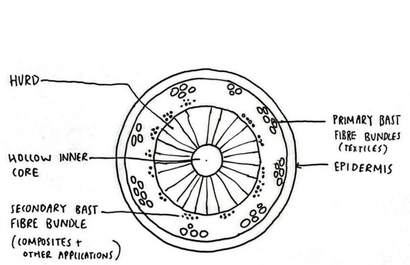
2. DESKTOP RESEARCH

Biobased insulations

Natural materials usually have a lower embodied energy as they require less energy during the manufacturing process. Plants are a renewable source and will not deplete.

What are hemp fibres?

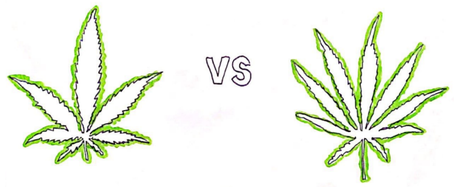
Hemp is an annual plant whose stem contains a woody core surrounded by an outer skin layer containing fibres.



Industrial hemp

Hemp (industrial hemp) and Marijuana plants are the **same species (Cannabis sativa)** but with different levels of tetrahydrocannabinol (THC), the psychoactive component of the plant.

Industrial hemp legally **cannot contain more than 0.02% THC** (Teagasc, 2023).



Hemp **Marijuana**

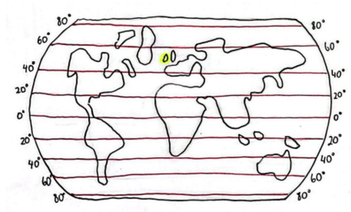
Why use hemp as a material?

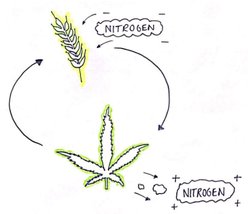
Locally grown & Break Crop potential

Hemp plants can be grown in Irelands climate, and legally with a license from the department of Health. Locally grown materials = less transportation carbon emissions.

Hemp is a good rotational break crop and will increase yield of of following crop. Harvested approx. 100 days after sew.

The hemp industry is slow to take off due to the lack of processing infrastructure in Ireland.

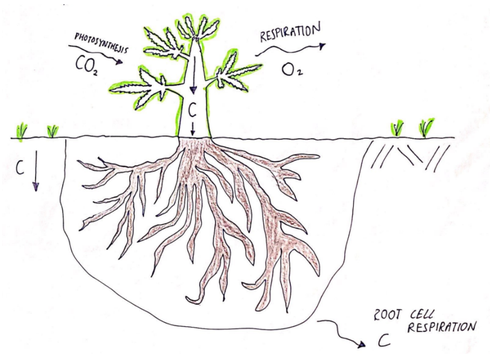




Carbon sequestration

The hemp plant sequesters carbon during its growth phase. Carbon dioxide is absorbed from the atmosphere and carbon is trapped and stored within the plant.

This carbon sequestration is high enough to overcome the emissions released from the use of fossil fuels to cultivate and process the hemp plant from the land.



Biodegradability

Hemp is a natural plant and can therefore be broken down by naturally ocurring microorganisms, unlike plastics.

Obstacles as an insulation product

Thermal Performance

Lower thermal conductivity - Higher thermal resistance and better insulation product.

Hemp is one of the **most used vegetal materials** in the building industry, largely due to its **physical and thermal properties**.

Hemp fibre can achieve a **thermal conductivity as low as 0.040 W/mK**. Typically polyurethane and mineral wool insulations achieve thermal conductivities of 0.022W/mK and 0.032W/mk respectively which are considered some of the best performing thermally.

0.039 w/mK

LOW THERMAL CONDUCTIVITY =

HIGH RESISTANCE =

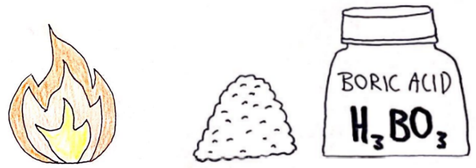
LOW U VALUE

Fire resistance

Natural fibres are very flammable and hydrophilic. Therefore, **modifications are necessary to improve fire resistance**.

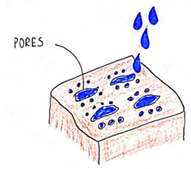
Hemp fibres are a **cellulosic material** and can be treated with flame retardants in the same way cellulose newspaper insulation is treated.

A **commonly used combination of flame retardants is Boric Acid, Borax decahydrate, and ammonium sulphate**. This combination of chemicals is added during the manufacture stage and is **gravity fed** into the cellulosic material and, in this way can be done similarly with hemp fibre insulation.



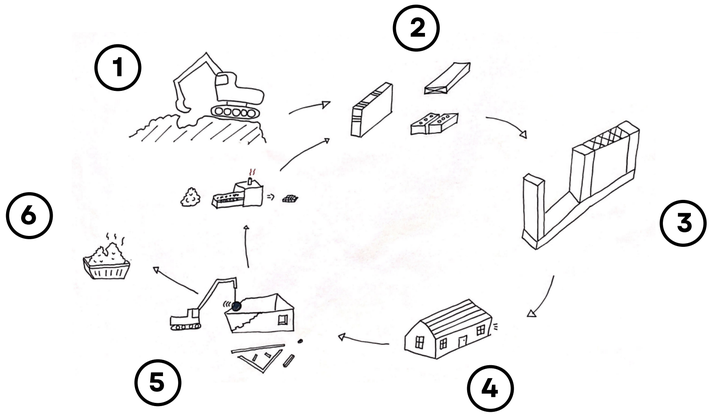
Moisture, Mold and Pest risk

Hemp fibres are hygroscopic. They can take up and retain moisture. Acts as a moisture buffer to regulate humidity. Boric acids prevent any mold growth.



3. LIFE CYCLE ASSESSMENT (LCA) RESEARCH

What is Life Cycle Assessment (LCA)?



Key:
1. Raw mater extraction 2. Manufacturing 3. Construction 4. Operation and Maintenance 5. Demolition 6. Disposal/ Reuse/ Recycle

Why do an LCA?

