

Flax Fibre Reinforced Composites with Foamed PLA Core for Fully Bio-based Sandwich Floor System

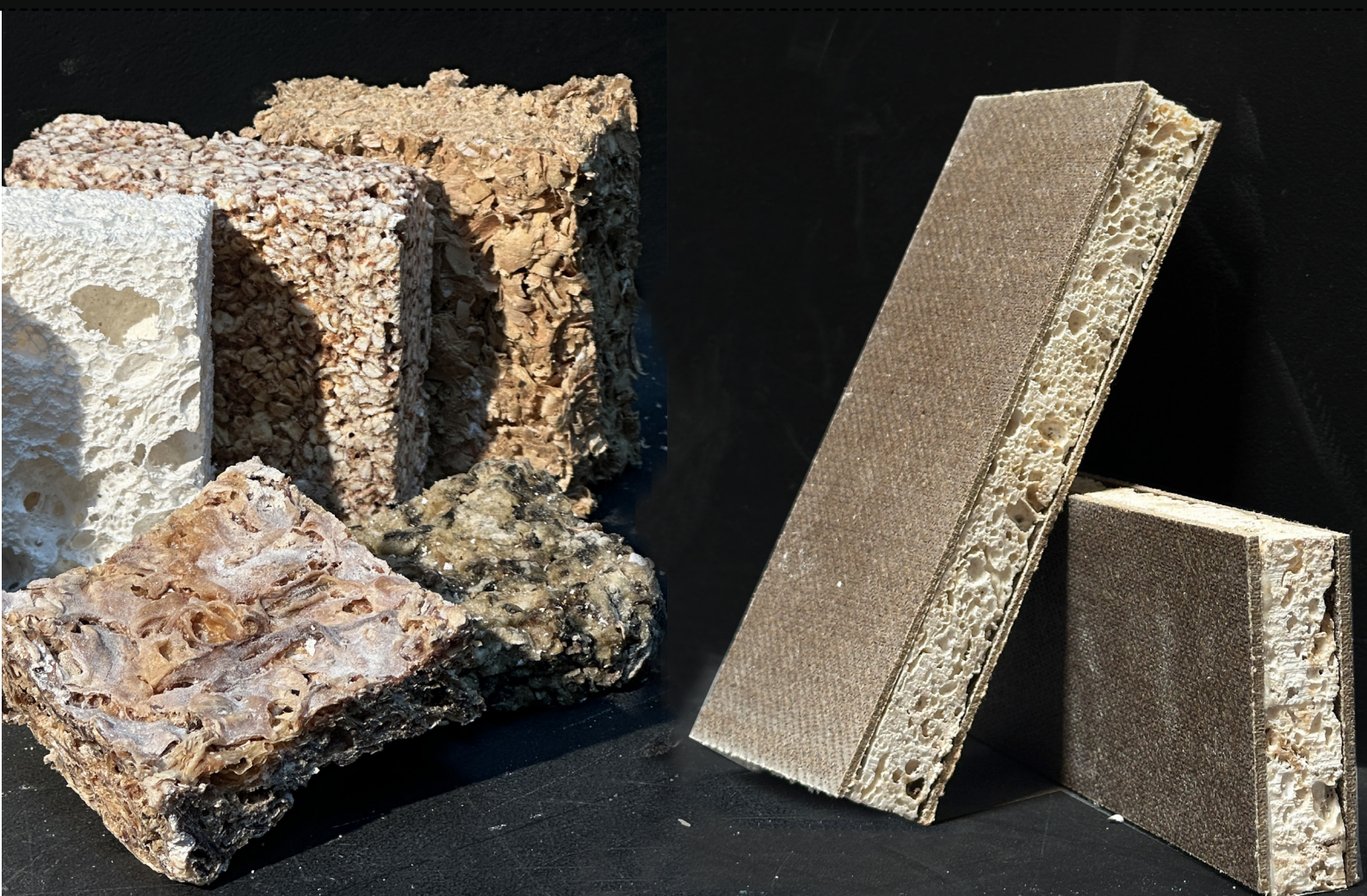
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ABSTRACT

The world is currently experiencing a major global warming problem, and the construction industry stands out as one of the major contributors to a high percentage of carbon emissions. This is primarily due to the usage and production of materials. When buildings are examined in detail, it becomes evident that floor systems constitute a significant portion of the construction within buildings. Essential structural components, such as concrete and steel, along with small-scale building materials used across diverse applications, are major contributors to high carbon emissions. These materials are primarily non-bio-based, emit unhealthy gases during production, and have limited sources.

In response to this problem, there is an urgent need to shift towards using alternative materials in the construction industry and explore materials and methods that are renewable, local, bio-based, biodegradable, and do not produce harmful substances during their production. Therefore, this research aims to map out the possibilities of bio-based materials that have the potential to be structural components but have not been extensively detailed in the literature. In the context of this thesis, flax fibers and bio-based polymers that can potentially replace petroleum-based products are chosen. Adopting a research-by-experiment approach, various bio-based materials for the core material will be tested to identify the most suitable core material for the sandwich floor system. Besides, for the face sheet, flax fibers with a PLA matrix have been chosen. In turn, the sandwich is produced by a PLA core and Flax/PLA composite.

The results highlight that the proposed materials are capable of resisting necessary loads for residential building construction. Additionally, the floor panel possesses high environmental positive properties and low carbon emissions during its production stages. It is expected that this material proposes a new system that can become mainstream in the construction industry as a sustainable option by replacing conventional methods. However, the material also has a higher cost compared to a residential concrete hollow core system. Additionally, the life cycle analysis of the product should be conducted to better understand the LCA of the material. In general, by contributing valuable knowledge in the realm of sustainable construction materials, this research aligns with global goals for eco-friendly practices and underscores the potential for carbon-neutral materials to bring transformative advancements in structural applications within the construction industry.

ACKNOWLEDGEMENT

The thesis process has been a great journey, leading me towards becoming an engineer and material researcher with an architectural background. For that reason, my first gratitude is to TU Delft and the AE+T department, especially my mentors, Prof. Dr. Mauro Overend and Dr. Ing. Marcel Bilow.

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One special aspect of the project was the insights I gained at the Aerospace Engineering department. For this, I'd like to thank Prof. Clemens Dransfeld for introducing me to the great people at Aerospace Engineering at TU Delft and everyone who supported me at the composite lab. It was an invaluable experience to broaden my knowledge of composites with such an amazing group of people, discussing materials from both architectural and engineering perspectives.

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chapter 1

RESEARCH FRAMEWORK

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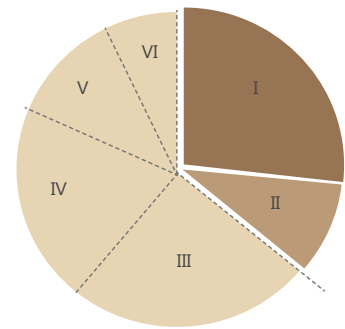
Research questions, introduction and boundaries.

1 | FRAMEWORK

1.1 Problem statement

The construction industry is one of the major contributors to a high percentage of carbon emissions, primarily due to the usage and production of materials. This includes essential structural components such as concrete and steel, as well as small scale building materials (Barriers, insulation, acoustic materials...) which are used across diverse applications. These materials are mainly non-bio-based, cause unhealthy gases in production, and are limited sources.

When investigating buildings based on their structure, the superstructure and substructure contribute 30% and 27% of the emissions, respectively (LETI, 2023). The LETI guidelines recommend a 40% reduction target for these emissions, emphasizing the importance of addressing this issue. Evaluating the structural volume of components reveals that floor slabs account for the highest percentage at 65%, indicating that floor systems significantly contribute to carbon emissions (IEA, 2021; IEA, 2020; LETI, 2023). This underscores the crucial role of material selection in the construction industry for reducing carbon emissions on a global scale. Achieving this reduction will require a shift in approach, decreasing the demand for conventional materials, and promoting the use of local, renewable, low-carbon, and bio-based materials (EA, 2021; ETC, 2018).



I Building operation	by 27.3%
II Building material	by 7.7%
III Industry	by 28%
IV Transport	by 22%
V Other	by 8%
VI Infrastructure	by 7.3%

Figure 1: Carbon emission by sectors. (Why Buildings – Architecture 2030; ISA; Statista)

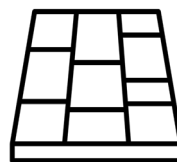
Even though wood is a bio-based material and commonly used supply, it is also limited, and excessive usage might even lead to deforestation. Therefore, looking for further fibre non-wood bio-based approaches are needed to address this environmental impact. It is important to explore alternative, natural, and sustainable materials that are renewable, easily accessible, and do not result in extensive energy loss. Despite the urgency of this matter, the existing literature provides limited insights into comprehensive natural solutions for mitigating the environmental footprint associated with fibre-based natural building materials for their primarily structural building applications which are derived from renewable sources.



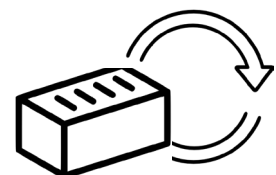
AIM
Reduction in carbon footprint



TARGET
Construction industry and materials



APPLICATION
Floor panels
(as the main approach)



HOW
By going full green for building components

1.2 Research Question

“Could a novel biobased sandwich flooring systems outperform conventional flooring systems”

Sub-questions on the core

- * What are the possibilities of bio-based resin as the matrix for the fiber reinforced composites.
- * What are the possibilities of biobased materials as the core?
- * What are the effects of foaming agents on bio-polymers on the density and strength of the bio-based core?
- * What is the overall performance of bio-based polymers compared to petroleum-based materials?

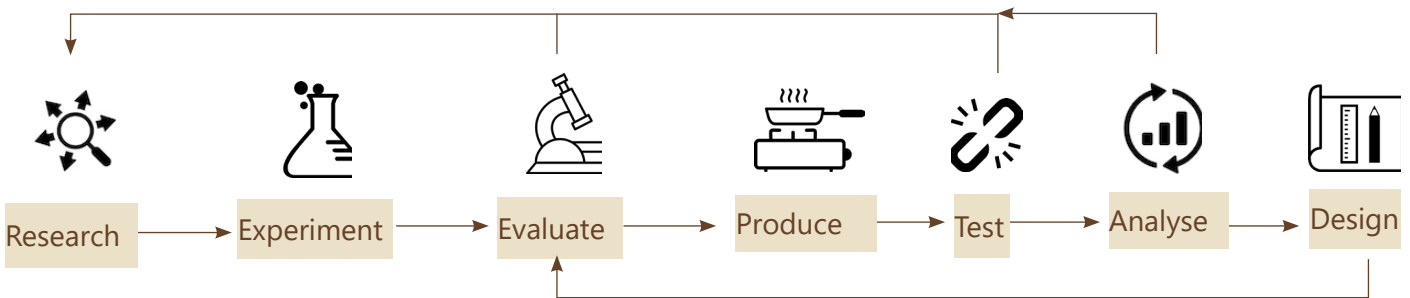
Sub-questions on composite:

- * To what extent will a fully based floor system be used in the building industry?
- * What are the mechanical properties of a green composite?
- * How easy is it to construct/repair/replace the material?
- * What is the assumed CO2 emission comparison of the green composite compared to conventional flooring?

1.3 Research Objective

The primary assignment is to investigate, experiment, produce, and evaluate by lab testing the mechanical and structural properties of natural flax fibre-reinforced bio-composites with a PLA experimental core. However, through the structural lab analysis, different dimensions might be produced.

Through comprehensive bio-based materials investigation, several composite formulations, and structural testing, the study aims to contribute valuable insights into the feasibility, performance, and environmental sustainability of this bio-based sandwich floor system that can replace conventional floor systems. By doing so, this research aims to understand and adopt eco-friendly construction materials within the built environment.



1.4 Boundaries

The focus of the thesis is on testing the mechanical, the core shear properties of the proposed composite materials. Throughout the research different manufacturing techniques of flax fibers reinforcement composite and bio-material based core material will be investigated. As the scope of the thesis the production life analysis will be explained. As the end product, the manufacturing and connection details will be proposed. The test is expected to be done with specimens suggested by ASTM standards. Additionally, the testing scope is only limited to shear mechanical properties of the core material, as literature review on facesheet is exist separately. Furthermore, further tests such as acoustical and thermal are excluded from the scope.

1.5 Relevance to Building Technology Track

The chosen research aims to enhance current design standards using non-wood fibres, specifically focusing on two Building Technology aspects: structural design and mechanics, and product design. The structural component aims to create a robust floor system with proven shear strength through testing. Meanwhile, the product design aspect emphasises methodology, testing, and efficient connections/tools for the floor system. Aligned with the Building Technology track's focus on innovative and sustainable components, the proposed research, titled "Investigations of Flax Fiber Reinforced Composites with Algae-Derived Polymers for Bio-based Floor Systems," aims to research for innovative solutions aligning with the track's objectives.

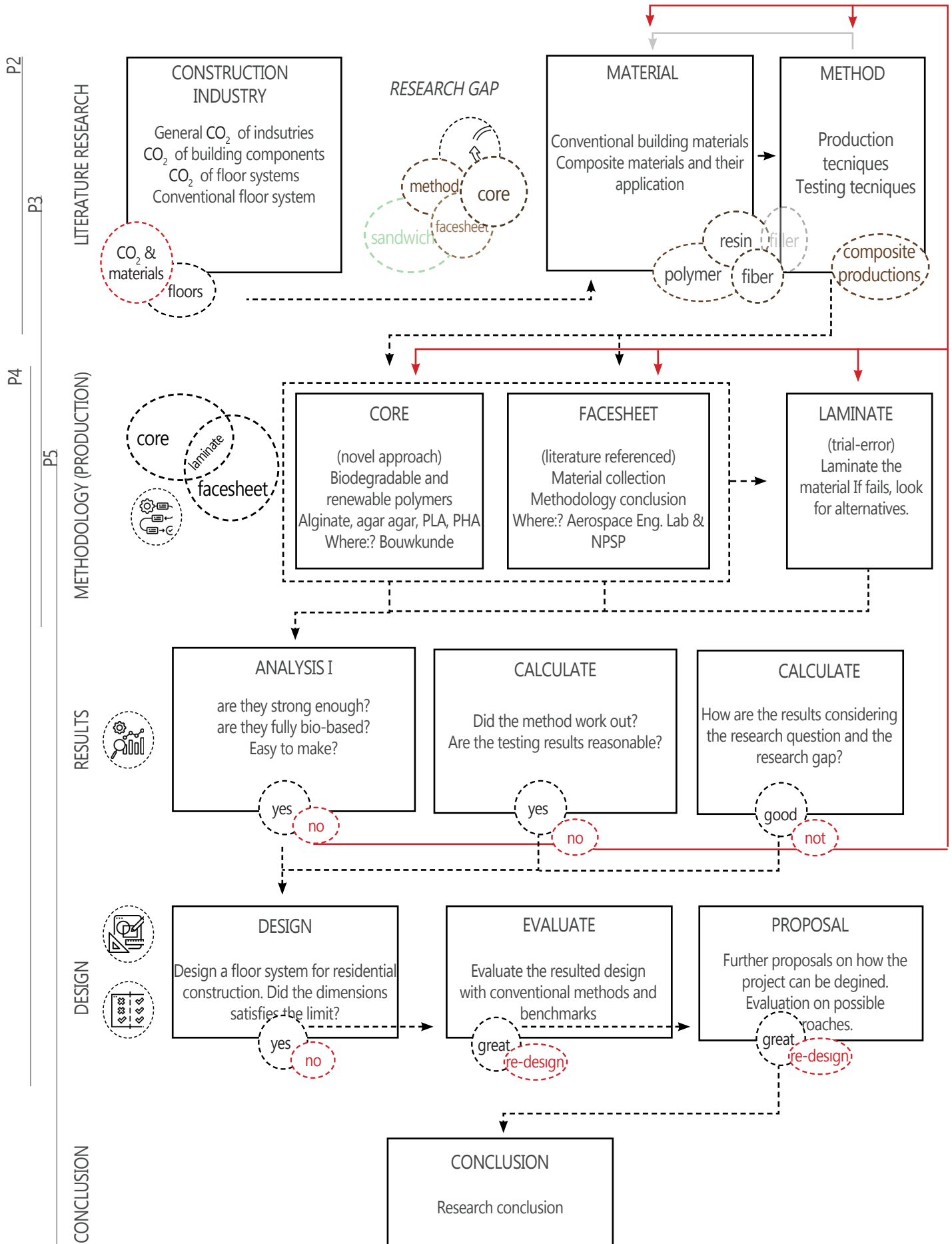
Relevance social, professional and scientific framework

The graduation work demonstrates significant relevance across social, professional, and scientific frameworks. It addresses the environmental impact of the building industry by proposing a sustainable floor system using non-toxic, renewable resources. This initiative aligns with global Net Zero targets and offers long-term, cost-effective solutions. While the initial focus is on the Netherlands, the adaptable nature of the chosen fibre allows for broader applications.

Professionally, the work contributes to the industry's shift toward sustainability through exploration of flax-fibre composites and experimentation with bio-based resin and foam formation. This aligns with global sustainability goals and presents innovative solutions for structural applications. Collaboration with Aerospace Engineering at TU Delft enhances the scientific framework, providing insights into the strength and stiffness of algae-derived foam under different environmental conditions.

In the scientific realm, the research addresses gaps in understanding flax-fibre natural composites for structural building applications and delves into the chemistry of bio-based and foam insulation. The collaboration with Aerospace Engineering adds depth to the exploration of PLA foam, contributing to state-of-the-art bio-based lightweight materials with minimal environmental impact. This comprehensive approach positions the work as a valuable contribution to the scientific community.

1.5 Research Framework



chapter 2

LITERATURE REVIEW

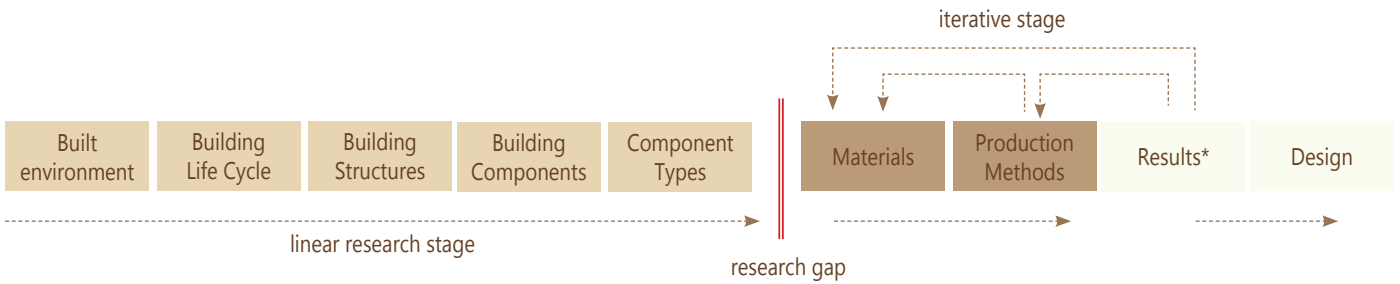
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Research on current literature on construction industry, biobased materials and their production methodology.

2 | LITERATURE REVIEW

The literature review is divided in sections starting from larger scale review to product scale review. In the built environment section, the industry based carbon emissions are explained, which led the second stages to be investigated as building life cycling and leading the structural based carbon emissions. Afterwards, the building component and which component takes the highest carbon emission within the building is reviewed.

After researching on building component taking the highest carbon emission, the detailed research has been carried for further analyses to which materials are suitable for a sustainable construction. Afterwards current literature on sustainable materials have been explained. Later on, the production methods are analyzed. The literature review has been concluded by researching on end of life and product life scenarios.



2.1 BUILT ENVIRONMENT

In 2021, construction activity surged back to pre-pandemic levels in major economies, causing a 4% rise in buildings' energy demand. CO2 emissions increased 5% in 2020 which is a more peak compared to 2019 and the record became around of 10 GtCO2 due to increased fossil fuel use. The simplest fact is that the reduction in the carbon emission or the energy demand has not shifted even since 2015 the policy and investments have made progress, the effort for lower carbon emission and improvement in energy efficiency still needs to be in higher effort (LETI 2023).

As the most carbon emission is released during the construction and production, low-carbon material selection plays a crucial role on high-performance buildings having low operational energy (LETI 2023). For that, the materials should be selected not only for their easy production or construction but also for their climate performances to decrease the operational energy as much as possible. For instance, substituting a concrete exterior wall with a biobased structure can significantly reduce both upfront embodied carbon and ongoing emissions (LETI 2023).

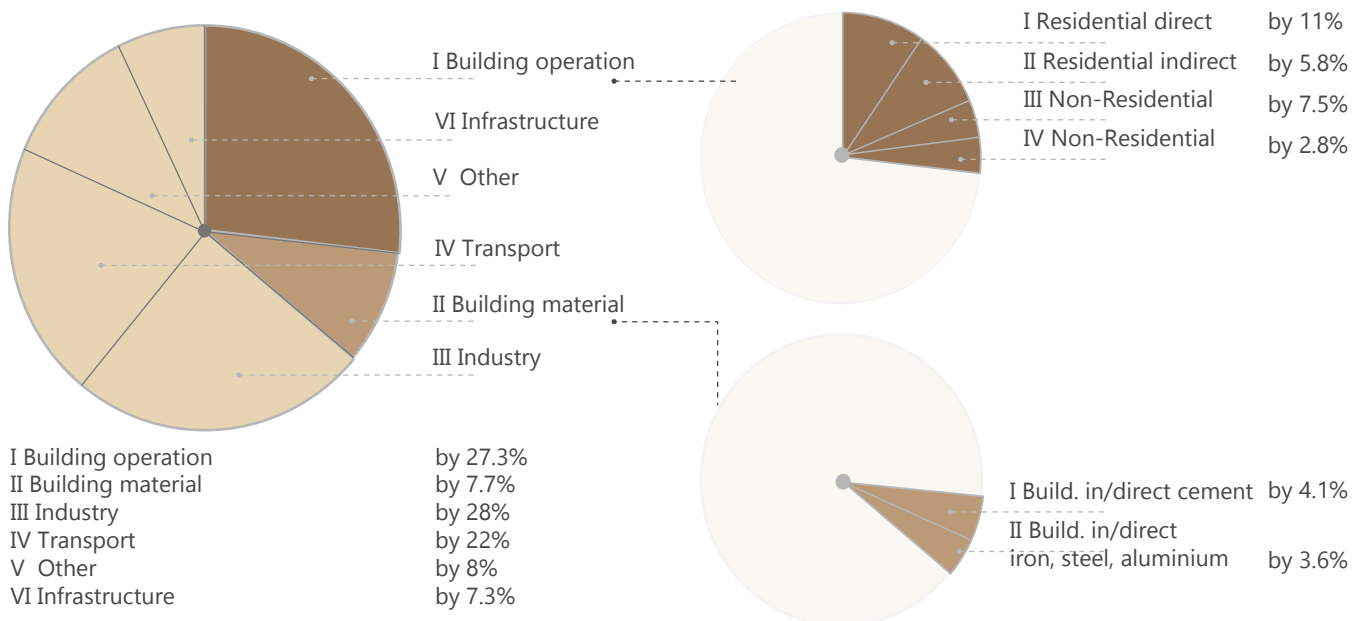


Figure 2: Carbon emission by industries. Left side; industry based percentages. Right side, building operation and material detailed percentages. Carbon emission by sectors. (Why Buildings – Architecture 2030; ISA; Statista)



Sector based strategies

Construction and real estate sectors need comprehensive zero-carbon strategies for both new and existing buildings across all regions, aligning with governmental policies effectively.



Construction industry strategies

II. Building material and construction industries should pledge to cut down CO2 emissions across their value chains in accordance with the Paris Agreement, aligning with governmental aims for a carbon-neutral building inventory.



Research funds for advancement

Immediate and increased funding for public-private research collaborations. These partnerships aim to expedite innovations that decrease embodied carbon in buildings, advancing development, demonstration, and commercialization.

*Key recommendations adapted by the report are as follows (LETI 2023)."

Worldwide, construction, renovation, and demolition generate roughly 100 billion tonnes of waste, of which around 35% ends up in landfills. In developing economies experiencing rapid growth, construction materials are predicted to heavily drive resource consumption, potentially doubling associated greenhouse gas emissions by 2060. It's crucial to address the embodied carbon in buildings and regarding materials and construction to prevent negating the carbon reductions (LETI 2023).



2.2 BUILDING COMPONENTS

From a detailed perspective, in a small scale building, the footprint primarily comes from various stages; material production with 80%, with maintenance 14%, transportation 5%, construction 1%, and end-of-life accounting for 1%. The percentage of embodied energy of components in the building framework analysis shows that the superstructure and substructures are claiming the largest percentages 30% and 27% respectively. Internal finishing 20%, facades 17% and mechanical, electrical and plumbing systems 5%. (LETI, 2023). The LETI, recommends a reduction of 40% for these emissions, which highlight the importance of selecting materials having as low embodied energy as possible.

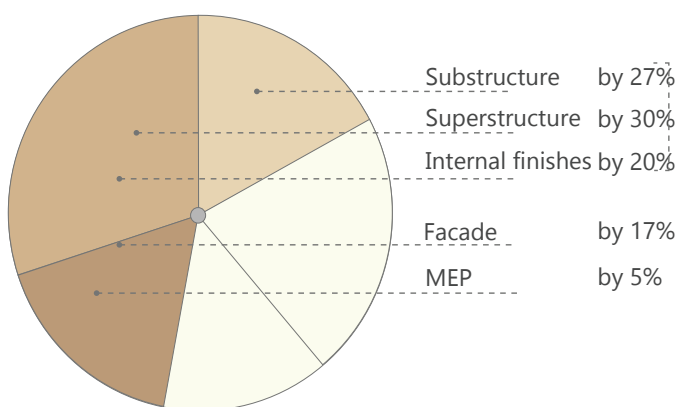


Figure 3: Embodied carbon percentages of each building structures for a small scale building. Diagram is reproduced.

2.3 COMPONENT TYPES

In the component framework, upon evaluating the structural components of the overall building, it is seen that the floor slab (having 250 mm thickness) has the largest percentage as 65% in comparison to foundation (450mm) at 14%, a reinforced concrete wall (225mm) at 12% and reinforced column (450x450mm) at 6% and the roof (450mm) at 4% (LETI, 2023). These percentages highlight the material selection of the floor system contributes significantly to carbon emissions, addressing that the shift in the material selection on the floor system is highly important in mitigating the overall environmental impact of building construction and operation.

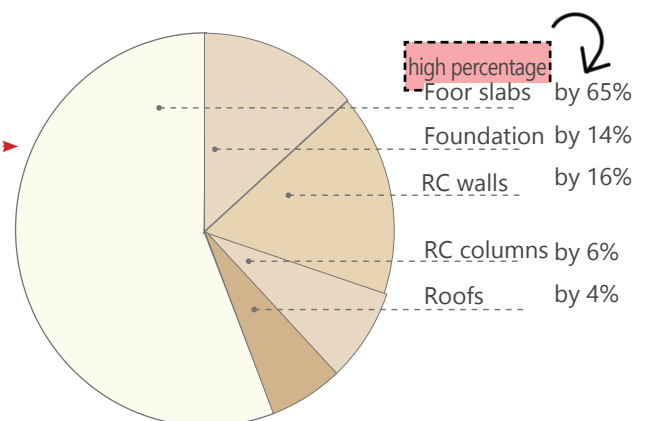


Figure 4: Embodied carbon percentages of building elements for a small scale building. Diagram is reproduced (LETI,2023)

2.4 LIFE CYCLE STAGES

The embodied carbon energy has been underestimated in the reduction needed for building carbon emission (LETI 2023). Mainly, the building codes focus on operational carbon energy but do not take into account the product related carbon emissions including construction, maintenance, disposal, manufacturing and production of the products. Therefore, the strategy of “avoid, shift and improve”. Avoiding involves adopting circular approaches by building less and low-carbon materials considering longevity. Improving deals reduces the carbon emission of the current materials, while the shift strategy focuses on the improvement in the market options of low-carbon materials (LETI 2023). The life cycle of a product with different stages and what they refer to are given below, leading to a better understanding of materials phases. by referencing EN 15978 and EN 15804 standards, LETI 2023.

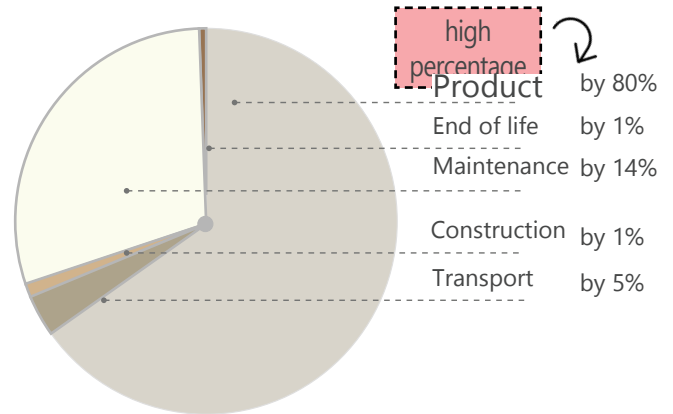


Figure 5: Carbon emission percentages by life stages. Diagram reproduced. (Climate Emergency Design Guide, LETI, 2023)

Stage A: A1-A3 The Product Stage

- [A1] Raw Material Extraction and Supply
- [A2] Transport to Manufacturing Plant
- [A3] Manufacturing and Fabrication

Stage A: A3-A4 The Construction Process

- [A4] Transport to Project Site
- [A5] Construction and Installation Process

Stage B: The Use Stage

- [B1] Use
- [B2] Maintenance
- [B3] Repair

[B4] Replacement

- [B5] Refurbishment
- [B6] Operational Energy
- [B7] Operational Water

Stage C: End of Life Stage

- [C1] Deconstruction and Demolition
- [C2] Transport to Disposal Facility
- [C3] Waste Processing for reuse, recovery or recycling
- [C4] Disposal

Stage D: Benefits & loads beyond the system

Reuse, recovery, recycling potentials

Reducing the embodied carbon in building components stands as an important step in decarbonizing the construction sector (IEA, 2019a). These sectors pose challenges for decarbonization, necessitating actions. Strategies encompass reducing material demand, promoting the adoption of low-carbon and bio-based materials while maximising energy efficiency in manufacturing and transitioning away from high-carbon energy sources (ETC, 2018). There exist significant prospects in expanding practices facilitating the reuse and recycling of construction materials.

Incorporating local, low-embodied carbon materials emerges as an important factor for the embodied carbon in construction (IEA, 2019a; 2022 Global Status Report). Local sourcing is emphasised to mitigate transportation-related emissions that can inflate embodied emissions. Biomaterials derived from plants, not only reduce embodied carbon but also sequester carbon during their lifespan, storing carbon absorbed during their growth until eventual biodegradation or end-of-life scenarios (2022 Global Status Report).

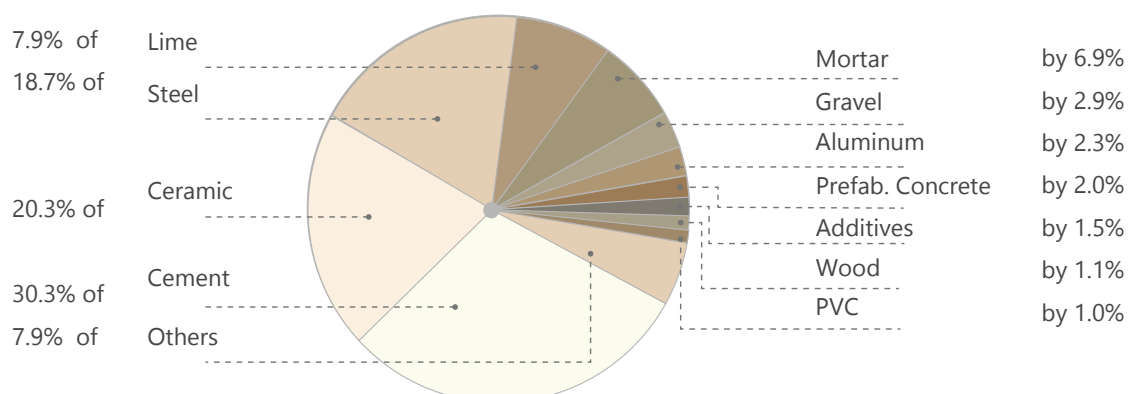


Figure 6: CO2 % of construction materials. Diagram reproduced (Kilgore, 2024)

2.5 CIRCULARITY

In order to ensure fully sustainability, the R-ladder is an important circular economical approach that should be taken into account. Each R-stage stands for an important attempt from moving from linear economy to circularity. The stage starts firstly with "Refuse", "Reduce", "Redesign" and continues with "Reuse, Repair, Refurbish, Remanufacture, Recycle and Repurpose"; which leads to recovering the value of the material.

Additionally, the value hill represent the idea that, when a material is produced, it gains value. However after use its value decreases as it needs to go to landfill. However by recycling the value of a material increases back and be saved. Therefore, the R-ladder is an important step on, re-creating the value of materials.

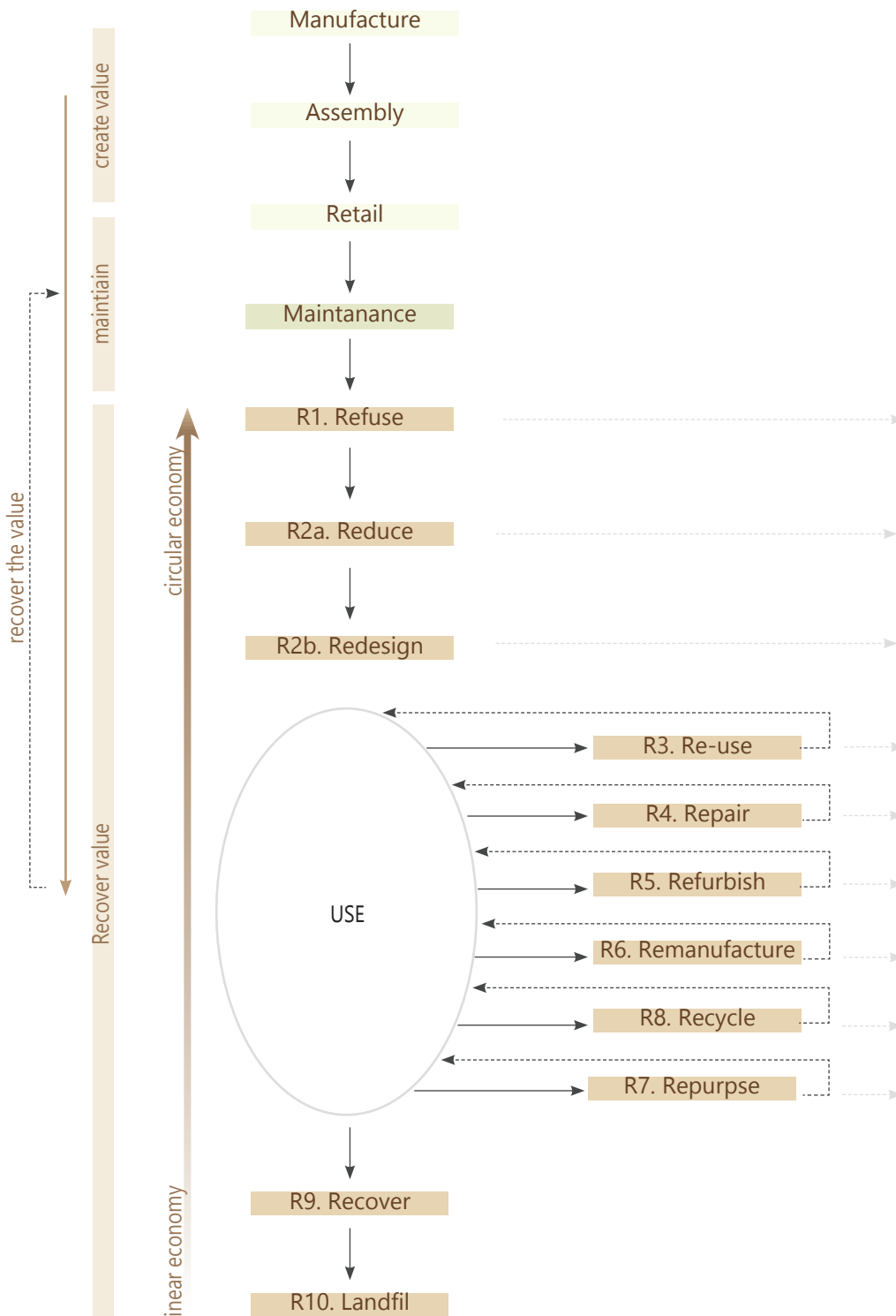
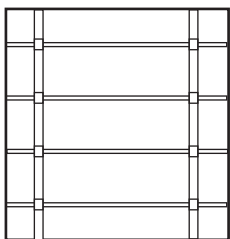
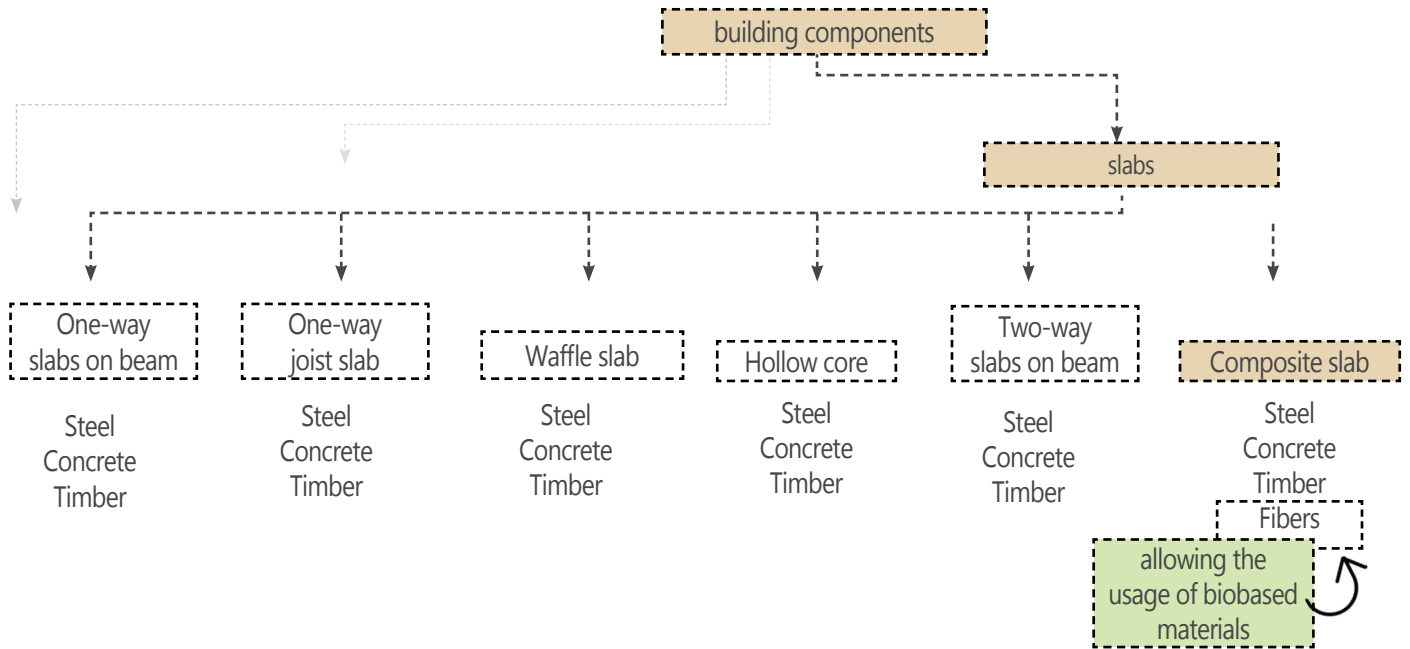


Figure 7: Diagram showing the circularity R-Ladder and the value hill. (Circular Purchising, Utrecht University & Inachainge, 2024)

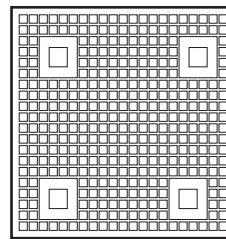
2.6 FLOOR SYSTEMS

Slabs are horizontal elements designed for the structure of floors, ceilings, and roofs. They play an important role in construction, serving several purposes such as evenly distributing the building's weight to the foundation, providing a sturdy ground for supporting other structural components, ensuring level surfaces, and offering a sturdy and secure base for various components within the structure (Types of Slabs Used in Construction | UltraTech Cement, n.d.).



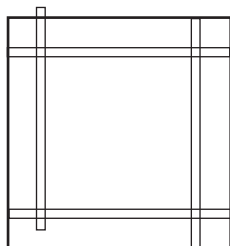
One-way slabs on beam

Withstand loads in one direction and these they are supported by parallel beams which transfer the load to columns.*



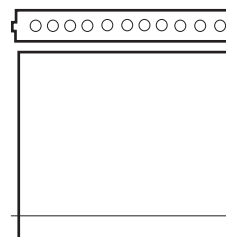
One-way slabs on beam

A waffle looking slab. Two-way slab with square or rectangular recesses. These parts reduce the weight of but still keep the strength of the system.



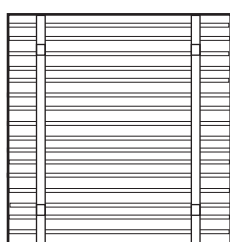
Two-way slabs on beam

Withstand loads in two direction and these they are supported by beams in both directions.



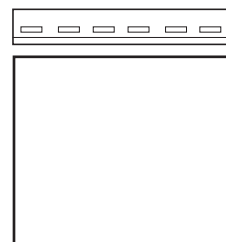
Hollow core

Precast concrete slabs, having hollow core goes through the length of the slab, reduced the overallweight, and make it easy to handle.



One-way joist slab

Held up by columns or walls. It uses small, T-shaped beams made of reinforced concrete, making the structure stiffer and allows less material overall.

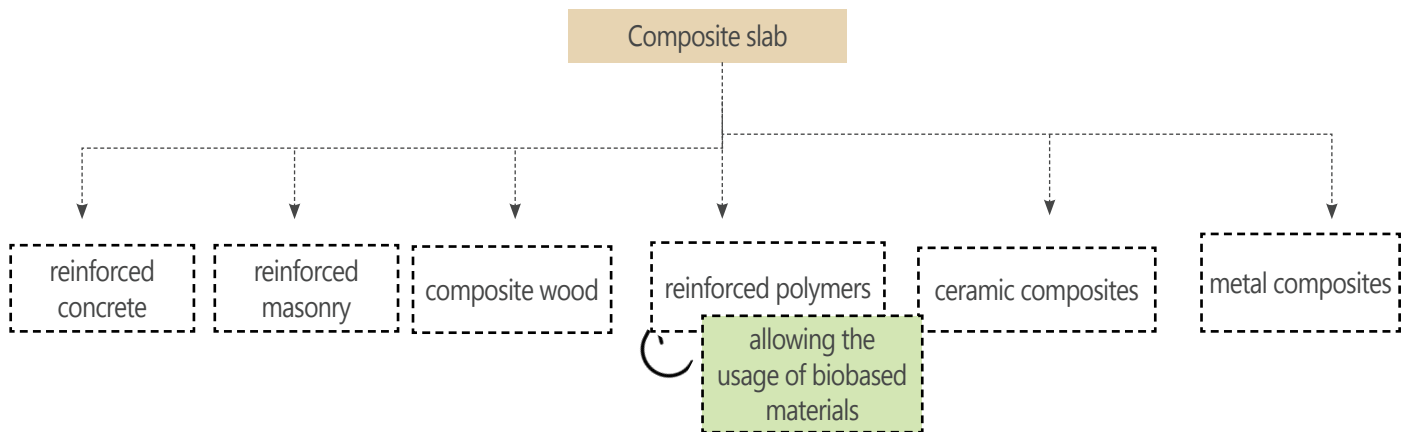


Composite Slab

Consists of more than two components to give te required stiffness and strength to the system.