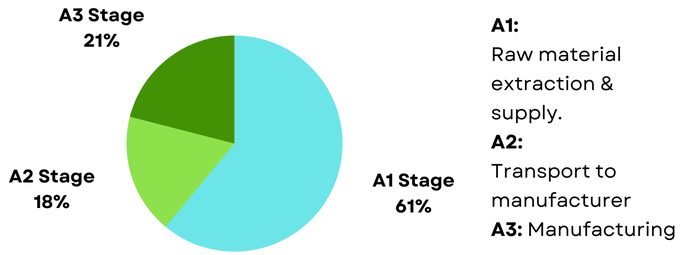
A Life Cycle Assessment is a process of evaluating the effects a product has on the environment over the entire period of its life (European Environment Agency).

By completing an LCA, or "cradle-to-grave" analysis, products can be compared and analysed to see which product is more sustainable or has a lower impact on the environment.

Key elements of an LCA include:
1. Identifying and quantifying the environmental loads involved (energy and raw materials used, emissions and waste generated).
2. Evaluating the potential environmental impacts of these loads.
3. Assess the options available for reducing these environmental impacts.

Case study - Ekolution - EPD

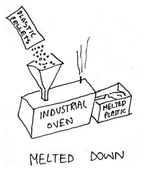
Hemp fibres: 85% Bi-component fibres 12% Casutic Soda: 3%



Ekolutions Enviormental Product Declaration (EPD) for their product states that **binding fibres (Polyethylene and Polypropylene) accounts for 40% of the total environmental effect (Stages A1-A3)**. Their EPD did not include information on the energy required for disposal.

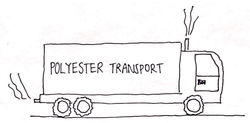
LCA of Hemp fibre batt insulation


Manufacture Plastic Pellet

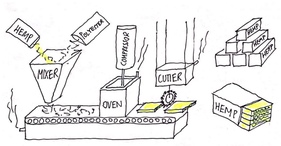


Melt Plastic Pellet

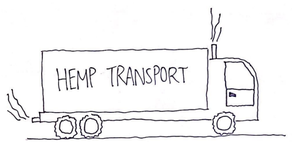
Manufacture Polyester fibre



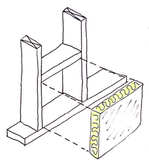
Transport Polyester

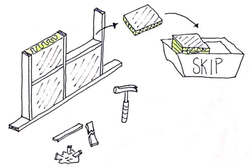


Manufacture & package Hemp batt

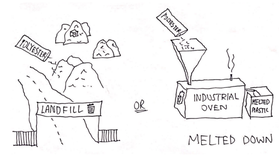


Transport Hemp batt

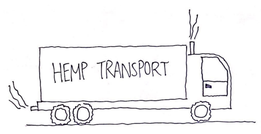

Install Hemp batt

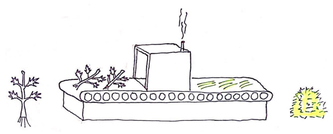


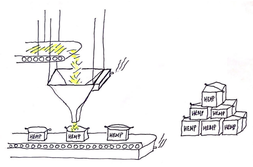
Remove Hemp batt

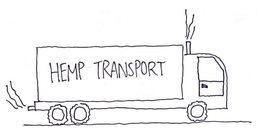


Dispose of Hemp batt - Recycle or landfill





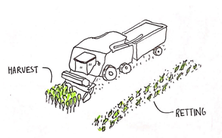




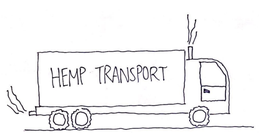
Some processes of the LCA between the two products are shared as both have hemp fibre as their primary material.

Hemp plants sequester carbon during the growth phase, which makes hemp based materials a lower carbon construction material alternative.

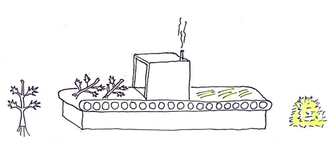
LCA of Hemp fibre loose-fill insulation

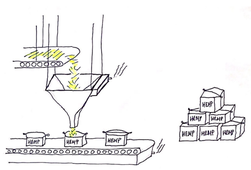


Harvest of Hemp plant

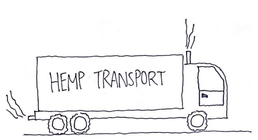


Transport hemp plant

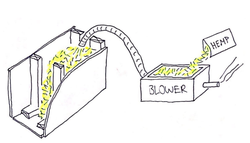

Process the hemp fibre



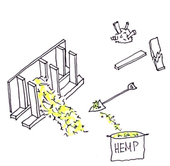
Package the hemp fibre



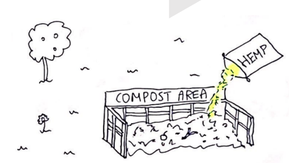
Transport hemp fibre



Pump hemp fibre



Remove hemp fibre

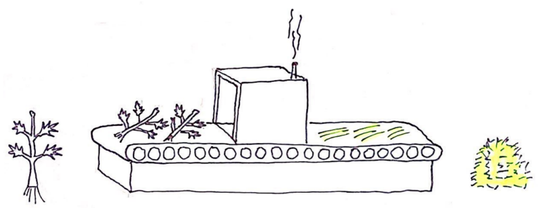


Dispose of hemp fibre - compost

Desktop Research - Processing hemp fibre

Industrial Processing

Hemp is processed at an industrial level using **machinery** which breaks and cuts the hemp fibre. Different **parts of the hemp plant are separated for their each individual use**. This is done to **save time** and to be efficient but the machines often require energy in the form of fossil fuels to operate.

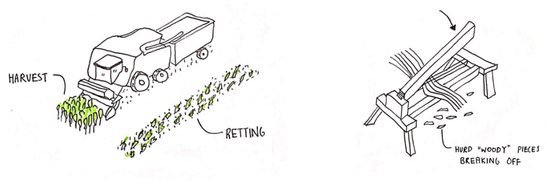


Harvesting & Hand Processing

Hemp has been used for a very long time. It has been used in mortar mix dating back to 6th century in france to form pillars.

Hemp fibre was also used in the past for textiles and clothes. There were hand processing techniques in place to isolate the fibres. **Depending on its purpose, the fibre required specific amounts of isolating to remove the "hurd".**

I**t is normal to have some remaining "hurd**" piecesin hemp based insulation so **for efficiency, I went for the breaking and combing process** for this study.

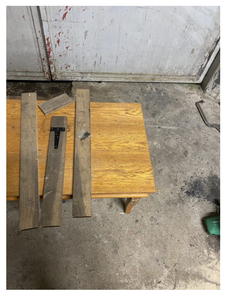


CREATING A BREAK

1

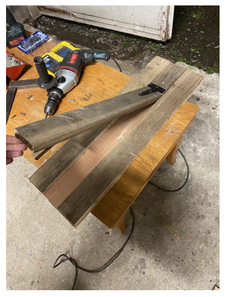
Wooden Floorboards were salavaged and a saw was sourced.

2



The floorboards were cut to size. The boards were then screwed to a plywood base.

3



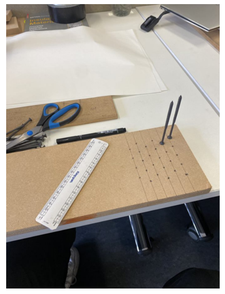
A door hinge was used to create a moveable board which would break the stalks.

4

A salvaged handle was then screwed to the middle board to allow for easier breaking.

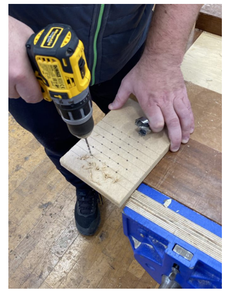
CREATING A COMB

1



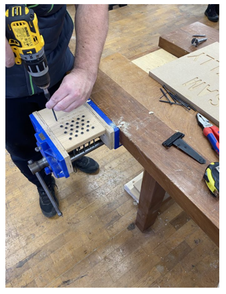
A waste cut of MDF was used and the location of screws were marked out.

2



Pilot holes were used to mark the location of the screws.

3



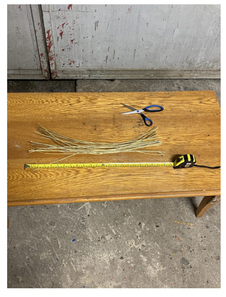
Screws were screwed into the MDF board.

4

The comb was created and ready for use. Extra space was left to allow it to be clamped down.

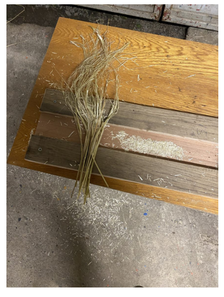
PROCESSING THE HEMP FIBRE

1



2

3



4

The root and flower part of the plant were cut off initially. The hemp stalks were then broken up and the largest amount of hurd is removed. The stalks are then combed to remove the finer pieces of hurd.

5

6

Once the fibres were processed, they were cut to the desired length needed for testing. The sample was then weighed to see how much was obtained from the processing procedure.

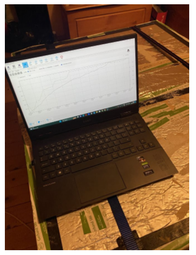
The processing procedure was relatively fast and it took roughly 6.5 minutes on average to obtain 10g of hemp fibre fit for testing processes. Of the initial plant, in this study, 17% of the plant was fibre usable for testing purposes (17% of plant mass is fibre).

HOT BOX TEST (ISO 8990:1997)

Apparatus

Temperature loggers.

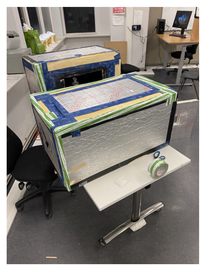
Hot/ Cold Box set up.



Laptop with logger reading software.

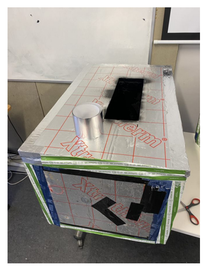
Retrofitting a hot box

1



2

3



The hot box was airtight sealed. New faces were applied to the hot box and sealed with airtight tape.

6

7

8

A new baffle board was created. The inside chamber was spray painted black to absorb light and convert to heat.

9

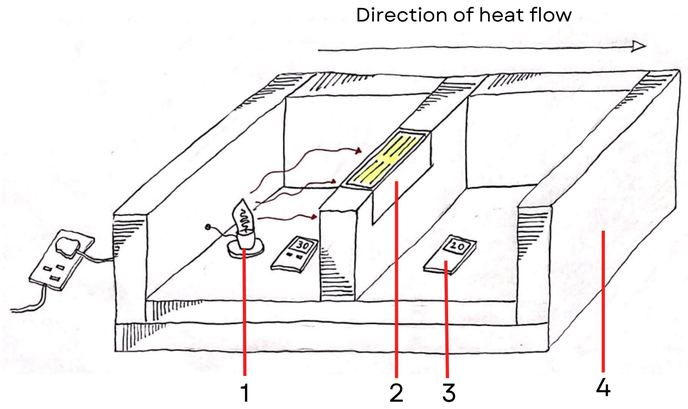
10

A new light bulb was placed inside as the heat source.

A new specimen holder was created to hold the samples.

Test Procedure

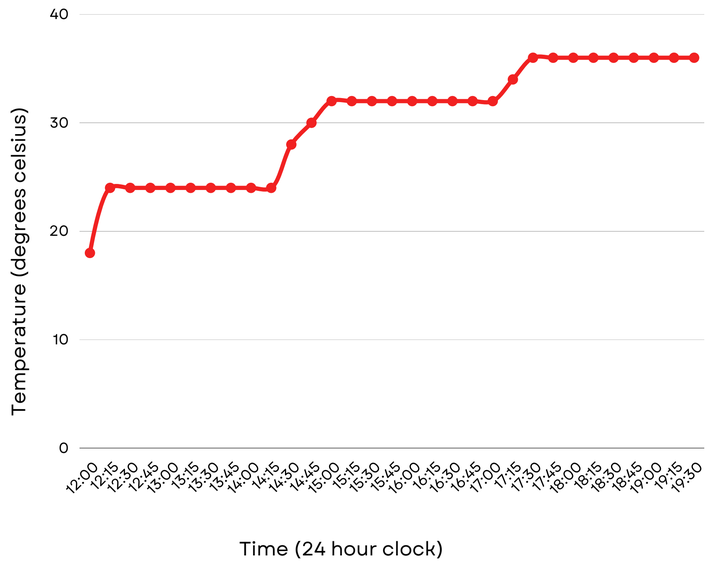
Hot Box Test Procedure Diagram



Key

1. Heat source
2. Hemp fibre sample container
3. Temperature logger
4. External insulation of hot box

Sample Graph - desired results



Once a sample reached steady state for 2 hours minimum the temperature was recorded in both the Hot and Cold Box. These were used to calculate the samples thermal conductivity.