Figure 8: graph, showing different types of structural floor slabs. (Types of Slabs Used in Construction | UltraTech Cement, n.d.); Images are reproduced by referencing from <https://www.dimensions.com/>

2.3 COMPOSITE FLOORS



Composite materials consist of more than two primary elements. In the construction and building industry, composite slabs encompass various categories, including reinforced concrete and reinforced masonry, where steel serves as the reinforcement. Additionally, ceramic composites and metal composites are among the alternatives.

It's important to note that not all reinforced polymers are natural materials.

Sandwich floor panels

Sandwich structures have a great stiffness-to-weight ratio and exhibit good stiffness and strength performances. They consist of two main load-bearing, high-stiffness skins on the top and bottom, with a low-density core material in between, as illustrated in Table 1. The high-stiffness skin can be made of either composite such as GFRC, NFRC and CFRC or non-composite materials, such as plastic, metal, or aluminium.

Additionally, the core material significantly influences the mechanical performance of the system and has the capability of reducing the overall weight of the component (Ma et al., 2021).

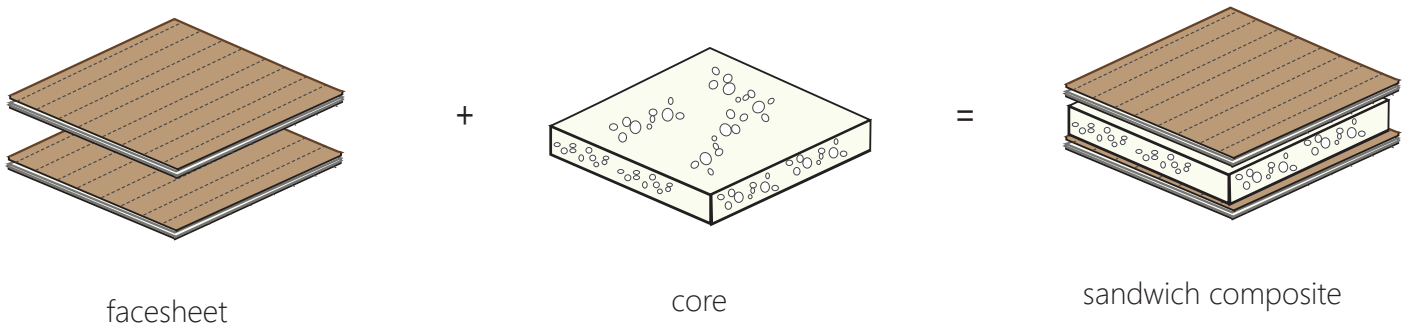


Figure 9: diagrammatic explanation of the composition of composite materials

2.7.1 Facesheet Material

The facesheets are essential for imparting primary tensile and compressive strength to the sandwich structure, thereby significantly enhancing its overall stiffness and durability. Figure 11 illustrates the preparation of the facesheet. Additionally, Table 1 presents various conventional facesheet materials along with their environmental properties, such as being biobased, biodegradable, renewable, and recyclable. The table also compares their lightweight and mechanical strength properties.

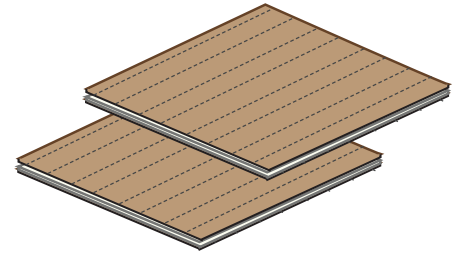


Figure 10: Representation of facesheets.

Table 1: Various facesheet materials and their related environmental friendly and mechanical properties.

Material	Bio-based	Biodegradable	Renewable	Lightweight	Recyclable	Mechanically strong
Aluminium	X	X	X	✓	✓	✓
Steel	X	X	X	X	✓	✓
Glass fiber	X	X	X	✓	X	✓
Carbon fiber	X	X	X	✓	X	✓
Plywood*	✓	✓	✓	X	✓	✓
RESEARCH GAP	✓	✓	✓	✓	✓	✓

2.7.2 Core Material

The core material is vital for providing shear strength and stability to the composite structure, thereby significantly enhancing its overall stiffness and mechanical performance. Figure 12 illustrates the preparation process of the core material. Additionally, Table 2 lists various conventional core materials and their environmental properties, including biobased content, biodegradability, renewability, and recyclability. The table also compares the materials based on their lightweight nature and mechanical strength. Additionally Figure 12 shows different core materials; honeycomb, cellular and solid.

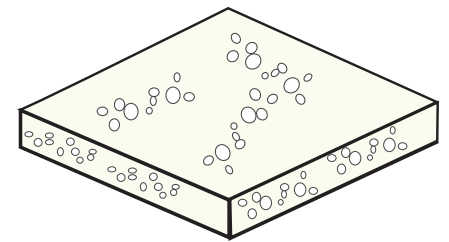


Figure 11: Representation of facesheets.

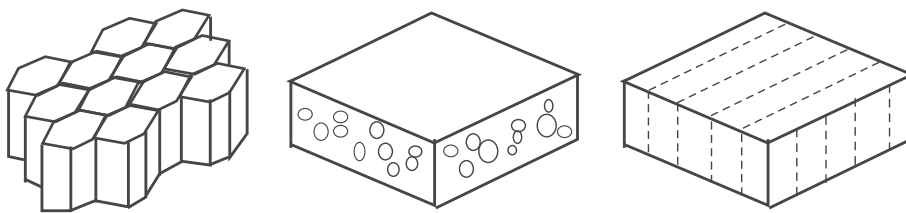


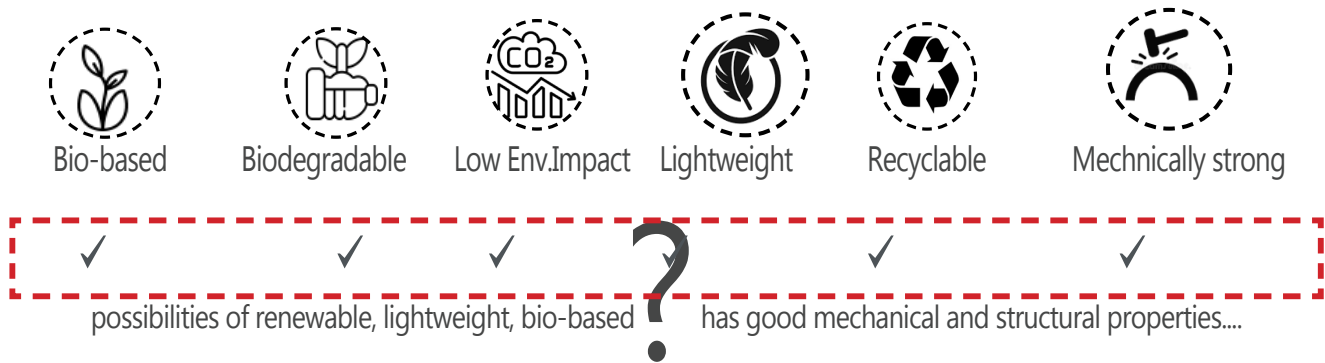
Figure 12: Different core types. a) honeycomb, b) cellular, c) solid Diagrams are reproduced. (Carlsson & Kardomateas,

Table 2: Various facesheet materials and their related environmental friendly and mechanical properties.

Material	Bio-based	Biodegradable	Renewable	Lightweight	Recyclable	Mechanically strong
Aluminum	X	X	X	✓	✓	✓
Polyurethane	X	X	X	✓	-	✓
Styrofoam	X	X	X	✓	-	✓
Rockwool	X	X	X	✓	✓	✓
Cardboard	✓	✓	✓	✓	✓	X
RESEARCH GAP	✓	✓	✓	✓	✓	✓

RESEARCH GAP

As shown on the previous page, the current literature lacks fully biobased materials, meaning materials where all components are derived from natural resources for structural load bearing applications. While there are some biobased approaches involving wood, further research is needed to explore additional and more lightweight alternatives derived from wood. This research gap leads to the primary research question: what are the possibilities of biobased composite materials, and how can they replace conventional materials?



GREEN-FRP COMPOSTIES

Green Material Approach

The table on the right shows the main approach to addressing the research gap. This approach involves not only choosing a material that is biobased or biodegradable but selecting a material that possesses both properties simultaneously, making it fully biobased. Such materials can also be referred to as "green composites."

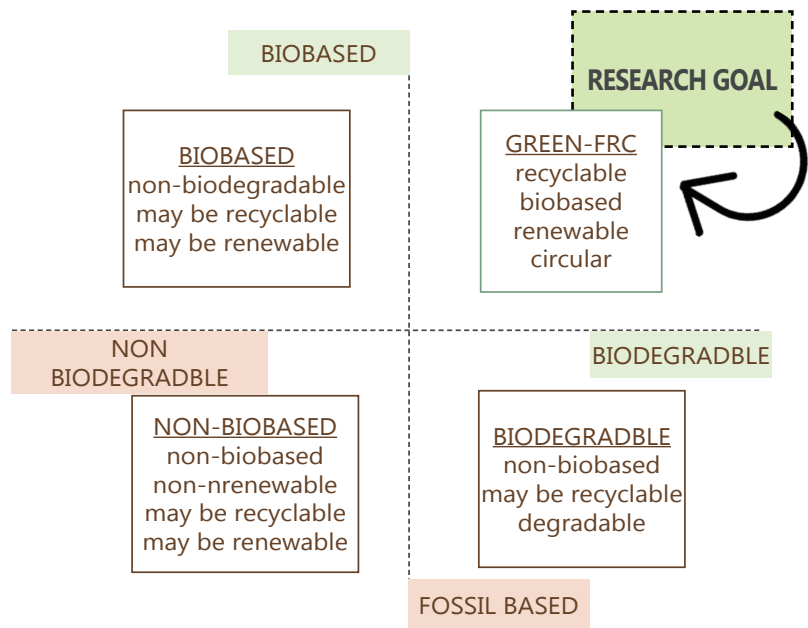


Figure 13: Table is reproduced by referincing Manger, C. (n.d.). European Bioplastics E.V. European Bioplastics e.V. <https://www.european-bioplastics.org/>

2.8 COMPOSITE MATERIALS

As previously discussed, the building industry's extensive use of materials stands as a primary contributor to carbon footprint and environmental impact due to the life cycle of nature-prone materials like concrete and steel, notorious for their high carbon footprint. While these materials boast strength, their environmental toll is significant. Wood, an excellent bio-based alternative, presents sustainability challenges due to potential deforestation from excessive usage. Therefore, exploring alternative materials becomes imperative in striving for sustainable structural solutions. This lead to a "research gap" in the literature to have a material that having proper mechanical properties for a structural floor slab while being consisting from natural sources.

One promising avenue lies in investigating natural fibre materials for structural applications, aiming to mitigate the environmental impact. This shift toward more eco-conscious materials is crucial for fostering sustainable living practices as well as it also has been mentioned previously at the report from LETI. In this pursuit, designing a floor system using natural fibre composites emerges as a viable solution. This involves research into various components, primarily focusing on natural fibres, matrix compositions, and resins. Table 3 explains the meaning of different fiber composite materials and their explanations. The research gap and the solution could be attributed on research for Green Fiber Reinforced Polymer by means of all its components being derived from natural resources.

Table 3: Various explanation of different fiber reinforced compositions (Van Der Toom, 2023)

Composite materials	Advantages
Fibre-reinforced polymer (FRP)	General term for reinforced composites using fibres and polymers
Fibre-reinforced polymer w/ glass fibres (GFRP)	Glass fibres and petroleum-derived polymers
Bio-Based Fibre-Reinforced Polymer RP (BFRP)	At least one of the component is derived from natural resources
Green Fiber-Reinforced Polymer (Green-FRP)	All components are derived from natural based resources

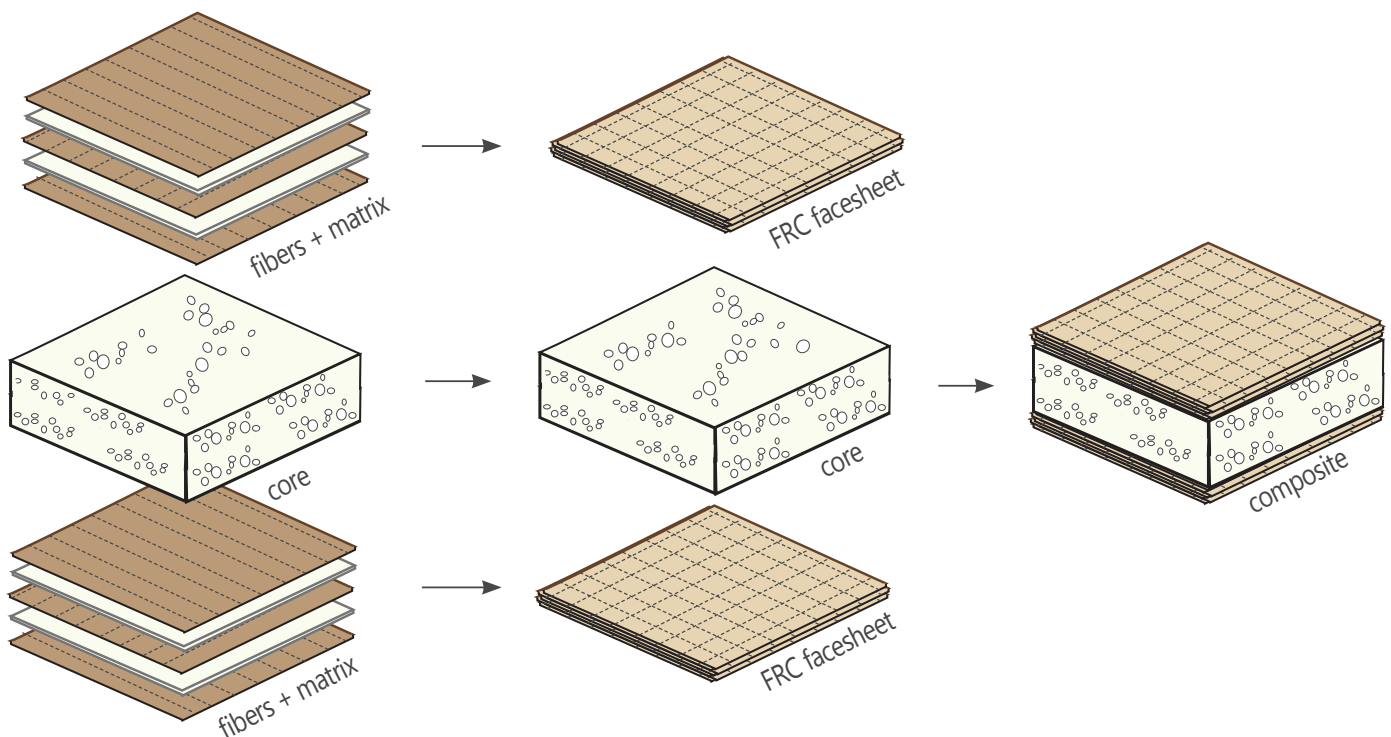


Figure 14: Exploded diagram explanation of composite materials composed of natural fiber reinforced facesheet and a core material


What they are composed of?

Composite materials are created by combining two or more materials having different physical and/or chemical properties. Thus, the end result is showing a material with different properties.


Typically, composite materials consist of fibers, a matrix, and fillers. For the thesis research framework, fillers are not investigated; only reinforcement with natural fibers and the matrix with biobased polymers are examined.

 **2.8.1 FIBERS**

Fibers are the primary reinforcing elements, providing strength and stiffness. They carry the load and determines the strength of the material mostly.

 **2.8.2 FIBERS**

The matrix binds fibers, transfers loads, protects from damage, enhances durability and toughness. It ensures the composite maintains its shape and resists impact.

 **2.8.X (excluded) FIBERS**

Particals that are to a composite to improve its properties (mechanical, thermal, etc..) or reduce costs. They can be organic or inorganic and in various shapes and sizes.

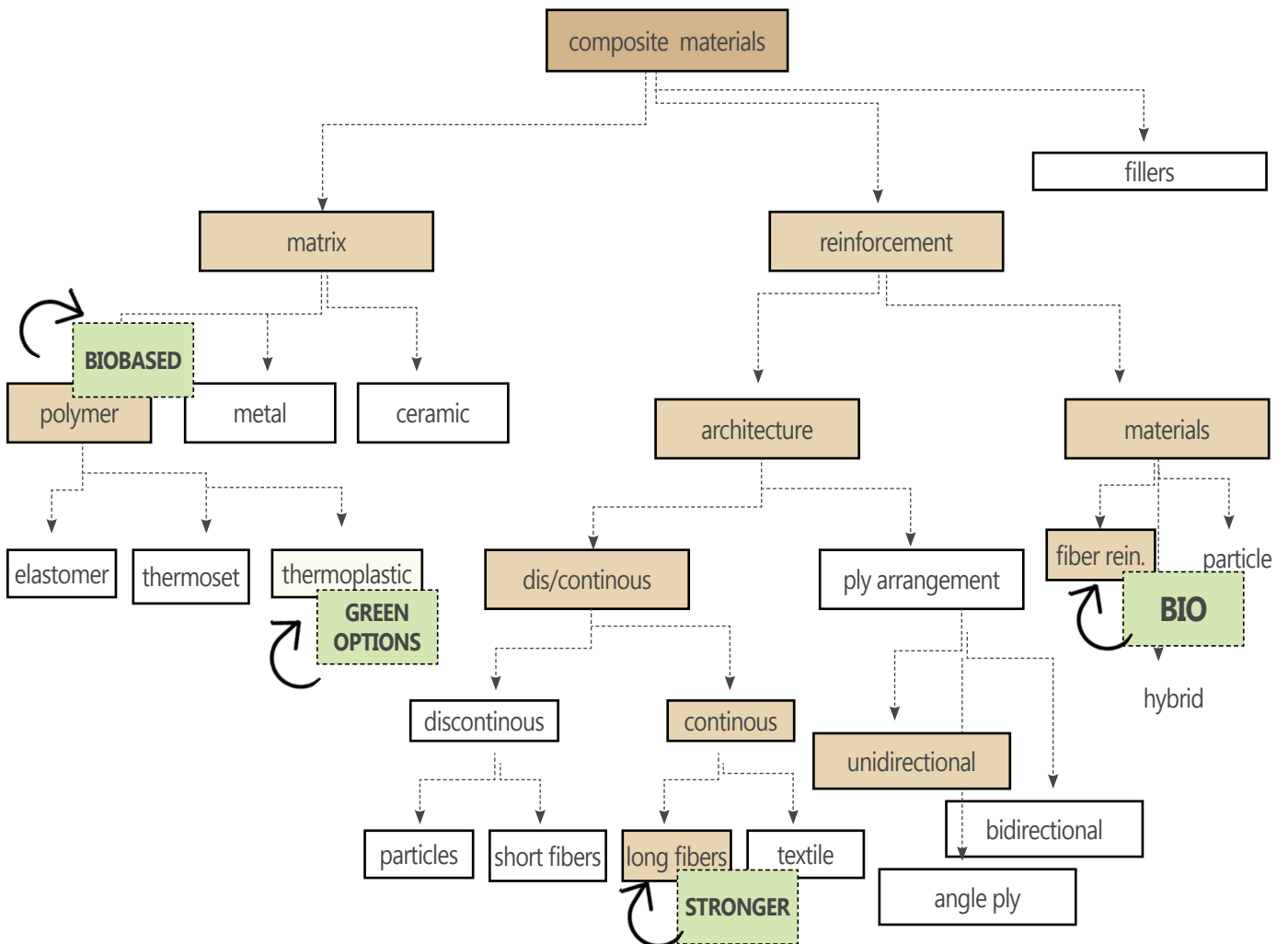


Figure 15: Figure, showing the classifications of composite materials. Re-produced. (Milan Polymer Days, 2022)

2.8.1 FIBERS

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Fillers

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2.8.2 NATURAL FIBERS

Green buildings aim to be eco-friendly, comfortable, and healthy places for living and working. Biocomposites are a major material in use, categorised into structural and nonstructural applications within the building industry (Uddin, 2013). They are considered a significant application in advancing green buildings, creating healthy and ecologically friendly environments. Natural fibres offer several advantages that make them appealing for various applications. They are biodegradable, renewable, and sustainable, aligning with environmentally conscious practices due to their minimal impact on the environment.

Additionally, they boast a low cost and are abundantly available in nature, contributing to cost-effective manufacturing. The processing of natural fibres requires low energy, making their production more energy-efficient. Furthermore, their non-toxic nature and recyclability enhance their appeal in eco-friendly product development. Natural fibres also exhibit high specific strength, providing robustness in diverse applications. (Ramamoorthy et al. (2015); Kargarzadeh et al., 2017; Pappu et al., 2012; Jawaid, Sapuan, & Alotman, 2017; Sydow & Bienczak, 2018).

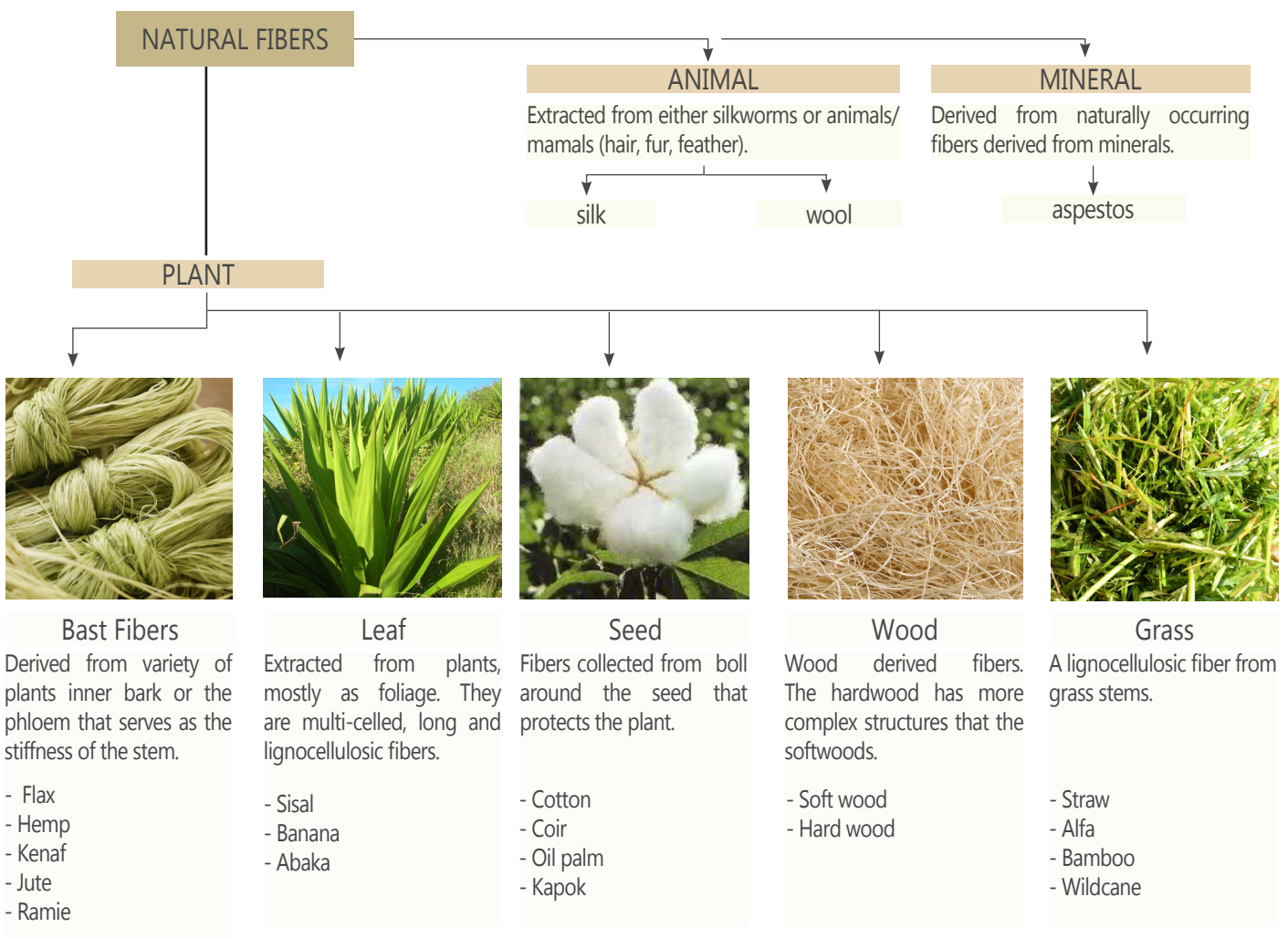


Figure 16: Natural fibers classifications. Table reproduced referencing Houck 2015. Images, respectively; Allende 2021; School & School, 2018; Encyclopaedia Britannica, 1998; Mills 2023; Grass Fiber-based Paper for Sustainable Packaging Products, 2024.

Comparison with CFRC & GFRC

Natural fibres are eco-friendly qualities as they are biodegradable, and their manufacturing process incurs minimal energy consumption and compared to glass and carbon fibres (Mallick, 2017). This leads them to have light weight properties. Additionally, certain natural fibres exceed E-glass fibres in the modulus-weight ratio, establishing them as strong contenders in designs prioritising stiffness (Mallick, 2017). Natural fibres also have better acoustic damping qualities that makes them suitable for various applications. Moreover, natural fibres offer a substantially more cost-effective alternative to both glass and carbon fibres (Mallick, 2017). Image below shows overall natural fibres and their categories.

Some Drawbacks

Despite their merits, natural fibres present certain drawbacks that need consideration. They have high moisture uptake, which can affect their performance in certain environments. There's also a tendency for natural fibres to agglomerate with resins during processing, impacting the material's uniformity and structural integrity. Poor compatibility with matrix materials poses challenges in achieving optimal bonding between fibres and matrices, affecting the overall strength of the composite. Additionally, the properties of natural fibres can vary depending on their origin, impacting consistency and predictability in manufacturing. While they offer moderate strength, their poor wettability with resins further complicates their integration into composite materials. These limitations warrant thorough consideration and mitigation strategies when utilising natural fibres in various industrial applications (Ramamoorthy et al. (2015); Kargarzadeh et al., 2017; Pappu et al., 2012; Jawaid, Sapuan, & Alotman, 2017; Sydow & Bienczak, 2018)

Application in the Industry

NFRC has been used in many different fields, especially in engineering, construction, automotive, packaging, and design (Shalwan & Yousif, 2013, Sassoni et al., 2014 and Jain & Jariwala, 2022). Table 4 shows some of their application areas. Their popularity in polymer composites stems for their lightweight nature, relatively high strength, cost-effectiveness in production, corrosion resistance, biodegradability, mechanical properties, and their availability as renewable resources, setting them apart from synthetic fibres. (Shalwan & Yousif, 2013; Shinoj, Visvanathan, & Panigrahi, 2010).



Figure 17: Natural fibers construction. (Natural Fibre Structures, Cluster of Excellence Integrative Computational Design and Construction for Architecture, University of Stuttgart.

Table 4: Application of various natural fibers in the industry. (Mohammed et al., 2015; Ticoalu, Aravinthan, & Cardona, 2010; Sen & Reddy, 2011; Bongarde & Shinde, 2014; Mwaikambo, 2006.)

Fibers	Advantages
Hemp	Construction products, textiles, paper, packaging, manufacturing of pipes, furniture, geotextiles
Oil palm	Windows, door frames, insulated panels a structural building systems, fencing, sliding, roofing
Wood	Window frames, door shutters, decking, railing systems, fencing, panels
Flax	Panels, decking, window f., tennis racket, bicycle frame, fork, seat post, snowboard, laptop cases.
Kenaf	Packing materials, insulations, oil & liquid absorbing materials, bags, mobile phone cases.
Jute	Building panels, door shutters, packaging, geotextiles, chipboards, roofing sheets, door frames.
Cotton	Textile, furniture, yarn, goods
Rice Husk	Bricks, building panels, window frames, panels, decking, railing system and fencing
Coir	Building panels, flush door shutters, roofing sheets, storage tank, packing materials, helmets and postboxes, mirror casing, projector cover, brushes and brooms, ropes, bags, seat cushions

Table 6: Showing the physical and mechanical properties of natural fibres. (Triverdi, 2023; Sahu & Gupta, 2017; Yan, Chouw, & Jayaraman, 2014; Al-Maadeed & Labidi, 2013; Sathishkumar et al., 2013; Saxena et al., 2011)

Origin	Fiber	Diameter (um)	Density (g/m ³)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation %
bast	Jute	25.250	1.3-1.49	393-800	13-26.5	1.16-1.50
	Flax	25	.150	500-1500	27.60	2.70-3.20
	Hemp	25-600	1.47	690	70	2.0-4.0
	Kenaf	40-90	1.22-1.40	295-930	22-53	3.70-6.90
	Ramie	22-80	1.50	400-938	61.4-128	3.6-3.8
	Sisal	100-300	1.30-1.50	507-955	9-28	2.0-2.90
	Banana	100-250	0.80	161.80	8.5	7-8
leaf	Cotton	-	1.50-1.60	287-597	5.50-12.60	2.50
seed	Oil palm	-	1.55	248	3.20	3.0
	Coir	150-250	1.20	175	4-6	2.50
	Bamboo	240-330	0.91	441	35.90	13-26.60
	Sea grass	5	1.50	453-692	6.42	

Table 5: The chemical components of the natural fibres. (Triverdi, 2023; Sahu & Gupta, 2017; Sathishkumar et al., 2013; Tong et al., 2014; de Rosa et al., 2010)

Origin	Fiber	Ceullulose (%)	Hemi-Ceullulose (%)	Lignin (%)	Pectin (%)	Moisture (%)	Wax (%)
bast	Jute	61-71.5	12-20.40	11.8-13,	0.2	12.5-13.7	0.50
	Flax	4.10-71.9	16.70-20.60	2.0-2.2	1.8-2.30	8-12	1.70
	Hemp	70.20-74.4	17.90-22.40	3.70-5.70	0.90	6.2-12	0.80
	Kenaf	31-39	21.50	15-19	-	11	-
	Ramie	68.60-76.20	13.10 - 16.70	0.60-0.70	1.90	7.5-17	0.30
	Sisal	67-78	10-14.20	8-11	10	-	2
	Banana	63-64	10-19	5	-	10-12	-
leaf	Cotton	82.70-90	5.70	-	0-1	7.85-8.50	0.5
seed	Oil palm	65	10.12	17.50	-	-	4
	Coir	32-43	0.15-0.25	40-45	3-4	8	-
	Bamboo	24-43	30	21-31	-	-	-
	Sea grass	57	38	5	10	-	-

Mechanical properties of natural fibers

The flammability of natural fiber composites is critical for building applications. These composites weaken and decompose at high temperatures, with specific flammability varying by fiber type (Gholampour & Ozbakkaloglu, 2019; Faruk et al., 2012). Enhancing fire resistance involves altering cellulose content, increasing crystallinity, reducing polymerization, and using coatings and additives like intumescent materials, ceramics, silicone, and nanoparticles. Degradation begins around 240°C for natural fibers, with lignin at 200°C and hemicellulose/cellulose at higher temperatures (Gholampour & Ozbakkaloglu, 2019; Kozłowski &

Thermal Conductivity

Using heat-insulating materials is crucial in reducing energy costs and boosting efficiency. Natural fibres, with their air-filled lumens, decrease thermal conductivity as they increase in composite content, offering effective insulation. Various studies on natural fibre composites' thermal conductivity show that higher fibre volume fractions lead to better insulation. For instance, by some researches it has been found that jute and banana fibre/ epoxy composites at maximum fibre volume fractions exhibited thermal conductivities of 0.231 and 0.228 W/m K, respectively, within a temperature range of -20°C to

Structure of natural fibers

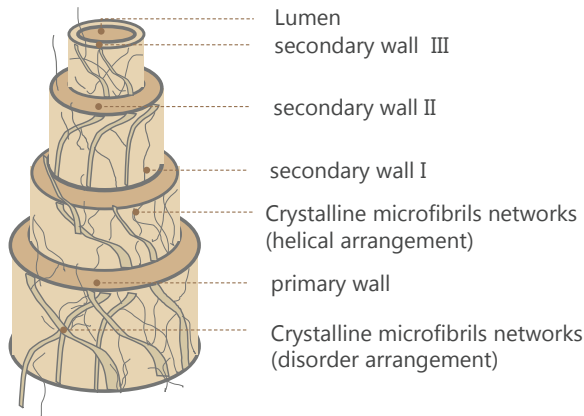
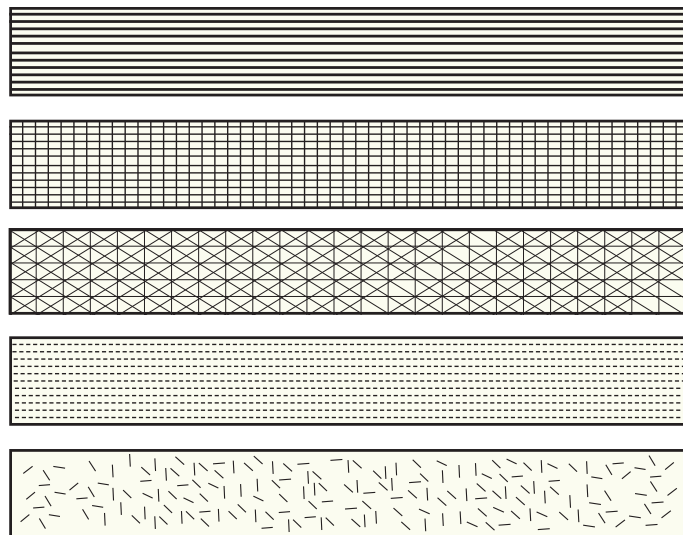


Figure 19: Structure of the natural fiber cell in digaramatic explanation. Image-eporduced. (Rong et al., 2001)

Fibre architecture refers to how fibres are arranged within a composite material, impacting both its properties and processing. The mechanical properties of a composite are influenced by specific characteristics of its fibre architecture. During processing, the flow of the matrix through the fibre arrangement determines factors. Some factors are the distribution of the fibers and the void content it has. Additionally, it can also be the fibre wetting, dry area, and more in the final composite, subsequently affecting its overall properties and performance. When continuous fibres are utilised, the fibre architecture can take the form of 1D , 2D, or 3D structures (Mallick, 2007).



The manufacturing of the NFRC includes the incorporation of fibres into a layer of a thin for ply. Generally fibers arranged in unidirectional orientation in continous ply (Fig.24a), in a bidirectional orientation which is in two directional as generally in their normal (Fig. 24b) or multidirectional orientation, where the fibres are arranged in more than two different directions (Figure 24c). For the discontinue fibres, they can either be unidirectional or random orientation (Figure 24d and Figure xe) (Mallick 2007).

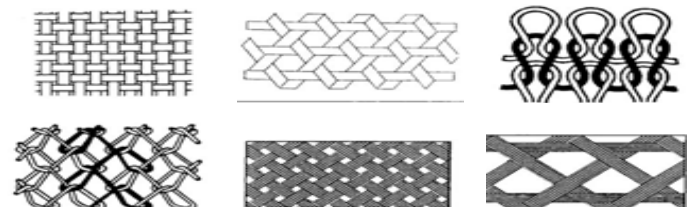
Figure 18: Directions of the fibers (Mallick 2007). Starting from the top to the bottom: Continuous fibres, unidirectional; Continuous fibres, bidirectional; Continuous fibres, Multidirectional; Discontinuous fibres, unidirectional; Discontinuous fibres in random orientation.

One-Directional

In one-dimensional architecture, continuous fibers align in a single direction, providing high strength and modulus along the fibers but lower values transversely. Multilayered composites with varying fiber orientations can mitigate these differences, but the risk of delamination from high interlaminar stresses is a drawback (Mallick, 2007).

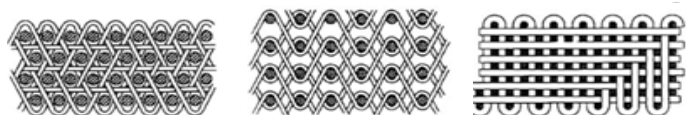
Two-Dimensional

Uses textile manufacturing methods in liquid composite molding, with liquid polymer injected into dry fibers. In bidirectional architectures, fibers are woven in perpendicular directions (0° and 90°). Knitting and braiding also form 2D architectures, with biaxial braids intertwining yarns in two directions and triaxial braids adding a third set along the braiding axis. Randomly oriented fibers, dis/continuous can also create 2D architectures (Mallick, 2007).



Three-Dimensional

Created similarly to 2D methods, addresses weaknesses in the z-direction by adding fibers in the thickness direction. Techniques include stitching woven fabric stacks and using weaving and braiding methods (Mallick, 2007).



PLANT FIBER

Plant fibres are acquired from the various parts of the plants and divided into three different main categories as bast, leaf, seed and wood fibres. As bast fibres have great strength, in the research they are taken into consideration for the reinforcement

2.8.3 FLAX FIBER

Flax (*Linum usitatissimum*L.) a source of seeds, oil and fibres. They have very great mechanical properties. Flax fibers have been used for variety of applications. It was used in ancient Egypt by making it among the world's oldest cultivated crops as the trace of its use dates from thousands years BC ago (Faruk & Sain, 2015; Kozlowski et al., 2012). The European processing of flax entered its modern phase during the 17th century, primarily in countries such as the Netherlands, Belgium, Poland, France, England, and Ireland. Subsequently, during the 19th century, production extended to South America, encompassing regions like Argentina, Brazil, and Chile

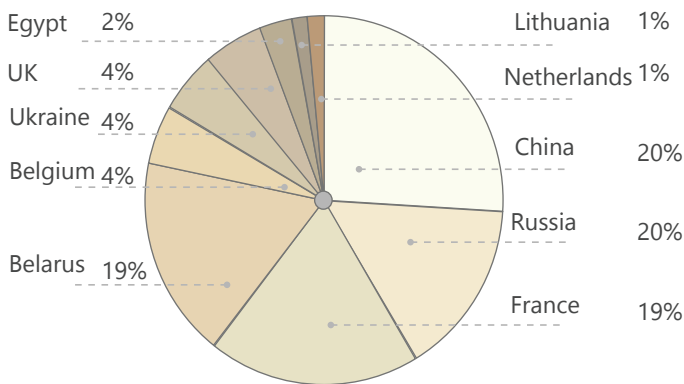


Figure 22: Flax percentages around the world according to how common they are. (Faruk & Sain,2015.)

Flax Structure

A flax fibre, plant cell, typically ranges from 10 to 25 mm in length, with a cross-section varying between 10 and 25 microns. Conversely, a fibre bundle is notably larger, comprising two to 20 individual fibres held together by pectin. These bundles of fibres are situated in the outer regions of the flax stem. The individual flax fibres that make up these bundles consist of multiple cell walls, where cellulose stands out as the most crucial component within the microfibrils. The organisation of microfibrils in the cell wall is a critical factor influencing the mechanical strength and rigidity of the fibre (Faruk & Sain,2015; van der Linden, 2017)

BAST FIBER

Bast fibres consist of a core surrounded by a stem and within the stem, there are a high amount of fibre bundles consisting of filaments or individual cells. They are extracted from dicotyledonous plants' stalks and to the plant's central woody part through gum, primarily composed of pectins. These fibre bundles play a crucial role in providing strength to the stalks of fibrous plants



Figure 20: Top left, Flax seeds; Top right: Flax flower plant. (NouveauRaw, Amie-Sue., 2021); Bottom left: Woven flax fibers, (Textile Sphere 2019); Bottom right: Flax fibers (Trivedi, 2019).



Figure 21: Flax Struc. (Faruk & Sain,2015; van der Linden, 2017).

Fibers



Fibers are the primary reinforcing elements, providing strength and stiffness. They carry the load and determines the strength of the material mostly.



2.8.4 MATRIX

The matrix binds fibers, transfers loads, protects from damage, enhances durability and toughness. It ensures the composite maintains its shape and resists impact.



Fillers

Particals that are to a composite to improve its properties (mechanical, thermal, etc...) or reduce costs. They can be organic or inorganic and in various shapes and sizes.

2.8.4 Matrix



The strength characteristics of natural fibre composites significantly rely on the proportion of fibres within the resin matrix. Therefore, In fibre-reinforced composite materials, the essential component is the matrix, responsible for binding the fibres, distributing loads uniformly, safeguarding against environmental elements, ensuring compatibility for robust adhesion, and offering flexibility and resilience, collectively enhancing the composite's strength and longevity. Especially for the design of a structural floor system, the matrix is highly important as the system needs to resist load-bearing loads (Tripathi et al., 2021; Sanivada et al., 2020; Siakeng et al., 2018).

Main functions of the matrix (Pavlovic & Csillag, 2018)

1. Arranging the fibres in the desired geometric configuration.
2. Transmitting forces among and between the fibres,
3. Averting the buckling of the fibres.
4. Shielding the fibres from environmental impacts.