Calculating thermal conductivity

The only unknown value once tests were conducted was K. K is thermal conductivity. **K was identified by using algebra (using known values to find the unknown).**

Watts - Measured amount of watts (heat) being input into the box from the light bulb - measured using a watt reader

Delta T - Difference in temperature measured in degrees celsius - Hot box temperature minus Cold box temperature

$$Q = U \times A \times dT$$

U Value - U value = Thickness(t) in meters/Conductivity(k) - t is known and k is what we're looking for

Area - the face area of the sample being tested in meters squared - Width x Length

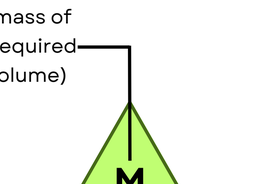
Test Samples

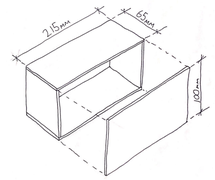
A previous study found that a polish variant of the hemp plant gave an optimum density of 85kg/m³ in their study reaching a thermal conductivity as low as 0.040W/mK.

Therefore 85kg/m³ was used as base for this study.

The hemp fibre was held within a sample container. The density for each sample was calculated using a density formula.

Mass - The mass of hemp fibre required (Density x Volume)



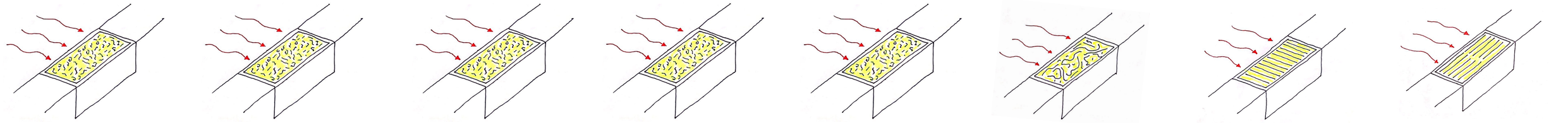


Volume - In this case we can calculate the volume by length x width x depth (in meters)

Density - The required density for each sample

The sample container is made from 3mm MDF. Therefore the volum is 0.209m x 0.065m x 0.094m = 0.00128m³

6. RESULTS AND ANALYSIS



Sample 1 - 30kg/m³ - Mixed Orientation - 33mm Fibre Length

Sample 2 - 75kg/m³ - Mixed Orientation - 33mm Fibre Length

Sample 3 - 80kg/m³ - Mixed Orientation - 33mm Fibre Length

Sample 4 - 85kg/m³ - Mixed Orientation - 33mm Fibre Length

Sample 5 - 90kg/m³ - Mixed Orientation - 33mm Fibre Length

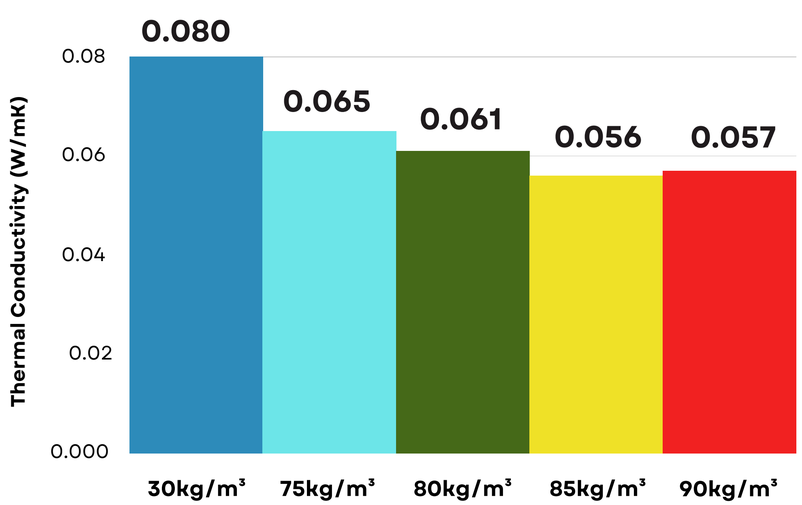
Sample 6 - 85kg/m³ - Mixed Orientation - 65mm Fibre Length

Sample 7- 85kg/m³ - Parallel to HF - 65mm Fibre Length

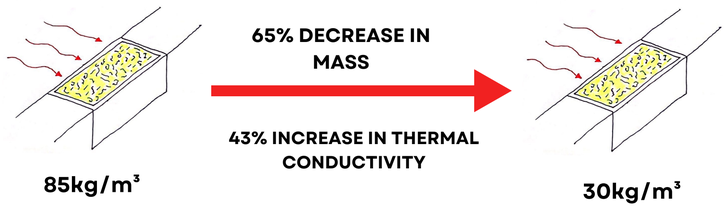
Sample 8- 85kg/m³ - Perpendicular to HF - 65mm Fibre Length

Density - Thermal Conductivity Results

Sample no.	Lambda Value @ Heat setting 1 (W/mK)	Lambda Value @ Heat setting 2 (W/mK)	Lambda Value @ Heat setting 3 (W/mK)	Average Lambda Value (W/mK)
1	0.141	0.014	0.085	0.080
2	0.061	0.077	0.058	0.065
3	0.072	0.027	0.083	0.061
4	0.006	0.077	0.086	0.056
5	0.039	0.076	0.055	0.057

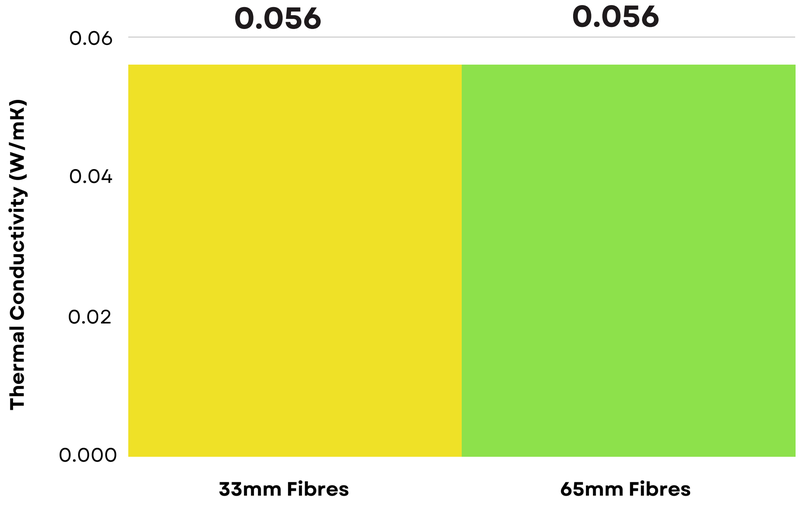


85kg/m³ was the optimum density for thermal performance with a thermal conductivity of 0.056 W/mK. This aligns with a study conducted in 2017 by Kosiński et al. who found 85kg/m³ to be optimum density for a polish variant of the hemp plant. A density of 30kg/m³ was also tested. This sample achieved a thermal conductivity of 0.08 W/mK which is an increase of 43% from 85kg/m³. This shows the optimum density is not the most efficient.