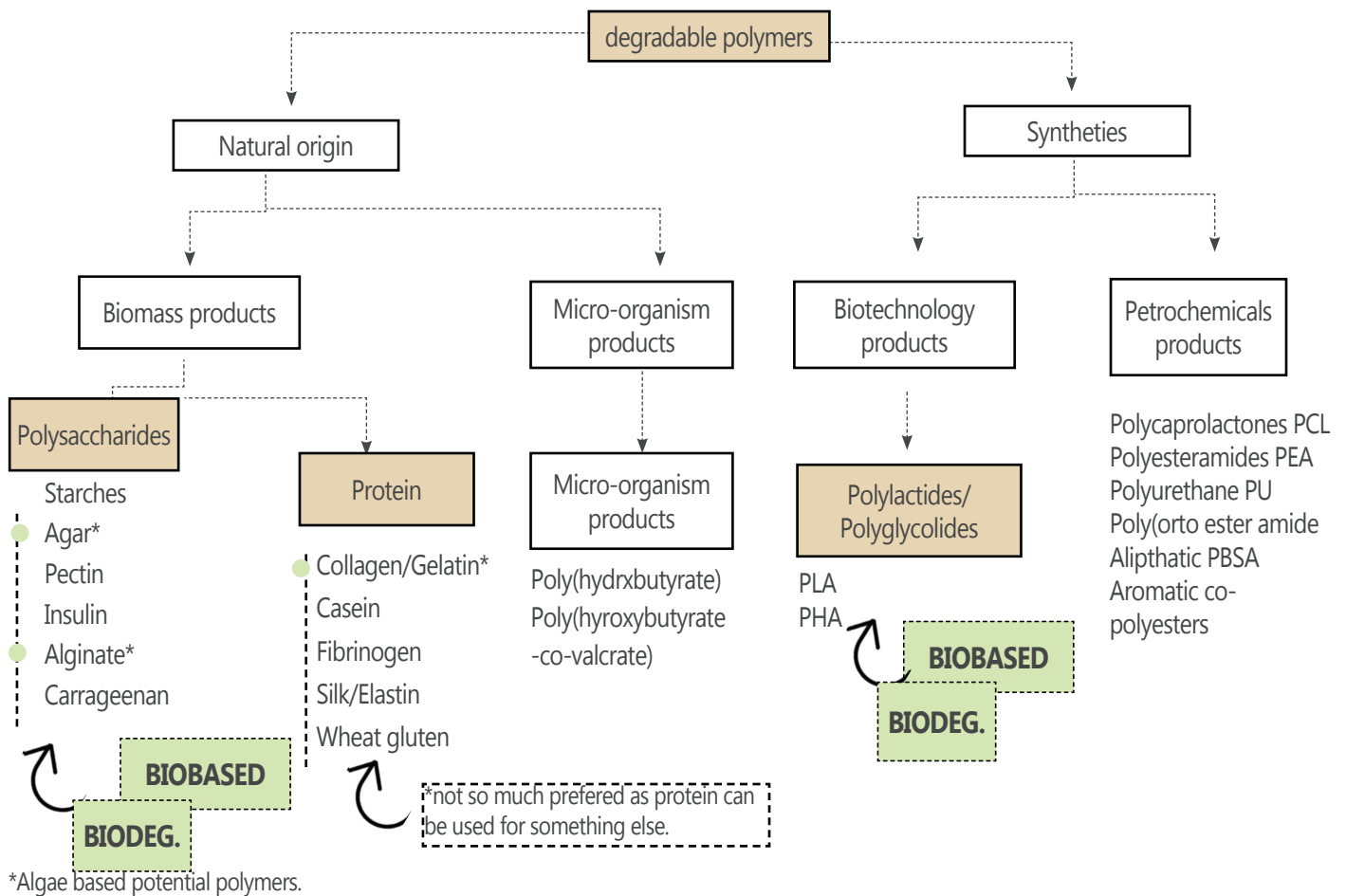
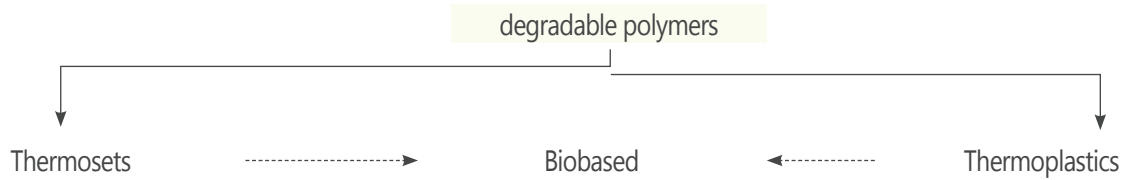


Figure 23: Showing the polymer categorisations based on their biodegradability. Chart is reproduced andreferenced from; Andrew & Dhakal, 2022; Gurunathan et al. 2015.



THERMOSETS

Thermoset resins, distinguished from thermoplastics by their incapability to be melted and reshaped through heating, are infusible and insoluble materials cured by heat or a catalyst. Due to the establishment of three-dimensional covalent bonds among polymer chains through a chemical change, these resins exhibit a higher modulus, enhanced creep resistance, superior thermal stability, and increased chemical resistance compared to thermoplastic resins (Gholampour & Ozbakkaloglu, 2019; Faruk et al., 2012; Sinha, 2004; Mohammad, 2007). However, they demonstrate brittleness at room temperature and have lower fracture toughness. The molecules within thermoset polymers are interconnected via cross-links, creating a rigid network structure that renders them impervious to melting upon polymerization (Al Maadeed, et al., 2020; Merhi, 2022).

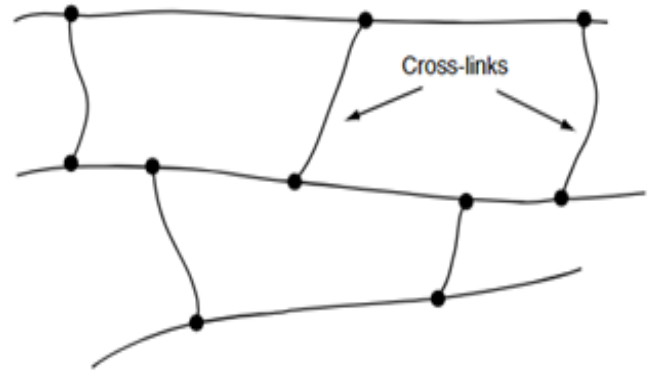


Figure 24: Representation of the cross-linking, where the molecules are chemically joined together leading a 3D rigid structure (Mollick, 2017).

Table 7: : Thermoset resins’ advantages and disadvantages (Gholampour, 2019; Lokensgard, 2016).

Fibers	Advantages	Advantages
Epoxy	High thermal and mechanical properties High water resistance Low curing shrinkage Long working times ability	More expensive than vinyl ester Corrosive amine hardener Difficult to process
Polyester	Easy to use Lowest cost	High curing shrinkage Limited range of working times Moderate mechanical properties
Vinylester	Very high chemical and environmental resistance Higher mechanical properties than polyester	High curing shrinkage More expensive than polyester High styrene content Requires post-curing for good properties
Phenolic	High fire resistance	Difficult to process
Polyurethane		

THERMOPLASTICS

Thermoplastics can be easily moulded while in a thick, liquid state and solidified by cooling, leading to a physical change (Gholampour & Ozbakkaloglu, 2019; Baeurle, 2006). The individual molecules aren’t chemically bonded together; instead, they’re linked by weaker secondary bonds that can temporarily break when heat is applied, allowing molecules to move and adopt a new configuration under pressure (Merhi, 2022; Drobny, 2007).

Compared to thermosets, they offer higher impact resistance, increased capability for reshaping, greater tolerance to damage, and the ability to withstand higher processing temperatures and pressures. Additionally, their viscosity in the melted condition is around 500–1000 times higher than that of uncured thermosets (Gholampour & Ozbakkaloglu, 2019; Faruk et al., 2012).

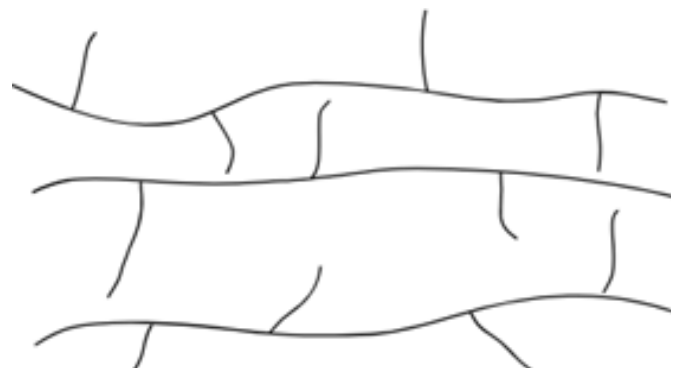


Figure 25: Representation of the weak secondary bond of thermoplastics, that are not chemically joined together, which can be broken (Mollick,2017)

Table 8: Petrochemical-based thermoplastic resins' advantages and disadvantages (Gholampour, 2019; Lokensgard, 2016.)

Fibers	Advantages	Disadvantages
Polyethylene	High ductility and impact strength Good fatigue resistance Lightweight , Low cost Low moisture absorption	Poor weathering resistance Flammable High thermal expansion
Polypropylene	High temperature resistance High dielectric resistance Excellent chemical resistance Good fatigue resistance	Difficult to process Comparatively expensive Limited availability
Polystyrenet	Good chemical resistance Resistance to stress cracking Very low moisture absorption Weather resistance	Flammable Low impact resistance Brittle
Polyvinyl chloride	High impact resistance Versatility, Low cost Good chemical resistance Flame retardant Good dimensional stability	Poor resistance to UV Poor resistance at low and high temperatures

BIOBASED

In 2011, global bio-based polymer production was about 3.5 million tons, compared to 235 million tons of petrochemical-based polymers. Increasing bio-based materials is crucial to reduce environmental impact. Polylactic acid (PLA) from maize starch uses up to 50% less oil and emits 60% fewer greenhouse gases than petrochemical counterparts (Campilho, 2015; Gholampour, 2019).

Biodegradable polymers like PLA, PEG, PCL, PLGA, PHB are used as matrix materials. PLA, derived from sources like corn and soy protein, is a leading candidate to replace petroleum-based plastics due to its renewability and excellent properties. Its performance improves further when natural fibers are added to the PLA matrix (Tripathi et al., 2021; Sanivada et al., 2020; Siakeng et al., 2018).

Bio-based resins present numerous advantages over petrochemical-based ones: they exhibit higher energy efficiency during production, needing about 65% less energy, they remain non-toxic as they degrade, break down faster with less energy consumption, derive entirely from renewable biomass sources, and significantly reduce greenhouse gas emissions by approximately 68% (Gholampour & Ozbakkaloglu, 2019; PolymerOhio, 2015). Even though they have advantages, one negative aspect of the bio-based products are their production costs are roughly 10% higher than those of petrochemical-based resins (Gholampour & Ozbakkaloglu, 2019; PolymerOhio, 2015; Kuruppallil, 2011). However, it is thought that in the long term, this is not leading to a problem.

Table 9: Dis/advantages of bio-based resin (Gholampour, 2019; Bastioli, 2001; Edgar et al., 2001; Volova, 2004; Sharma & Mudhoo, 2011, Clarinval (Smith) 2005; Ashby, 2012)

Fibers	Advantages	Disadvantages	Glass Tempt. °C	Tensile Stren. (MPa)	Elastic Mod (GPa)	Elongation %	Type
Starch	Fully biodegradable Low cost	Brittle, Difficult to process Water-sensitive		5–6	0.125 – 0.85	31–44	Thermoplas Thermoset
PLA	High modulus High strength Nontoxic Relative low cost	Brittle Poor impact strength Low thermal degrad. temp. Low decomposition temp.		21–60	0.35 – 3.5	2.5–6	Thermoplas. Thermoplas.
PHA	High molecular weight Fully biodegradable	Low stability, Brittle Low deformability More expensive		18–24	0.7–1.8	3–25	
Cellulose	Abundant Relative low cost Ease to modify Moder. impact resist. Moderate heat resist.	High moist. absorb. Low decomp. temp.		7-7.5			Thermoplas Thermoset

2.8.5 Literature Examples

Research Papers

1.CO2 capturing NFR algae-derived PU composites by Sowrabh R. Shetty. This is a thesis research from the Aerospace Engineering faculty at TU Delft. In the thesis the Polyurethane polymer is produced from algae through the reaction of polyol which in mostly they are derived with isocyanate from petroleum based sources. The conclusion implies that this bio-based polyurethane has minimal environmental impact inexpensive and abundant, having high yielding. Furthermore, the research has been concluded as they are promising good mechanical properties while reducing the environmental impact (Shetty, 2022)



Figure 26: Specimens. (Shetty, 2022)

Bio-Based FRP Floors: A Comprehensive Feasibility Analysis by Iona van der Toorn from TU Delft Civil Engineering & Geosciences This study explores the BFRP floors in modular buildings as eco-friendly and cost-efficient alternatives. The research finds that while BFRP floors have similar construction heights to conventional ones, they are lighter and can be optimized to reduce material usage. However, their current environmental impact, assessed in terms of CO2 emissions, is higher than that of concrete floors. Despite this, advancements in resin usage and production techniques hold promise for future sustainability (Iona, 2023)

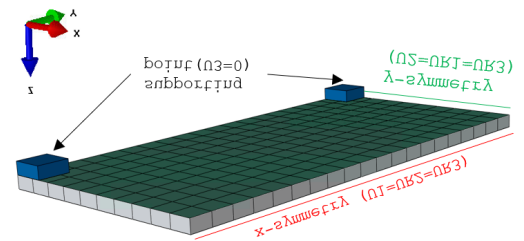


Figure 27: Analys's on FRP floor. (Iona, 2023)

Natural Fiber Reinforced Composites & Façade Applications Thesis researchby Nader Merhi from TU Bouwkunde Building Technology. The results indicates that natural fiber-based composites, exhibit competitive performance in certain applications, which in that research propped as facade applications. These composites combine natural fibers with non-petroleum-derived or biodegradable polymers. This study investigated the mechanical behavior of bio-composites under varying conditions of humidity, temperature, and UV radiation to assess their suitability for potential facade applications (Merhi,2022)

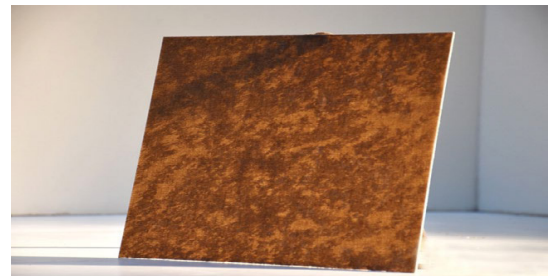


Figure 28: Flax-NFRC material. (Merhi, 2022)

Algae-based Biodegradable Polyurethanes Algenesis, a plant-based material science company, has patented Soleic, a technology producing fully biodegradable polyurethane from algae and non-food plants, replacing petroleum-based PU. The bioplastic is third-party certified with 52% bio-content. Soleic bioPU biodegrades in compost within months, lacks harmful PFAS additives, and boasts a 50% reduction in greenhouse gas emissions compared to petroleum PU. The foam degradation can be seen from Fig 34. (DOE Bioenergy Technologies Office (BETO) et al., 2023)



Figure 29: Bio-PU foam degradation. (DOE Bioenergy Technologies Office (BETO) et al., 2023)

1.IsoBouw BioFoam® ioFoam is a bio-based (PLA) product (See Fig 35) produced by BEWI raw, a plastic composite company. constitutes a particle foam crafted from Expanded Poly Lactic Acid (E-PLA). The process involves the fusion of foamed PLA beads, resulting in the creation of lightweight products, ranging from packaging components, uncomplicated plates and insulation foams. PLA's carbon footprint is minimal in comparison to fossil-based alternatives, owing to its biobased origin. Furthermore, any potential CO2 emissions at the end of a BioFoam part's life cycle are offset, as plants utilised in generating new feedstock for PLA recapture the released carbon dioxide (IsoBouw, 2022).



Figure 30: Upper, material image. Below, degradation of the material (BioFoam, IsoBouw)

Material District



The Material District is an annual event held in Utrecht, Netherlands, which took place from March 6th to 8th, 2024. This event brings together manufacturers, start-ups, and designers to showcase their projects and innovations. On this page, highlights of some of the materials can be found.

Figure 31: Image on the left (Van Der Wijk (2024)

Mogu Acoustics

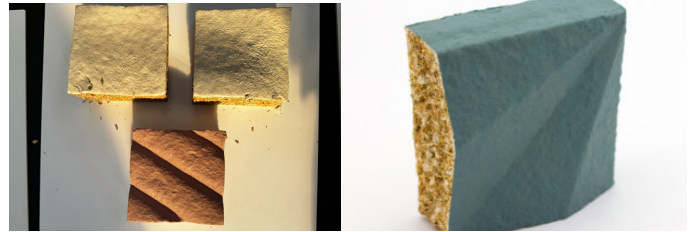
Purpose: Acoustic panels

Material: foam-like mycelium. Upcycled from textile residues.

Properties: 100% circular, excellent acoustical perf., VOC free Source:

Mogu Acoustic - MaterialDistrict, 2024

Figure 32: Mogu acoustic materials. left; own-taken picture at the exhibition; right (Mogu Acoustic - MaterialDistrict, 2024)



Pierreplume

Purpose: Wall covering or acoustical panels.

Materials: Recycled textiles. The materials are consists of at least 70% fabrics that are recycled from fashion industry.

Source: Material District, Pierreplume 2022

Figure 33: Pierreplume. (Pierreplume - MaterialDistrict, 2023)



ecoHAB from Smarter GmbH & CoKG

Purpose: Sandwich panel

Materials: Vegetable matter, agricultural waste, popped-corn

Properties: Possesses very good technical properties.

Source: ECOHAB - MaterialDistrict, 2023

Figure 36: ecoHAB. (ECOHAB - MaterialDistrict, 2023)



Glass Foam from Steven Akoun

Purpose: Insulation

Materials: industrial waste glass & natur. recycl. foaming ag.

Properties: Insulation for sound and temperature

Source: Glass Foam - MaterialDistrict, 2022

Figure 37: Glass Foam.s (Glass Foam - MaterialDistrict, 2022).



Bio-SIP from Qube Buildings

Purpose: Insulation

Materials: recycled plastic, natural materials (flax and hemp)

Properties: insulation, structural integrity, efficient assembly, lightweight, modular system construction

Source: Material District, Pierreplume 2024

Figure 34: bio-SIP. (Bio-SIPTM - MaterialDistrict, 2024).



Lisocore from Blok Plaatmaterial

Purpose: Sandwich panel

Materials: Cardboard

Properties: High load-bearing capacity, lightweight design.

Source: Lisocore® - MaterialDistrict, 2024

Figure 35: Lisocore materials. (Lisocore® - MaterialDistrict, 2024)



2.8.5 Production Methods

The production method is influenced by the moisture content of the fibre, value fraction, the overall composite temperature, length of the fibres as well as the content ratio and the chemical composition of the fibres. Fibre volume fraction increases the mechanical (stiffness, strength, water uptake) while decreasing its deformability (Camphildo, 2015; Gholampour & Ozbakkaloglu, 2020). As the mechanical chemical and physical properties of are changed by depolymerization, oxidation, hydrolysis, decarboxylation, dehydration, and recrystallization, above 200C within 20mins will lead to degradation for most of the natural fibres (Gholampour & Ozbakkaloglu, 2020; Stark, 1999; Araujo et al., 2008; Yildiz, 2006).

The primary techniques are compression moulding, extrusion moulding, injection moulding, and resin transfer moulding methods. Table 10 outlines advantages and disadvantages of some methods. As the fibers are chosen as continuous fibers with thermoplastic (PLA) production, the most suitable method is compression molding or film stacking method where previously Gosh (2023) has been conducted research on regarding the thesis on flax and pla composites.

Table 10: Various production methods for different resin and fibre types, and their dis/advanantages (Gholampour & Ozbakkaloglu, 2020; Chand & Dwivedi, 2006; Corradini et al., 2009; Elkington et al., 2015; Kumar et al., 2005; Mulinari et al., 2009; Richardson & Zhang, 2000; Rouison et al., 2004; Rouison et al., 2006; Santos et al., 2007; Scheru & Hintermann, 2005; Van Voorn et al., 2001; Zou et al., 2010; Araujo et al., 2008).

Fibers	Advantages	Disadvantages	Resin Type	Fiber type
Compression moulding	Fast setup time Low wasted material Low cost for large, complex comp. Good surface finish Even pressure distribution	Low production speed Suitable only for flat or moderately curved composite shapes	Thermoplastic	Short
Sheet moulding	Excellent part reproducibility High volume production ability Low labour requirements	Suitable only for the preparation of composites with a low fibre volume fraction	Thermoset	Short
Extrusion moulding	Fast setup time Low initial setup costs Low production costs	Moderate prod. speed Suitable only for uniform cross section Mediocre precision	Thermoplastic	Long
Injection moulding	Low operational & produc. cost High throughput Flexibility with complex shapes High precision	High initial setup costs	Thermoplastic	Short
Hand lay-up	Simple principles to teach Low tooling cost Wide choice of material & suppliers Flexibility in material design	Labour intensive Styrene emission from unsaturated polyester, vinylester resins Resins need to be low viscosity	Thermoset	Short
Resin transfer moulding	Product consistency than compr. Tighter tolerance, more intricate parts than injection moulding Fast setup time and low costs Low maintenance costs	More material is wasted than with compression moulding Production speed is lower than that of injection moulding	Thermoset	Long
Resin infusion moulding	Excellent surface quality Slow cycle times high consumable costs Short process time Even quality and material thick.	Slow cycle times and high consumable costs	Thermoset	Long

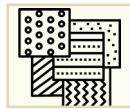
2.9 Benchmarks

In this section, benchmarks that determine the comparison of components for the conventional floor system are discussed. Additionally, in the following part of this section, the goals are discussed by referencing the building product life cycle and ongoing sustainability goals in Europe, considering industrial and sustainability aims.



2.9.1 Building Industry Benchmarks

As mentioned in the previous chapter "Construction and embodied energy", the report showed the embodied energy used for a small scale building in the UK, which creates the basis of the goals by referencing the report (LETI 2023). An overview of the approaches and the goals can be seen below.



2.9.2 Material Benchmarks

Material based benchmarks, considers two distinct floor systems as its base: a wooden hollow core slab with a 240mm thickness and a concrete hollow core slab with a 200mm thickness. Subsequently, the goals are established by referencing the benchmarks in the following categories (LETI 2023).



2.9.3 Local Construction

As the design assignment goals a benchmark of two hollow core floor systems are considered: wooded and concrete. The comparison primarily focuses on product cycle and environmental criteria sourced from local references specific to the Netherlands.



2.9.1 Building Industry Benchmarks

Product 80%

Reduce the embodied energy by 40%, the material of the floor system. Embrace natural materials, increase recycled content, use low VOC materials, use renewable resources and carbon neutral materials.

Maintenance 14%

Decreasing the need for maintenance for three main topics as, easily detachable for reduced energy; modular and easy to maintainable pieces; longevity and efficiency.

Transport 5%

Decrease the effort for transportation by handling efficiency using smaller products to reduce energy and use local sourced materials.

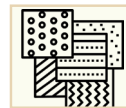
Construction 1%

Ease of Construction, Favour easily constructible materials with dry connections

Maximise material utilisation to minimise waste.

End of life 1%

Prioritise materials conducive to biodegradation, avoiding chemical-laden connections. Avoid synthetic resins that hinder recyclability, proposing reuse or recycling.



2.9.2 Material Based Benchmarks

Material Supply

Minimise material usage to prevent stock shortages, excess material usage, energy consumption, and a larger carbon footprint during production.

Climate and environmental systems effect:

Decreasing the need for maintenance for three main topics as, easily detachable for reduced energy; modular and easy to maintainable pieces; longevity and efficiency.

Product Life Span

Durability: material with an extended lifespan to ensure longevity.

Strength-to-Weight Ratio

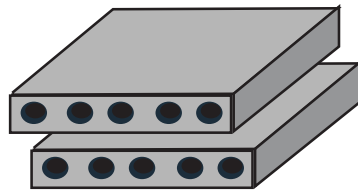
Lightweight High-Strength Material: Choose a light material with high strength to minimize weight and material usage while maintaining structural integrity.

End of life

Renewability and Biodegradability: Material's renewable sources and biodegradability at end of life. Environmental impact from extraction to disposal.

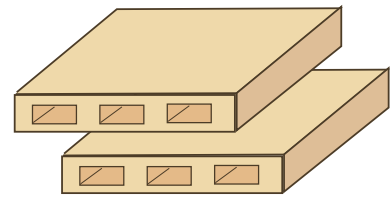


2.9.3 Local Constructions Benchmarks



Hollow Core Concrete

Prefabricated hollow-core slabs (200mm), where the seams are filled with a cement mortar and the floor is provided with a pressure layer. The concrete slabs have hollow channels and prestressed reinforcement.



Wooden Hollow Core Slab

Floor made of prefabricated wooden hollow-core panels (220mm). The wooden channel board is made of laminated spruce element with square hollow channels.

	NIBE Env. C.	2A: Good environ.l choice			1a: Best environment. choice		
	Mass per. unit	452,9kg			55,1 kg		
	Life Span	75 years			75 years		
	Shadow Cost	€ 6,35			€ 3,91		
	Transport dist.	150 km			150 km		
	Material supply	303 kg concrete, 7.7 kg rein. steel, 144 kg mortar			55.7 kg spruce, 1.1 kg glue, 0.8 kg rock wool.		
	Greenhouse effect	7.99E+1 kg CO2 eq			3,54E+1 kg CO2 eq		
OVERALL	A1-A3	86.1 % of total shadow costs			113.7% of total shadow costs		
	A4	17.7 % to shadow costs			3.5% to shadow costs		
	A5	-0.1% of shadow costs.			-0.8% of shadow costs.		
	B1	No environmental effects.			No environmental effects .		
	B3 & B4; B6 & B7:	No shadow costs.			No shadow costs.		
	C & D ; C2	-9.5% ; 5.7% of shadow costs.			-19.6% ; 3.2% of shadow costs.		
	Dimensions						
	Estimated Price	35 € / sqm *			100 € / sqm *		
MATERIALS	* Edupack 2023.	Concrete	Steel	Mortar	Spruce	Glue	RockWool
	Prod. Emb. Energy (MJ/kg)	4.0	16.3	5.0	43.5	-	48.5
	Prod. CO ₂ footprint (kg/kg)	0.8	1.12	4.2	0.335	-	1.15
	Prod. Water usage (l/kg)	3.20	46.5	36.7	700	-	17000
	Recyclable	yes	yes	no	no	-	no
	Downcycle	yes	yes	yes	yes	-	yes
	Renewable	no	no	no	yes	-	yes
	Biodegradable	no	no	no	yes	-	yes

Table 11: Different product stages of Wooded hollow core slab floor and concrete hollow core slab floor with the pressure layer (Houten Kanaalplaatvloer, NIBE and Kanaalplaatvloer Inc Druklaaf, NIBE); *Reference: Edupack 2023.

2.8.7 Summary of the literature review and the finalized materials

To serve as both the polymer matrix and core material in sandwich structures, various biodegradable and biobased polymer materials are being researched during the literature research. The aim is to achieve full biodegradability, creating what is known as 'green composite' materials

1. Core: alginate, agar-agar, PHA and PLA will be investigated for the "novel core"
2. Matrix for facesheet: Only PLA is used.

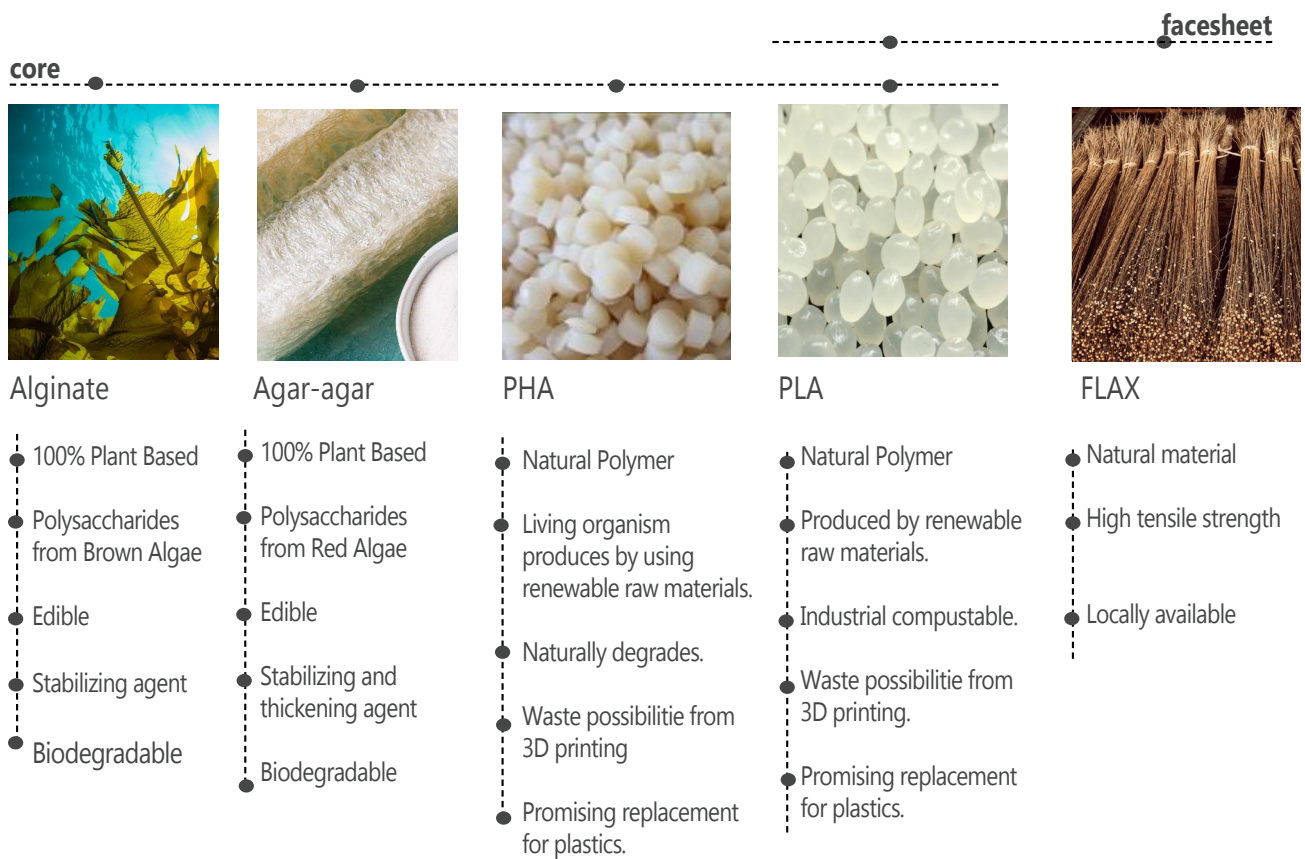


Figure 39: Image of brown algae. (Adams, 2024)

Figure 38: Agar-agar image. (Song et al. 2012)

Figure 40: PHA Pellets. (Van Der Hoeven, 2020)

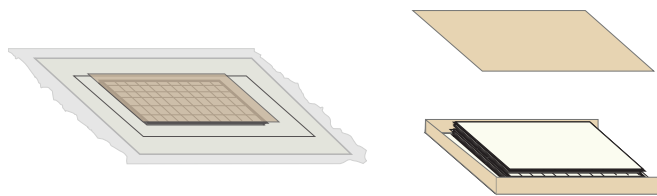
Figure 41: PLA pellets. (Bioplastics News, 2019)

Figure 42: Flax flower plant. (NouveauRaw, Amie-Sue., 2021);

2.8.7 Summary of the literature review and the finalized materials

For the production of the facesheet material, two different approaches are chosen regarding the material matrix:

1. Vacuum Assisted Resin Infusion
2. Film Stacking Method with Hydraulic Press Machine



Vacuum Resin Infusion

- Continous fibers
- Thermosetting resin (Bioepoxy)
- Labour intensive
- Even quality
- Longer processing time
- Complex Setup

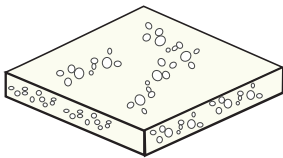
Film Stacking

- Continous fibers
- Thermoplastic resin (PLA)
- Easy to handle
-
-
-

chapter 3

METHODOLOGY

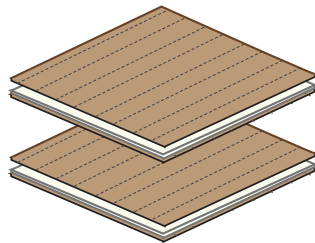
36 / 57



core

EXPERIMENT

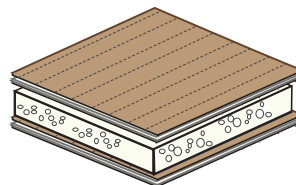
This section is based on exploration of a **novel idea** on "how to produce a fully bio-based core material"



facesheet

PRODUCE

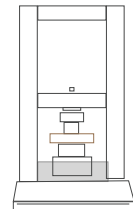
This section is based on producing the facesheet materials by **referencing** the literature reviews.



composite

LAMINATE

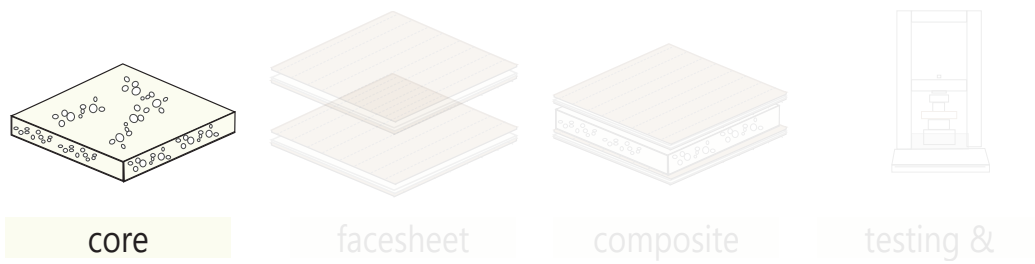
This section is based on laminating the 4.1 core and 4.2 facesheet materials.



testing & analyse

TEST

In this section the finalized composite 4.3 is testing methodology is given with formulas that will be used.



3.1 CORE PRODUCTION

The production of the core follows a “design by experiment” approach. Various bio-based materials and polymers are explored using different methods, including those inspired by bread, popcorn, and conventional techniques. Detailed explanations for each approach are provided in the following sections.



4.1.1

“foam”

PLA
PHA

This phase involves exploring the expansion of bio-based polymers using a foaming agent, often referred to as “the bread” due to its resemblance to the expansion process of bread.

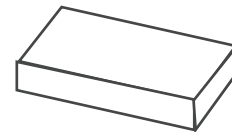


4.1.2

“popcorn”

pop-corn
rice waffles

This phase involves exploring the heat and pressure expansion of bio-based polymers. It is referred to as “pop-corn” due to its resemblance to the heat reacting process as well as for the material.



4.1.3

“dry”

Alginate
Agar-agar
Seaweed
Sawdust

This method includes investigation of different materials bio-materials by activating the polymer and mixing them. In general this step does not require heating beside drying the materials.

3.1.1 FOAMING METHOD

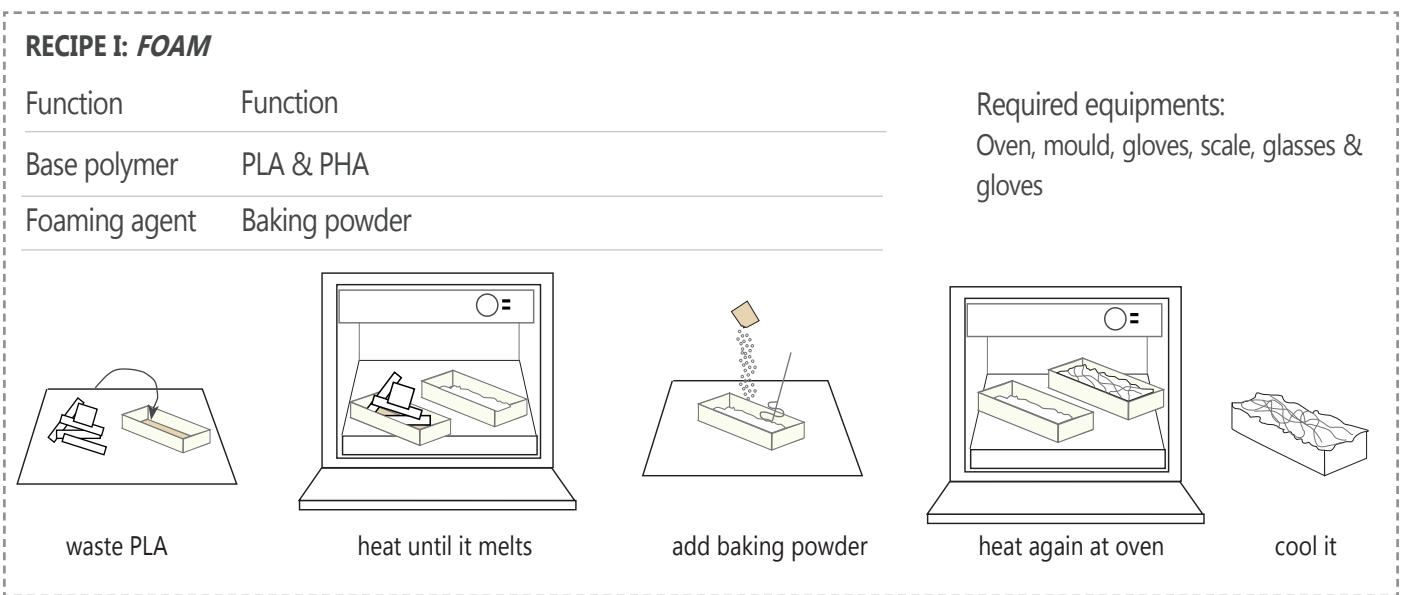


Figure 47: Diagrammatic explanation of the PHA biopolymer filaments foaming.

Foaming PHA

The PHA filaments that are purchased online from ColorFabb are in filaments shape. Initially, they are cut into smaller pieces to fit into the mold. The necessary amount of waste PHA and baking powder is measured. Subsequently, the PHA is placed in the oven at a temperature ranging between 150°C and 180°C for approximately an hour for each sample. The same process is applied to PHA as with PLA.

Once the material is melted sufficiently, the baking powder is added, whisked, and then returned directly to the oven, where it is actively controlled. The process of the foaming of PHA can be seen through between Figure 43 and Figure 46.



Figure 43: PHA filaments are scaled



Figure 44: left in the oven



Figure 45: baking powder added



Figure 46: final result

Further try-outs

Material ID	Mass (gr)	Foaming tempr. °C	Heating Time (hr)	Foaming tempet. (°C)	Time (hr)
PH10A	100	190	1hr	190	1hr
PH10B	100	180	2hr	180	1hr
PH10C	100	160	1hr	160	0.5

Foaming PLA

Waste Material Collection and Preparation

As PLA is a recyclable material, the 3D PLA printed materials are chosen for the experiment the foamed PLA idea. Therefore Initially, waste 3D printing materials are collected from the LAMA Lab, the 3D Printing lab at TU Delft Bouwkunde. These waste materials are broken into smaller pieces to fit into the mold. The 3D printed PLA materials can be seen in the image on the right.



Figure 49: Collected PLA from LAMA lab at TU Delft.

Waste Material Collection

The required amounts of waste PLA and baking powder are measured, after which the PLA is placed in an oven at 180-190°C for about an hour per sample. The material preparation process is illustrated in Figure 54: the first image shows the collected waste PLA from the LAMA lab, the second image shows the cutting of the pieces, and the last image shows the mold and materials. Periodically, the material is checked for any unwanted changes.

Once the PLA reaches a viscosity suitable for easy shaping, it is removed from the oven, and baking powder is quickly added to the melted PLA, as shown in subsequent figures. This step must be performed quickly to prevent the PLA from cooling too much, which could hinder the foaming process. The material is then returned to the oven and carefully monitored again for its foaming state, as seen in the third image of Figure 55



Figure 48: preparation of the waste PLA.

Further try-outs

Material ID	Mass (gr)	Melting tempt (°C)	Heating Time (ht)	Foaming tempt (°C)	Time (ht)
PL10A	100	180	1hr	180	1hr
PL10B	100	220	2hr	220	1hr
PL05A	50	190-200	1hr	190-200	30mins
PL10C	100	190-200	1hr	190-200	45mins
PL15A	150	190-200	1hr	190-200	45mins
PL20A	200	190-200	1.30hr	190-200	45mins
PL20B	200	190-200	2hr	190-200	1hr

3.1.2 HEAT PRESSURE METHOD

This phase involves exploring the heat and pressure expansion properties of bio-based polymers, a process colloquially referred to as "pop-corn" due to its resemblance to the way popcorn reacts to heat. Both the process and the material exhibit this characteristic behavior.

Diagram below provides a detailed diagrammatic overview of the approach and the recipe used in this exploration. This figure serves to visually explain the steps involved, from the initial heating to the resulting expansion, highlighting the similarities between the behavior of the bio-based polymers and popcorn.

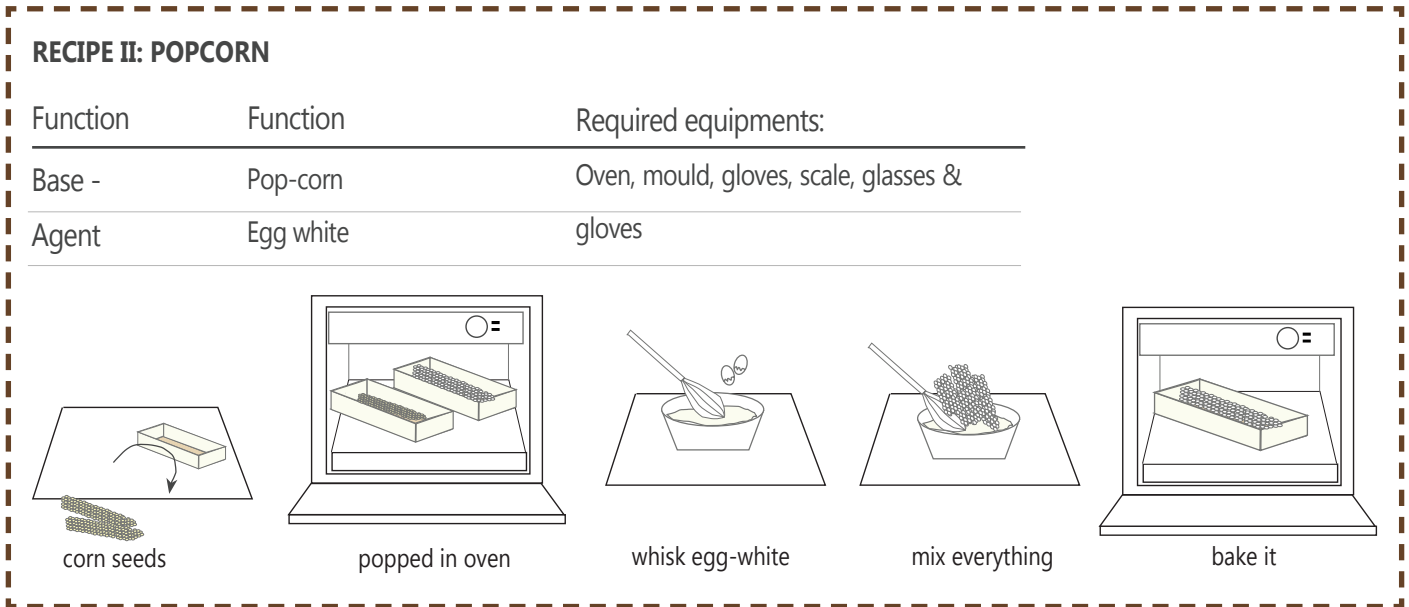


Figure 50: Diagrammatic explanation of the PHA biopolymer filaments foaming.

Raw-Corns

Preperation

The recipe is inspired by real rice waffles and popcorn waffles. To begin, raw corn kernels were heated in a pan with a small amount of oil until they popped into fluffy popcorn. At the same time, rice grains were heated in another pan with a bit of oil until they expanded under heat and pressure, forming the base for the waffles together with the popcorn, as seen in Figure 62. Afterwards, in another bowl, the egg whites were broken

Afterwards, the expanded corn and rice pieces were mixed with the creamy egg whites (Figure 64), shaped into the mold, and pressed slightly for better adhesion. In the final stage, the prepared sample was put into the oven and heated for 30-45 minutes to enhance adhesion. The final product is comparatively strong, as shown in Figure 65.



Figure 51: raw pop-corn



Figure 52: whisked with



Figure 53: oven-dried



Figure 54: final product

4.1.3 HEAT DRYING

In this approach, different bio-based materials are investigated and dried using an oven. The investigation mostly involves using seaweed and polymers extracted from the seaweed itself, which are alginate (a thickening agent used for food) and agar-agar, the vegan gelatine. Besides those materials, seaweed flakes are used as a filler. Additionally, another material used in combination with the algae-derived polymers is sawdust.