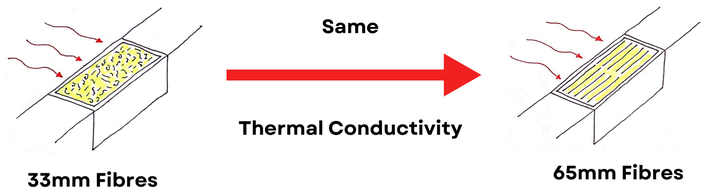


Fibre Length - Thermal Conductivity Results

Sample no.	Lambda Value @ Heat setting 1 (W/mK)	Lambda Value @ Heat setting 2 (W/mK)	Lambda Value @ Heat setting 3 (W/mK)	Average Lambda Value (W/mK)
4	0.006	0.077	0.086	0.056
6	0.057	0.057	0.052	0.056

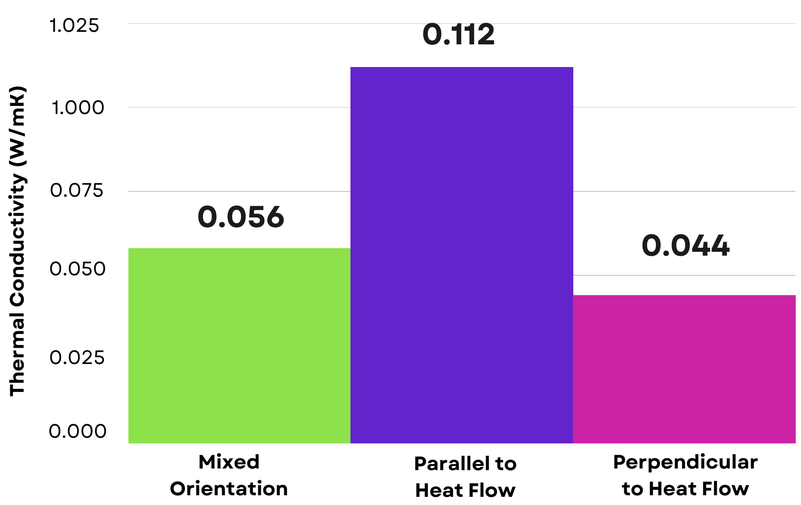


When laid in a mixed orientation, the shorter fibre length performed better thermally with a thermal conductivity of 0.056 W/mK. The **longer fibre lengths had an increase in thermal conductivity of 4%** making it worse thermally performing with a thermal conductivity of 0.058 W/mK.

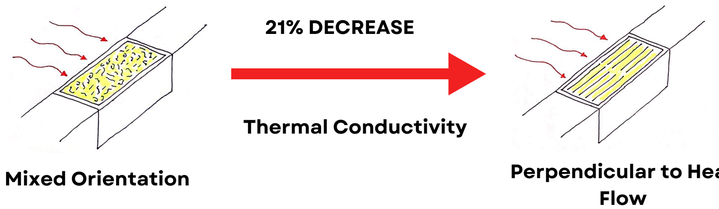


Orientation - Thermal Conductivity Results

Sample no.	Lambda Value @ Heat setting 1 (W/mK)	Lambda Value @ Heat setting 2 (W/mK)	Lambda Value @ Heat setting 3 (W/mK)	Average Lambda Value (W/mK)
6	0.057	0.057	0.052	0.056
7	0.160	0.099	0.076	0.112
8	0.034	0.042	0.056	0.044



Parallel to heat flow performed the worst thermally with a thermal conductivity of 0.112 W/mK. Although mixed orientation is the most practical , it achieved 0.056 W/mk, while Perpendicular to heat flow achieved 0.044 W/mK which is a 21% decrease in thermal conductivity making it the best performing thermally. **Research should be conducted in future to assess if there a way to have perpendicular laid fibres as a possible method.**



7. RESULTS AND ANALYSIS

What do the results from hot box testing mean?

This part of the study took the **thermal conductivity values obtained from the hot box testing** of the samples, and **applied them to insulation samples** within a wall system.

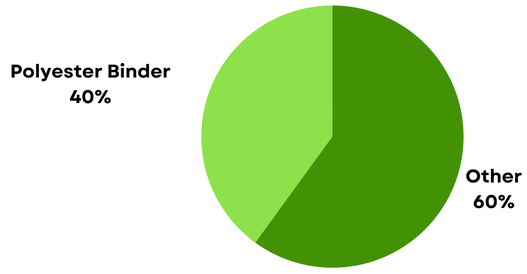
Each sample's density and overall mass was considered and the embodied carbon was roughly calculated based on an Environmental Product Declaration (EPD) of a hemp fibre based batt insulation from Ekolution. Their EPD states that **40% of the (A1-A3) embodied carbon came from the polyester binder so this figure was used to compare the insulations without the binder**.

All wall systems that are compared have the same aim of achieving the minimum **U-Value of walls which is 0.18W/m2K as per TGD part L**. Some U Values may vary between each wall system as the wall system was specified to have a standardized thickness to suit the insulation (for example, instead of a twin stud system being 266mm to suit the insulation, it is rounded to 270mm) .