General Preparation

As a general process of the recipe, the Figure 66 can be referenced. The first step of each sample preparation starts with mixing the base polymer (whether it is sodium alginate or agar-agar) with water. Afterwards, depending on the recipe additional agents are added, which are furtherly given in the recipe on the following pages. Afterwards, everything is mixed together, that can be seen in Figure 66)

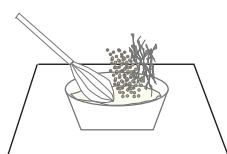
Afterwards, the fillers, which are either seaweed flakes or various particle-sized sawdust, are added to the mixture and mixed with the base polymer. Later on, they are molded into the required shape. Depending on the polymer type and the maximum temperature it can withstand, they are either heat-dried in the oven to reduce moisture content at varying temperatures or cooled in the freezer.

RECIPE II:

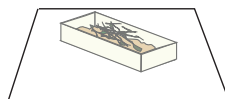
Function	Function	Required equipments:
Base polymer	Agar-agar or alginate	Oven, mould, gloves, scale, glasses &
Foaming agent	varies	gloves



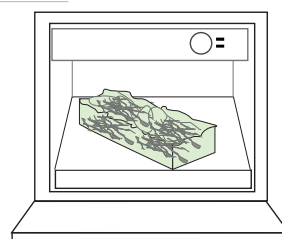
base polymer activate



heat until it dissolves



fillers and foaming agent are added



heated at oven to dry



cool it

Alginate | sample 4-5

Function	Material	Type	Mass (gr)
Base polymer	Alginate	Polysaccharide	50
Plasticizer	Glycerin		50
	Water		500 ml
Colouring Agent	Spirulina	Micro-algae	2
Foaming Agent	Dish soap		5
Reinforcing/Filler	Seaweed flakes	plant	25

Preperation This material is refereced from the recipe of thesis project of Kathryn Larsen at TU Delft (2022). Firstly, agar-agar and water is mixed and glycerin is added and heated until it dissolves. Later on to give colour spirulina bacteria added. Afterwards, seafakes and the dish soap is added to foam the material. Later on the material is left for air-dry for days.

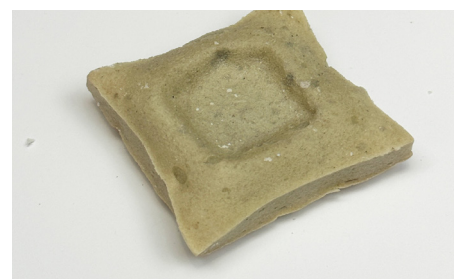


Figure 55: Samples 4-5.

Alginate | sample 6-7

Polysaccharide from algae with calcium carbonate

Function	Material	Type	Mass (gr)
Base polymer	Alginate	Polysaccharide	50
Plasticizer	Glycerin		50
	Water		500 ml
Activating agent	Calcium Carbonate	Oyster shells	15
Activating agent	Vinegar	Acid	10 ml

Preperation This material is referenced from the conference proceedings of Lazaro Vasquez et al. (2022). Firstly, alginate and water are added to a pan and mixed. The oyster shells are then added to vinegar in order to activate them. Afterwards, glycerin is added to the alginate and water, along with calcium carbonate, and heated until everything is dissolved. Water and glycerin are mixed with honey and heated until the glycerin is dissolved in the water.



Figure 56: Samples 6-7

Alginate | sample 8-9

Polysaccharide derived from seaweed has been used as a biobased polymer

Ingredients

Function	Material	Type	Mass (gr)
Base polymer	Alginate	Polysaccharide	100
Plasticizer	Glycerin		100
Plasticizer	Honey		50
	Water		50ml
Foaming Agent	Dish soap		5

Preperation This material is refereced from the recipe Laura Velgersdijk’s research and Margaret Dunne’s Bioplastic Cook Book. In the recipe animal based gelatin was used but in this option, the alginate is used as vegan gelatin and base polymer. The difference between this option is, as the plasticizer for shofthen the material honey is used next to the glycerin. Firstly, the alginate is soaked into the water and glycerin and honey mixed and heated until the glycerin is dissolved in the water. To create the cellular structure, the dish foam is added. (Foam for Material Activists by Laura Velgersdijk, 2020, Dunne, Bioplastic Cook Book, 2018). In the 2nd material flax fibers are added as a reinforcing material.



Figure 57: Samples 8-9

Agar-agar | sample 10

Function	Material	Type	Weight (gr)
Base polymer	Agar-agar	Polysaccharide	30
Plasticizer	Glycerin		2 gr
	Water		100 ml
Coloring Agent	Spirulina		5 ml
Foaming Agent	Dish soap		25
Filler	Seaweed flakes		

Preperation This material is referenced from the recipe of the thesis project by Kathryn Larsen at TU Delft (2022). However, different ratios are used as the seaweed flakes have a higher proportion in this recipe. Firstly, agar-agar and water are mixed, and glycerin is added and heated until it dissolves. Later, the seaweed flakes are added. The material is dried in the oven for 2hrs.



Figure 58: Samples10

Agar-agar | sample 11-12

Function	Material	Type	Mass (gr)
Base polymer	Alginate	Polysaccharide	100
Plasticizer	Glycerin		30
	Water		100 ml

Preparation

The sample is very similar to the previous one, however, the base polymer is used as alginate rather than agar-agar. Firstly, alginate and water are mixed, and glycerin is added and heated until it dissolves. The material is dried in the oven for 2hrs to lose its moisture.



Function	Material	Type	Mass (gr)
Base polymer	Alginate	Polysaccharide	100
Plasticizer	Glycerin		30
	Water		100 ml

Preparation

Polymers are mixed and used as the base polymer. Firstly, base polymers and water are mixed, and glycerin is added and heated until it dissolves. The material is dried in the oven for 2hrs to lose its moisture.



Figure 60: Samples 11-12

Sawdust Mid-fine particles | sample 13-14-15

Function	Material	Mass (gr)
Filler	Sawdust	100 gr
Base polymer	Alginate	30 gr
Filler	Glycerin	5 ml
	Water	100 ml

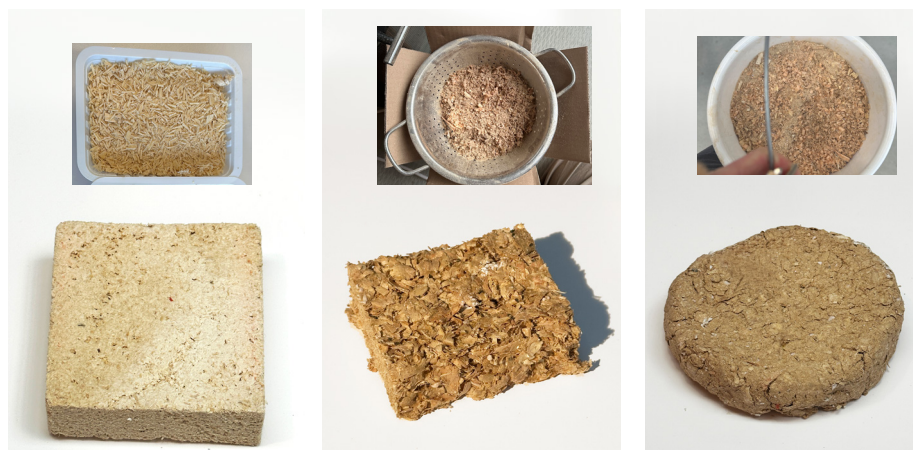


Figure 61: Samples 13-14-15

Drying Process

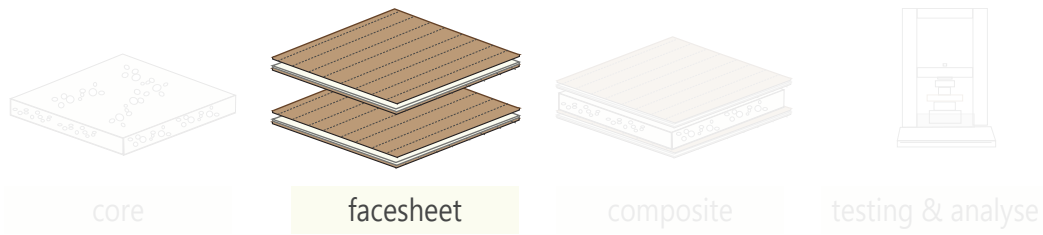
The drying process holds an important part of the sample preparation. This is because a significant amount of water has been used to prepare the base polymer. Therefore, after the mixture is ready, the material is quite heavy due to the water content inside it. Consequently, the material is left to dry in the oven for 2 hours at a temperature of 70-90°C. This duration is almost sufficient for the material to lose its moisture content. In Figure 59 the first samples' drying process in the oven can be seen.

Preparation

This recipe is referenced from Tamara Schwarz's sawdust | agar samples on Materiom. Sawdust is collected from the modeling hall at Bouwkunde TU Delft, which consists of sawdust from the woodworking activities within the faculty. For this experiment, sawdust is used as the filler, and alginate is used as the base polymer. (Recipe - Materiom, n.d.). Firstly, the base polymer is mixed with water and glycerin and heated until the mixture slowly boils, and the mixture is dissolved enough. Glycerin is optional, but it adds flexibility to the material and indirectly contributes to its strength. On the following page, three different options are investigated by examining particle size and the effect of glycerin.

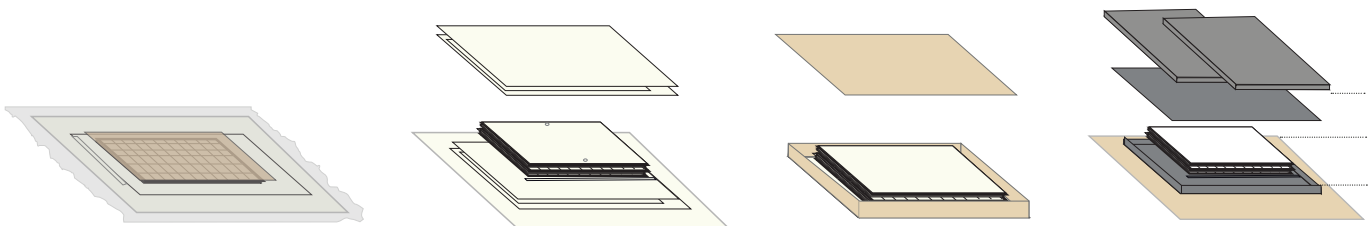


Figure 59: final product



3.2 FACESHEET PRODUCTION

The production of facesheet has been realized in three different methods in order to choose the most suitable one.



3.2.1

“Resin Infusion”

Resin infusion technique is a technique used for thermoset resins. In the scope of the research, flax fibers with bio-based epoxy have been used.

3.2.2

“film staking I”

Film staking technique is used for resin film consolidation for thermoplastic matrix. In the scope of the research, flax fibers with PLA films are used with a steel plate hydraulic pressure machine.

3.2.3

“film staking II”

The film stacking technique is used for resin film consolidation for thermoplastic matrices. In the scope of the research, flax fibers with PLA films are utilized by using a steel mold within a hydraulic pressure machine.

3.2.4

“film staking III”

The film stacking technique is used for resin film consolidation for thermoplastic matrices. In the scope of the research, flax fibers with PLA films are utilized by using a steel mold within a hydraulic pressure machine.

3.2.1 VACUM ASSISTED RESIN INFUSION | method 1

As the matrix used is epoxy, which is a thermoset resin, the resin infusion technique has been conducted at the Aerospace Engineering department at TU Delft in the Aircraft Hall. The entire process takes about 5-7 hours, with an overnight period to ensure the material is adequately cured. Overview of the materials that are used at the aircraft hall at Aerospace has been give on the image on the left side as an exploded diagram. Futher explanation with more detailed presentation and how they are managed are given in the following page. Additionally, the composite material details including brand and some properties are given below.

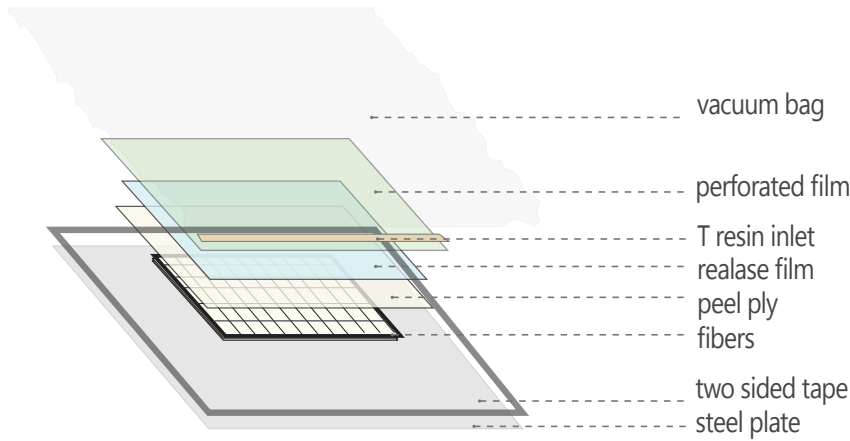


Figure 62: exploded diagram of the resin infusion plate.



FLAX FIBERS

- Sponsored by NPSP.
- Ecotecnilin (Brand)
- Flaxdry-BL360
- Twill 2x2 woven flax fabric.
- Density: 300 g/m²

Source: (Ecotechnilin, nd.)

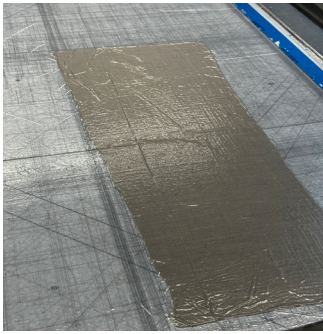


BIOBASED EPOXY

- Used from Aerospace Eng.
- Living R Concept (Brand)
- 100:30 mixing ratio
- 70-80MPa Compressive strength
- BPA free
- Curing agent needed.

Source: (Plankton, LivingRConcept, nd.)

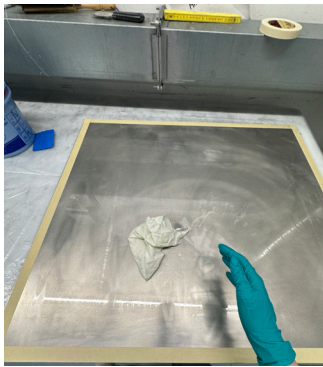
Process | at TU Delft Aerospace Engineering Aircraft Hall



First stage of the preparation involved the preparation of the fibers into required shape and dimensions. For that reason other they can be cut by scissors or a more professional computer aided system can be used for more precise applications. In thi figure on the left, shows the cutting arrangements.



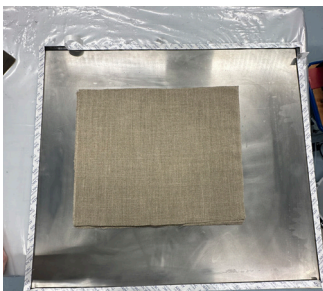
Afterwards, the vacuum bag is places on the steel plate. The vacuum bag is around 2 times larger than the laminates itself. The pinch positions are chosen which can be seen in the image on the right. The sealent has been done carefully in order not the have errors on in terms of the air.



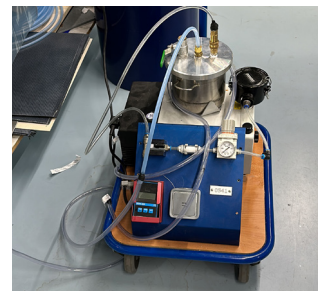
Clean the metal plates 3 times with wet acetone towel with 3 minutes intervals. Later on, again clean the plate with 3 times using isopropanol towels with 5mins intervals. As the final stage of preparation of the plate, the realising agent is applied three times with three minutes intervals. Later on, the plate can be take to the table.



Next stage is the matrix preparation. The Bio-based epoxy from Plankton is used with the curing agent. Firstly, they are measured and mixed with required ratio slowly to not the let bubbles. Later on resin is left at the de-gassing chamber around 20-30mBar.



After the plate is ready, it has been move to the preparation table. Firstly, two sided tape is located around the edges of the steel plate. Afterwards, the flax fibers are located on the plate, by arranging to the middle part of the steel plate.



The image on the right, shows the outlet for the excessive resin collection as well as the pressure for the vacuum bag. The pressure machine is set to between 10-40mbar. Later on, the vacuum bag is checked for any leaks and fixed if they are fixibale with tapes.



Later on, the peel ply is located on top of the fibers and on top of it the reales film (which chosen as perforared and can be seen through the image on the left) is used.



Later on, the resin insufion to the laminate has been started and resin allowed to go through the fibers. The floowed resin can be seen in the image on the right. The resin infusion is allowed until the breathe fabric gets the resin and the outlet tubes are close to collet it.



Then the flow mesh is located, which is the green mesh as seen in the figure on the left. Afterwards, add a breather fabric on the corner of the plate and the flow mesh. For the resin inlet, a T shaped tube (merged with two materials) is located on the perforated mesh.



After the inlet clamp is tightened not to allow further resin passthrough, the infusion left at the workspace for a whole day to be cured properly. The day after it has been collected and finale version can be seen from the image on the right.

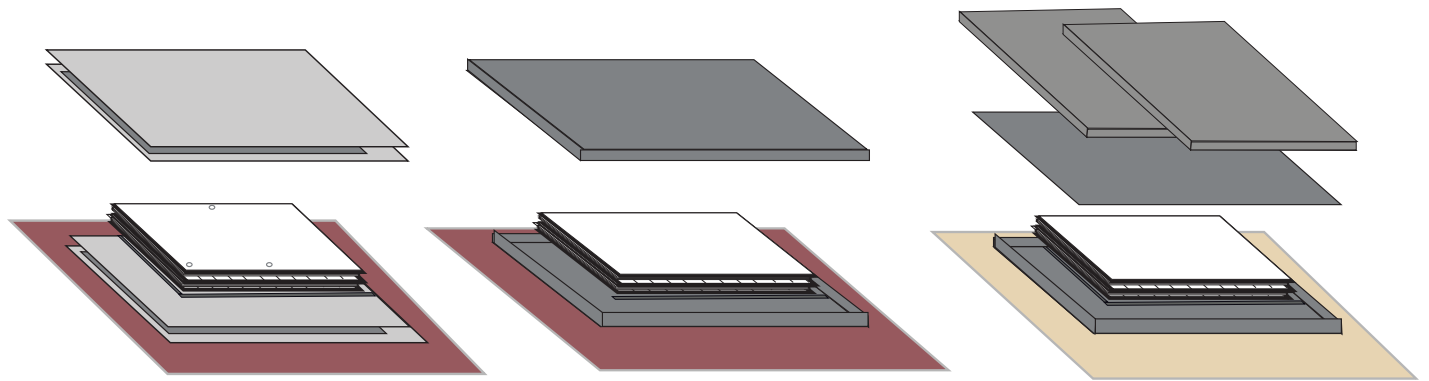
Figure 63: Step by step explanation of the resin film consolidation with using bio-based epoxy.

3.2.X FILM STACKING METHOD | method II

Resin film consolidation is the method used for thermoplastic matrices. The reason why this method has been chosen is because it is one of the most convenient ways to produce laminations with fibers using PLA. For this approach, the PLA films are supplied by Sidaplax, Belgium. The flax fibers are received from NPSP, and the brand of the fibers is Eco-Technilin.

The material properties are provided in the table below, along with some further details such as the melting point and glass temperature of PLA, and the architecture of the flax fibers.

Trials and explanations



Method A: steel plate
Aerospace Eng.

Method b: mould plate
Aerospace Eng.

Method c: mould plate
NPSP

Materials



FLAX FIBERS

- Sponsored by NPSP.
- Ecotecnilin (Brand)
- Flaxdry-BL360
- Twill 2x2 woven flax fabric.
- Density: 300 g/m²



PLA FILMS

- Sponsored by Sidaplax Belgium
- Thickness: 30 μm
- Modulus: 2484 MPa
- Glass tempt.: 55 and 60°C
- Melting point: 155 – 170°C

3.2.2 FILM STACKING METHOD | method II, trial I

The first method closely resembles the first approach. However, in this method of resin film stacking consolidation, a mold is not used due to its limited shape. Nonetheless, not using a mold brings further challenges. Unlike the initial approach, where the mold inherently secures the fibers in position, working with steel plates demands more labor and care

Dimensions: 500 mm x 500 mm
Steel plate: 600 mm x 600 mm

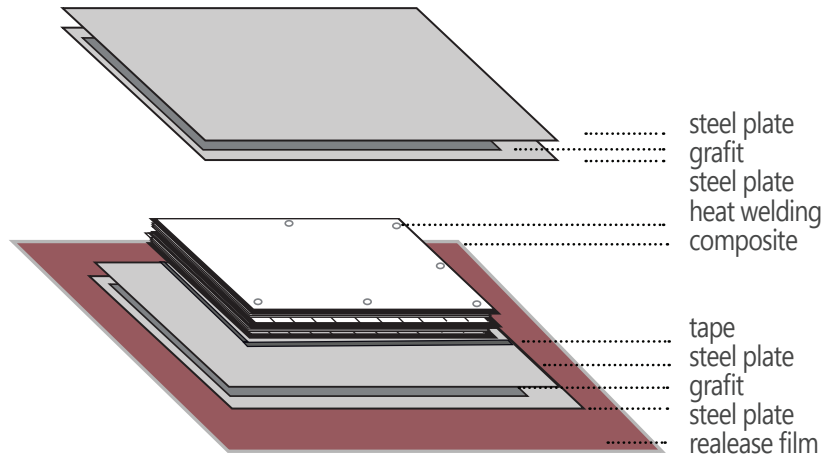


Figure 66: Exploded set-up of the manufacturing technique

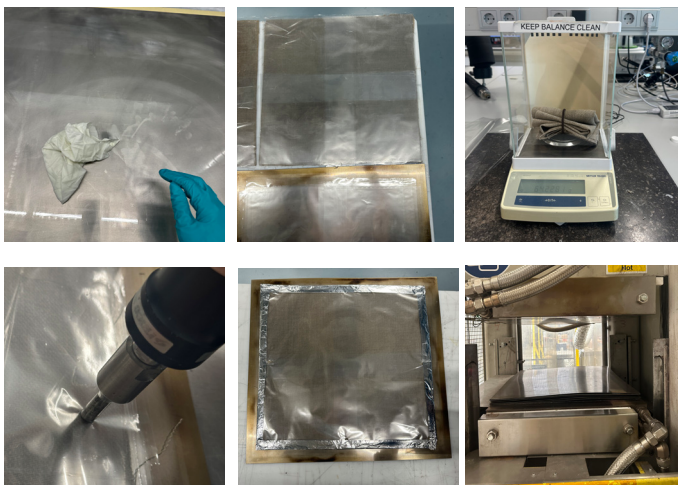


Figure 67: Process images of the film stacking method II B

Clean the metal plates three times with a wet acetone towel, allowing 3-minute intervals between cleanings. Then clean the plates three times with isopropanol towels, allowing 5-minute intervals between cleanings. Apply the releasing agent three times, with 3-minute intervals. Calculate the precise fiber mass ratio for flax fibers and PLA films: 40% flax and 60% PLA. Stack the layers in the following order: 8 PLA films, 1 flax layer; 10 PLA films, 1 flax layer; 14 PLA films, 1 flax layer; 10 PLA films, 1 flax layer; 8 PLA films. Use a hot welding gun to weld the edges of the stacked layers to keep them in order. Place the stacked materials back on the steel plate, surrounded by an aluminum folder to maintain precise order. Follow these steps on the press machine.