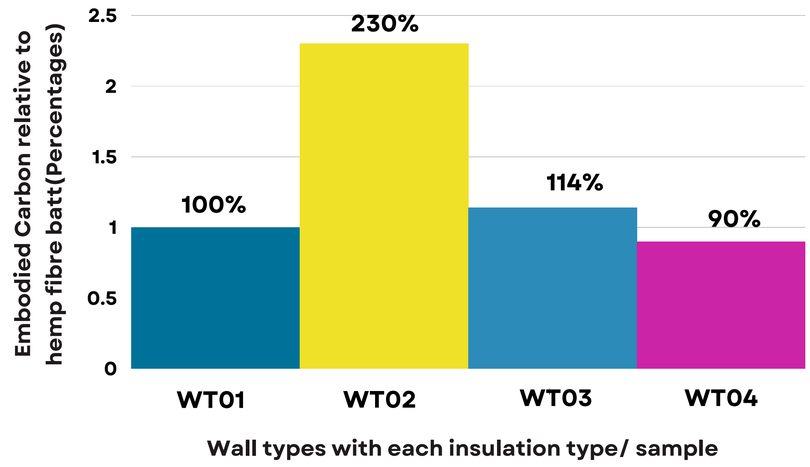
Case study - Hemp batt insulation from Ekolution

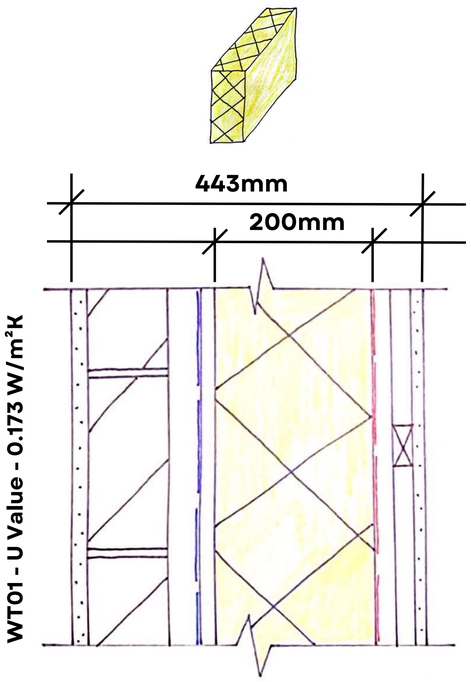
Hemp fibres: 85% Bi-component fibres 12% Casutic Soda: 3%

Embodied Carbon of composition (A1-A3) Stages



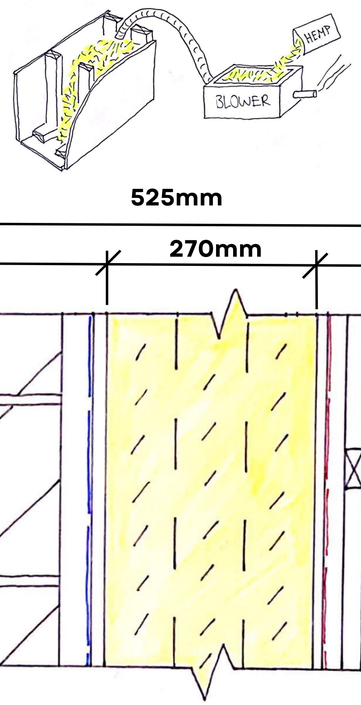
Graph of Embodied carbon from insulation types relative to hemp fibre batt insulation





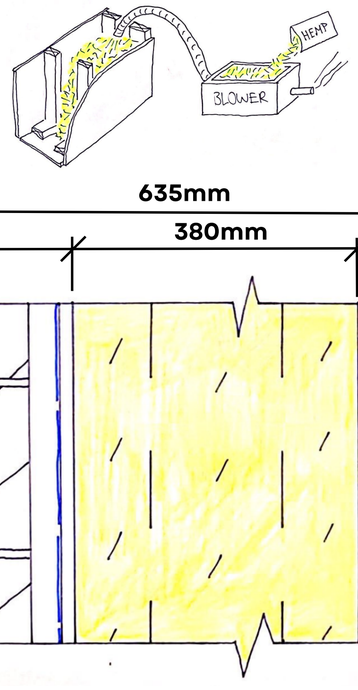
Hemp batt with binder - 35kg/m³

- 30kg/m³ of Hemp fibre.
- Contains Plastic Binder - 40% of Environmental Impact.
- 60% Environmental impact of Everything Left.
- 100% Embodied Carbon (Acting as a control to compare).



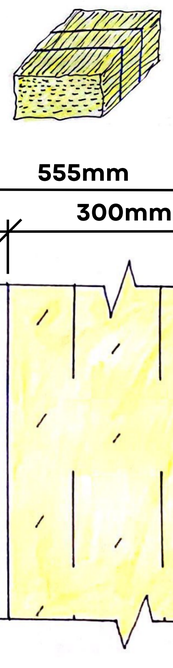
Loose-fill with no binder - 85kg/m³ - Mixed Orientation 33mm Fibres

- 85kg/m³ of Hemp fibre.
- No plastic Binder.
- 19% Increase in Wall thickness from Hemp batt insulation.
- 230% Embodied Carbon.



Loose-fill with no binder - 30kg/m³ - Mixed Orientation 33mm Fibres

- 30kg/m³ of Hemp fibre.
- No plastic Binder.
- 43% Increase in Wall thickness from hemp batt insulation.
- 114% Embodied Carbon.



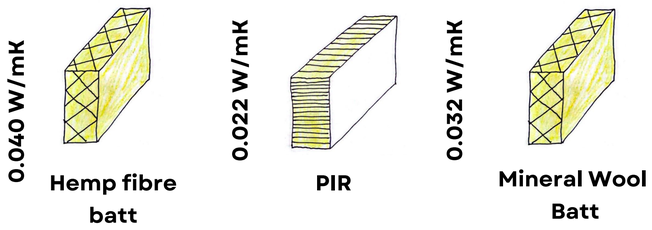
Loose-fill with no binder - 30kg/m³ - Perpendicular to Heat flow 33mm Fibres

- 30kg/m³ of Hemp fibre.
- No plastic Binder.
- 25% Increase in Wall thickness from hemp batt insulation.
- 90% Embodied Carbon.

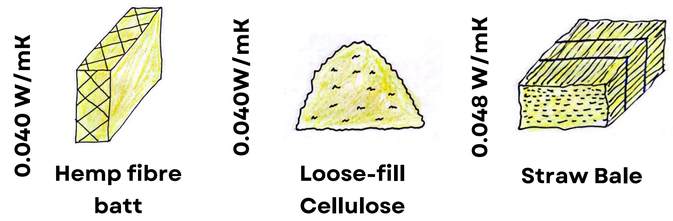
8. FUTURE RESEARCH AND RECOMMENDATIONS

FURTHER LIFE CYCLE ASSESSMENT

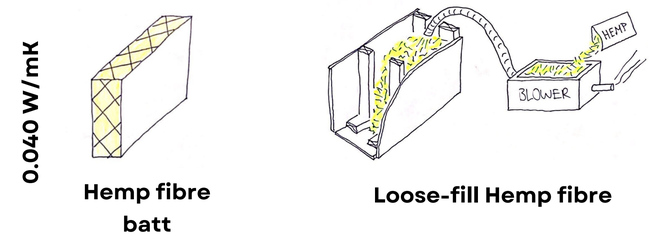
One Click LCA or other software which can compare materials for their embodied carbon and/ or Global Warming Potential GWP) should be used in future to compare hemp based insulations to commonly used synthetic insulations. These include insulations such as PIR, PUR and Mineral wool. This study should be conducted to confirm that Hemp fibre insulation is a lower embodied carbon alternative.



An LCA should also be conducted on hemp based insulations and other suggested "lower embodied carbon" natural insulation alternatives such as Cellulose loose-fill insulation and straw bale insulation to see which insulation has the lowest embodied carbon value.



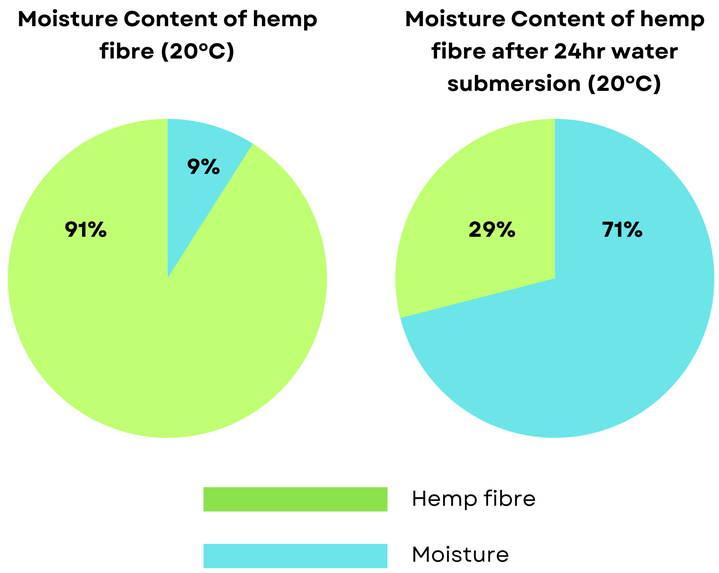
Finally, to really help this study, an LCA should be conducted on hemp fibre batt insulation that uses a polyester binder from Cradle to Grave to assess what exact embodied carbon value is on the polyester binder compared to a loose-fill hemp fibre insulation with no binder. This study would be precise and give further reasoning to identify if removing the binder is a viable solution to create a lower embodied carbon insulation alternative which does not contain plastics.



FUTURE TESTING & BIODEGRADABLE BINDERS

Water Absorption test (ISO 29767:2019)

A short term water absorption test, to mimic rain, was conducted. After 24 hours the hemp fibre had a moisture content increase of 62%. This is due to hemp fibres hydroscopic ability as a natural plant material which makes it a good construction material as moisture will not decay it.



FURTHER TESTING

Hemps ability to absorb moisture and its thermal conductivity make it a very good insulation material.

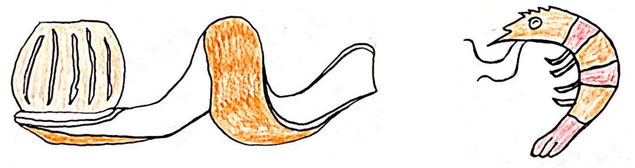
These physical properties should not be hindered by additives, such as a binder, in an attempt to make an insulation material.

This data was taken from this investigation to act as a control for any future testing that may be conducted. Future investigations can perform the Hot Box Test Procedure (ISO 8990:1997) and the Short Term water absorption test (ISO 29767:2019) on their samples with any additives and compare their results to this data. This will **allow further investigations to determine what affect the additives had on the material.**

Potential biodegradable binders

OrganoClick are a green chemical company who develop and manufacture products and export them around the world. They are based in Sweden. Their vision is a world free from plastic waste and chemical pollution.

They manufacture products using chemistry to mimic natures "smart solutions". In the case of binders, they studied how strength and stiffness are created in natural materials such as orange peel, wheat bran, and shrimp shells.

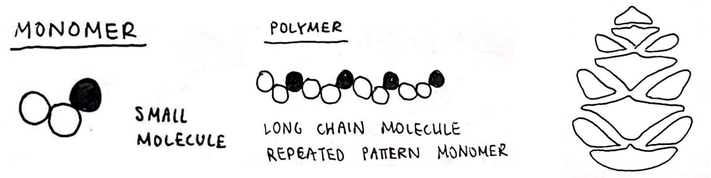


They created their "OC-BioBinder" range of biodegradable binders by combining different biopolymers from residual flowers such as Lily, Pine, Oak.

Product	Softness/ Stiffness	Dry strength	Wet strength	Character	Fire protection	Application method	Typical applications
OC-BioBinder Lily	Soft	++	++	Hydrophilic	No	Spray, impregnation	Airlaid, wetlaid, carded
OC-BioBinder Clover	Soft	++	+	Hydrophilic	No	Spray, impregnation	Airlaid, wetlaid, carded
OC-BioBinder Pine	Stiff	+++	+	Hydrophilic	No	Spray, impregnation	Wetlaid, carded
OC-BioBinder Oak	Very stiff	+++	+++	Hydrophilic	No	Spray, wetend	Wetlaid, carded
OC-BioBinder Lotus	Soft/stiff	++	+++	Hydrophobic	No	Spray, impregnation	Wetlaid, carded
OC-BioBinder Olea	Medium	++	+	Lipophobic	No	Spray, impregnation	Airlaid, wetlaid, carded
OC-BioBinder Ashtree	Medium	++	+	Hydrophilic	Yes	Spray, impregnation	Airlaid, wetlaid, carded

Product chart of BioBinders from Organoclick

The OC-biobinder made from Pine is most suited for the use of hemp fibre batt insulation as it stiff and is suited to replace polyester, which is typically used in the hemp fibre batts.



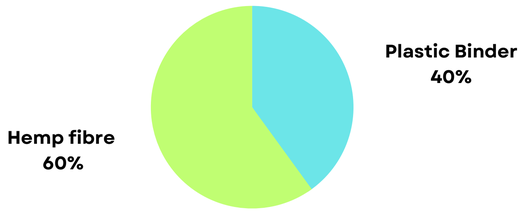
9. CONCLUSION

OBJECTIVE 1

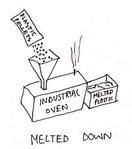
The use of plastics can have a negative effect on the environment for many reasons.

1. Plastics are not a renewable resource and will deplete over time.
2. Plastics require a high energy manufacturing process which increases the embodied energy and carbon emissions.
3. Plastics are not biodegradable. They require energy to dispose of. If they are not disposed of correctly they can break down (fragmentation) into microplastics which can cause harm to larger organisms when ingested (health problems.)

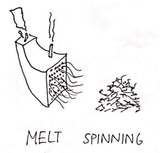
Embodied Carbon of sample hemp fibre batt from Case study (85% Hemp fibre, 12% Polyester Binder)



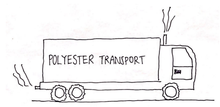
Manufacture Plastic Pellet



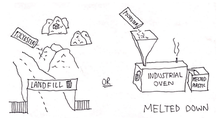
Melt Plastic Pellet



Manufacture Polyester fibre

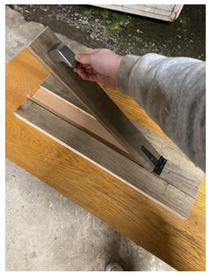


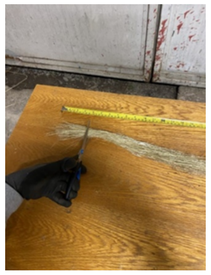
Transport Polyester



Disposal or dumping of used Plastics

OBJECTIVE 2



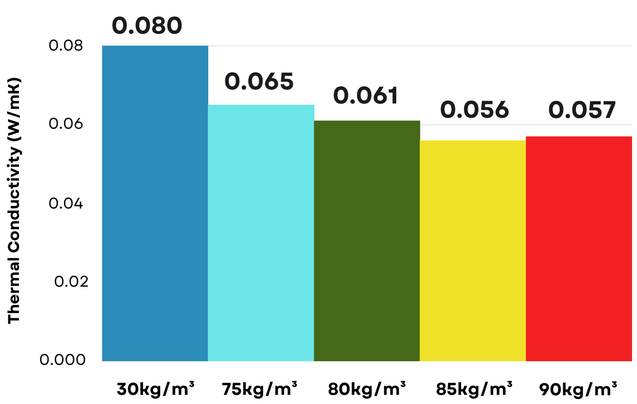


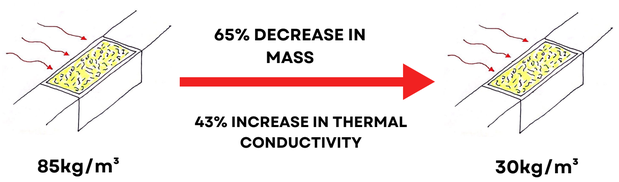
The processing of hemp fibres can be easily done by hand and does not require any additional machinery or large energy requirements.

This process highlights how the process procedure can be carried out and offers a greater understanding how it can be conducted in Ireland.

For large scale projects, processing machinery will be required. The larger scale machinery can follow the same principals as the procedures which have been conducted in this study.

OBJECTIVE 3



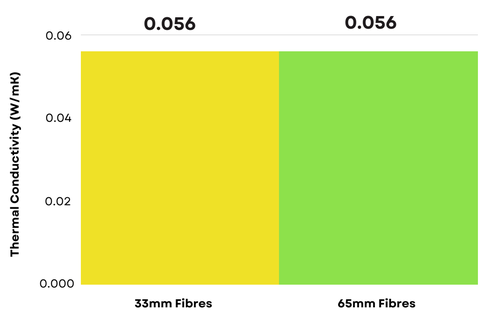


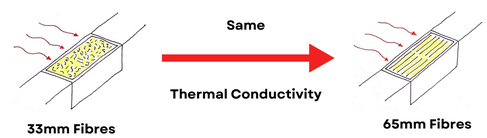
Density has an influence on thermal conductivity, as was expected. The increase in density lead to the decrease in thermal conductivitiy until it reached 85kg/m³ where it then began to plateau.

The lowest thermal conductivity of the mixed orientation samples was 0.056W/mk. This was achieved at 85kg/m³. This optimum density aligns with Kosiński et al. (2017) study on a Polish variant of the hemp plant. This suggests that the optimum density remains at 85kg/m³ in all variants of the hemp plant, even grown abroad.

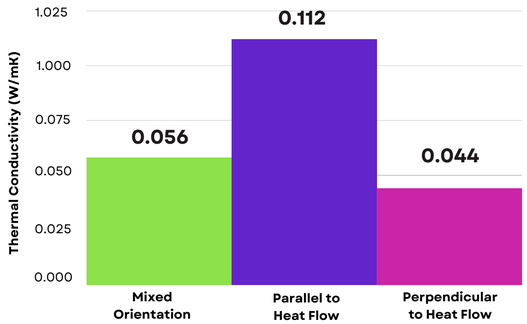
This also suggests that the orientation does not effect optimum density. However, further research should be conducted to confirm this. This study shows that Irish grown hemp fibres shows identical properties to hemp grown abroad and should be capatalised in Ireland as an insulation material as it is abroad.

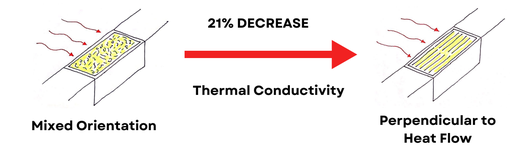
OBJECTIVE 4





Fibre Length does not have an impact on thermal conductivity of hemp fibre as an insulation material. This is important as the fibres can be cut to small lengths to be used within a blowing machine to be installed within a wall system without affecting thermal conductivity.





Parallel to heat flow performed the worst and should not be used. Perpendicular to heat flow performs 21% better in terms of thermal conductivity than mixed orientation and should be considered for future research on making this a viable insulation type in the form of a potential panel.

Killian Markey
C19422132
DT175 – 04

OLLSCOIL TEICNEOLAÍOCHTA BHAILE ÁTHA CLIATH
DUBLIN
TECHNOLOGICAL UNIVERSITY DUBLIN