- S3: 2 bars pressure for 30 seconds
- S4: 165°C for 10 minutes
- S5: Hold for 10 minutes
- S6: 6 bars pressure for 5 minutes
- S7: Hold for 10 minutes

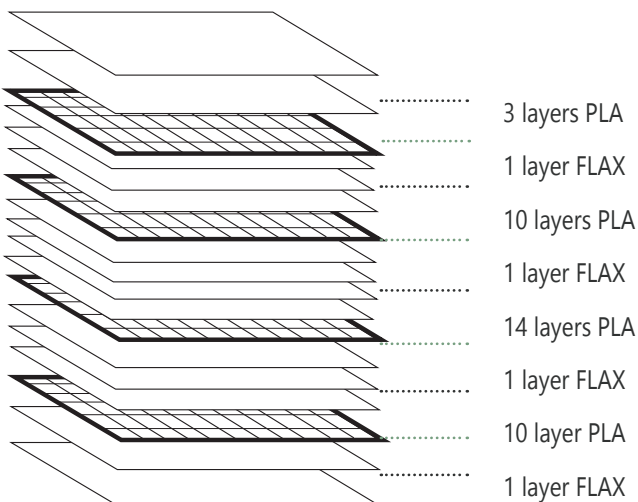


Figure 65: P-FLAX I layouting

3.2.3 FILM STACKING METHOD | method II, trial II

In the first approach of resin film consolidation a mold is used, which was already existed at TU AE Aircraft Hall. The usage of mold make it easir to keep the materials in shape.

Dimensions: 240mm x 150mm

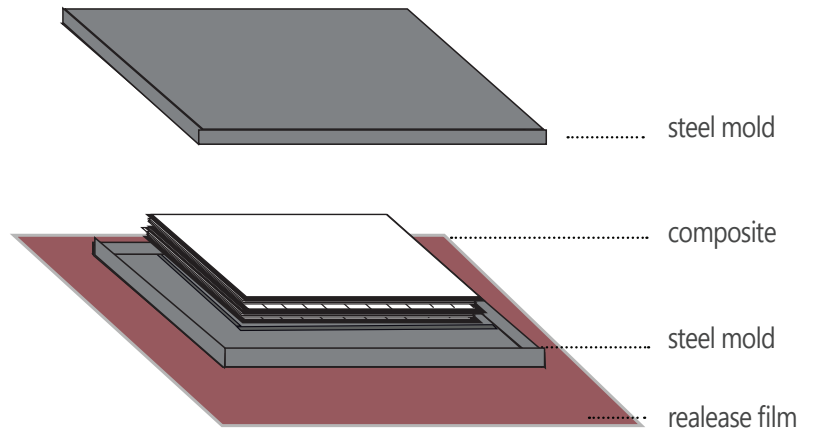


Figure 68: Exploded set-up of the manufacturing tecnique

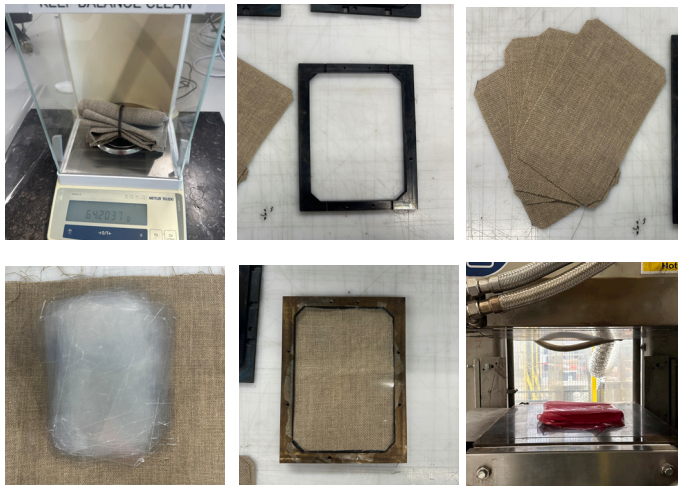


Figure 70: Process images of the film stacking method II B

Clean the metal plates three times with a wet acetone towel, allowing 3-minute intervals between cleanings. Then clean the plates three times with isopropanol towels, allowing 5-minute intervals between cleanings. Apply the releasing agent three times, with 3-minute intervals. Calculate the precise fiber mass ratio for flax fibers and Flax: 70%; - PLA films: 30% The flax fibers are cut into the required shape as shown in the image on the right. A total of four layers of flax fibers are prepared. Similarly, the PLA films are also cut into the required shape, with four layers prepared. The materials are then arranged in the required layers within the mold. The mold is placed in the press machine, and the following steps are performed for this experiment:

1. Apply 2 bars of pressure for 30 seconds.
2. Heat to 165°C for 10 minutes.
3. Hold for 10 minutes.
4. Apply 6 bars of pressure for 5 minutes.
5. Hold for 10 minutes.

The resulting material did not perform as expected. The reasons for this are explained in the results section. To ensure proper curing, the material was subsequently placed in an oven at 170°C for 2 hours.

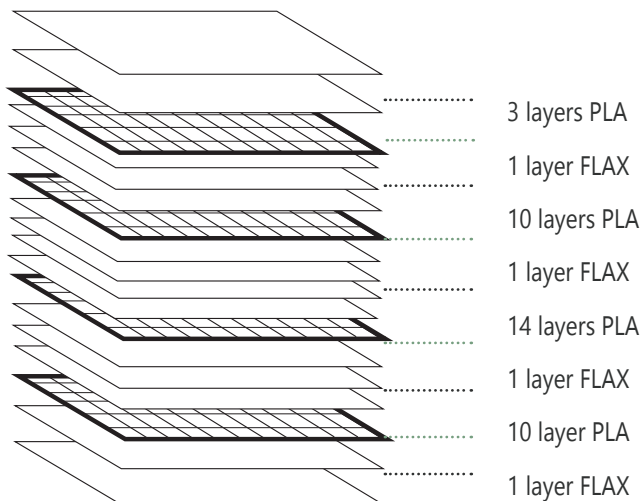


Figure 69: P-FLAX I layering

3.2.4 FILM STACKING METHOD | method II, trial III

The third method closely resembles the second approach. However, this method has been utilized by an easier press machine that does not have cold pressing. The press machine is very easy to handle and everything can easily be adjustable. This time a different pressing equipment is used. Since the mold has yielded better results compared to the first two approaches. However, there were no proper molds to be used. Therefore, a simple baking steel plate is used. Later on, two heavy steel plates are placed on top of the plate to apply pressure.

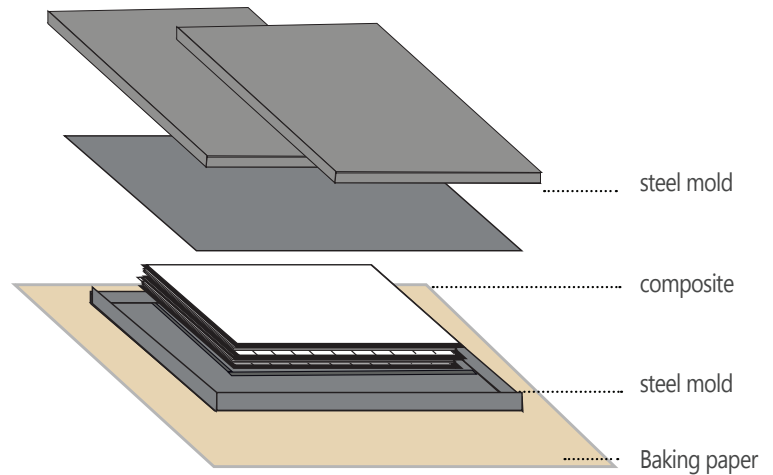


Figure 71: Set-up of the manufacturing technique

Dimensions: 200 mm x 300 mm
 Steel plate: 220 mm x 320 mm



Figure 73: Process images of the film stacking method II B

Clean the metal plates three times with a wet acetone towel, allowing 3-minute intervals between cleanings. Then clean the plates three times with isopropanol towels, allowing 5-minute intervals between cleanings. Apply the releasing agent three times, with 3-minute intervals. Calculate the precise fiber mass ratio for flax fibers and PLA films: 50%; - PLA films: 50%. The flax fibers and PLA films are cut in required amounts.

The materials are then arranged in the required layers within the mold. The mold is placed in the press machine, and the following steps are performed for this experiment:

1. Heat the press machine for 15mins.
2. Apply 75kN of pressure for 10 minutes.
3. Change the plates center of gravity.
4. Apply 100kN of pressure for 3 minutes.
5. Change the plates center of gravity
6. Apply 100kN of pressure for 3 minutes..

The resulting material did perform as expected. The reasons for this are explained in the results section. The process was easier to handle compared to previous methods.

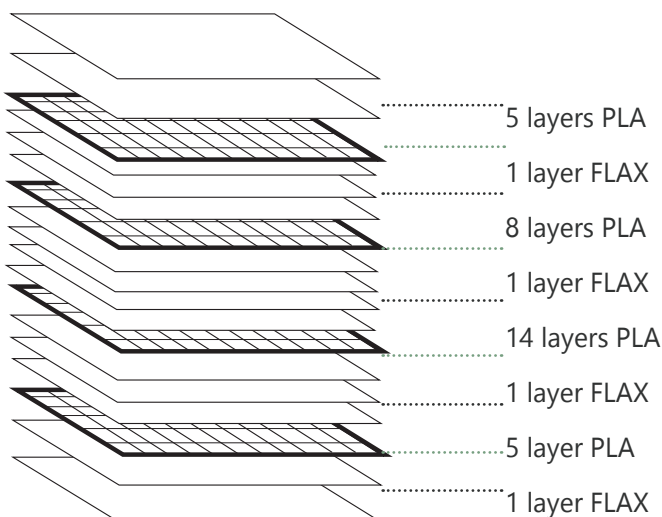
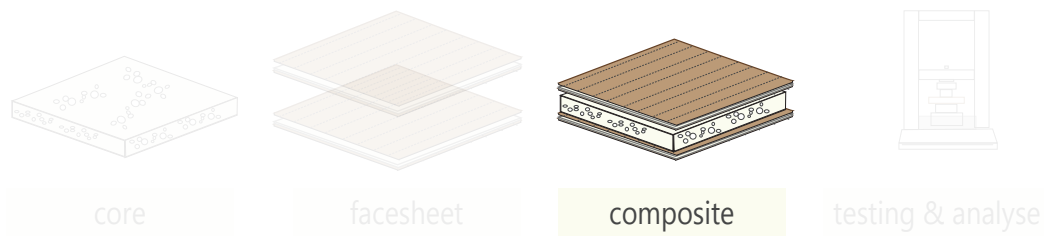
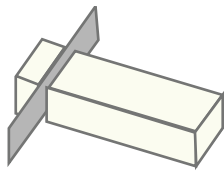


Figure 72: P-FLAX I layouting



3.3 COMPOSITE PRODUCTION

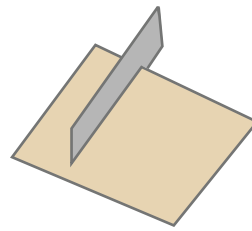
The production and the lamination of the composite



3.3.1

Core preparation

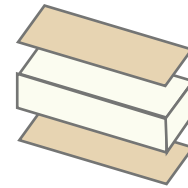
The core material has been cut but using bandsaw machine at wood workshop TU Delft modelling hal.



3.3.2

Facesheet preparation

The facesheet material has been cut but using bandsaw machine at wood workshop TU Delft modelling hal.



3.3.3

Lamination

After the materials are ready, the lamination is processed. Lamination involves three different process as, using heat gun, using an iron and using a glue.

3.3.1 Core Preparation

The core has been chosen as foamed PLA. Despite its strength, the material's brittleness and the presence of open cells on its surface make it challenging to handle. Therefore, the shaping process of the core material has to be handled by carefully in order not to damage the material. Inially, a milling machine at the model hall has been used (Fig 124). Due to the longer sides of the foam, a different blade was necessary. Thus, a Japanese hand saw was utilized to shape the material. However, this method is a time-consuming approach and a labour-intensive power. Achieving precise positioning with clamps without causing damage to the material is a considerable challenge. This approach resulted in issues such as the material not maintaining a linear shape as required. In turn, another approach has been used. Therefore, later on, a bandsaw hammer machine at the TU Delft BK Model Hall wood workshop was utilized. An additional point to consider was ensuring that the heat released by the blade did not damage



Figure 74: left; close up to cut the piece; right, the bandsaw machine

Sanding the surface of the foam: Even though the bandsaw made the surfaces quite flat, they were not as flat as needed due to the initial surfaces not being perfectly straight lines for an accurate reference point. Therefore, in order to make them smoother and more even, a circular, electrical hand sandpaper machine with coarse-grit paper. However, the machine did not achieve a perfectly smooth finish as it was quite difficult and time intensive for the surface to be fully flat. The sandpaper machine itself and the way texture on the material can be seen in Figure 126.



Figure 75: electrical sandpaper machine and the texture of the core

3.3.1 Facesheet Preparation

Cutting the facesheet does not take an excessive amount of time, as it is done in the same process as cutting the core material. The facesheet is also cut using the same bandsaw machine in the wood workshop cutting hall. The cut pieces and the machine can be seen in Figure 127. However, it should be carefully handed that the fibers do not get burn because of the movement of the saw.



Figure 76: left; close up to cut the piece; right, the bandsaw machine

3.3.3 LAMINATION

The lamination process has two approaches: first, heating the surface without adding a binder for a fully green method; and second, using a two-component binder to prevent failure during testing.

Biobased Approach

APPROACH I: Staking PLA films and heating the surface
Cutting the facesheet does not take an excessive amount of time, as it is done in the same process as cutting the core material. The facesheet is also cut using the same bandsaw machine in the wood workshop cutting hall. The cut pieces and the machine can be seen in Figure 127. However, it should be carefully handed that the fibers do not get burn because of the movement of the saw.

APPROACH I: Only using heat gun

Cutting the facesheet does not take an excessive amount of time, as it is done in the same process as cutting the core material. The facesheet is also cut using the same bandsaw machine in the wood workshop cutting hall. The cut pieces and the machine can be seen in Figure 77. However, it should be carefully handed that the fibers do not get burn because of the movement of the saw.



Figure 77: left, heating the surface of the core; right, heating the surface of the flax fibers

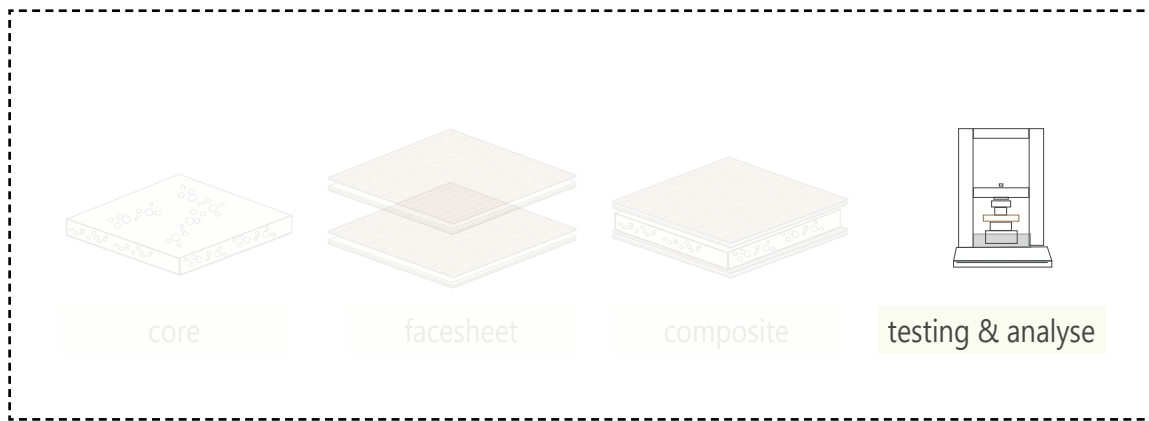
Two Component Epoxy Approach

To prevent the material from failing during the 4-point bending test due to inadequate binding, a strong two-component glue has been utilized. This glue serves as the non-biobased material within the specimen. Despite its use in this experimental setup, it is important to note that in the proposed industrial production line, an epoxy would not be necessary for laminating the materials. Instead, advanced equipment and techniques would enable the use of entirely biobased binding methods.

The use of this glue is driven by the limitations of the available equipment. In an industrialized setting, more appropriate machinery would allow for the lamination of the materials without relying on non-biobased adhesives. Therefore, while the current setup includes this glue, the envisioned production process prioritizes the use of sustainable, biobased materials for all components, ensuring both environmental compatibility and structural integrity.



Figure 78: left laminated materials, right the used epoxy from Praxis store (Source: praxis.nl)



3.4 TESTING AND FORMULAS

3.4.1 TEST STANDARTS

The aim of the mechanical tests is to determine the shear properties of the core material. The reason for this is that while there are existing results in the literature for flax fibers with PLA lamination, there are none for the approach involving 'experimented PLA'. Since the core material in sandwich materials primarily contributes to shear resistance, its shear properties are of particular interest. Therefore, the "ASTM C393: Core Shear Properties of Sandwich Constructions by Beam Flexure" test is selected as the reference standard for testing. The testing is planned to be conducted at the 3ME faculty at TU Delft.

This standart geometry of the specimens are stated as 75mm in width and 200mm in length. However, for non-standart geometries it is stated that the width should not be less than the two times of the tickness. The length is suggested to be equal to the support span plus 50mm or one half of the thickness. The standart geometry is followed and the chosen dimension can be seen in the Figure 128 "ASTM C393, Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure, 2020".

ASTM C393 specifies the standard configuration for the loading fixture, which is given for the 3-point bending. However, to have a precise approach in this testing, the 4-point bending flexure test is applied. For that, the standard suggests a third-span 4-point configuration, where the support span is denoted as S and the load span as $S/3$. As for the 3-point bending configuration, it suggests having a support span of 150mm, the same distance is taken. Figure 127 on the right shows the

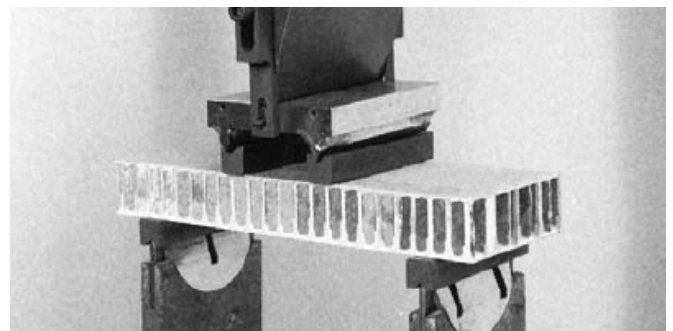


Figure 79: Short beam loading configuration ASTM Standarts. (ASTM C393, 2020)

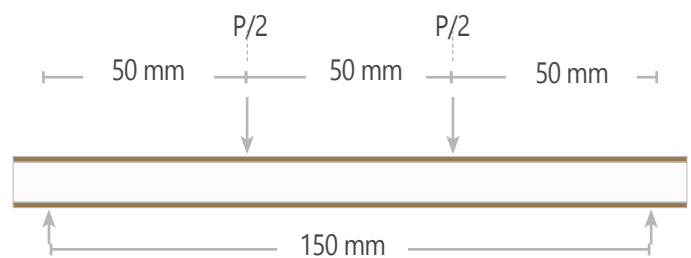


Figure 80: Planned test configuration. Reproduced. (ASTM C393, 2020)

3.4.2 TEST SPECIMENS

TEST I:

Laminated using heat gun, therefore there are no additional binder. However this lead materail to shrunk from the previous versions. After the lamination, only 4 specimens are prepared due to one of them has failed. They are named as PLAX A1-A4. Their relative properties are provided in the table below, and their images can be seen on the right side.

Figure 81: PLAX A1-A5



Table 12: Properties regarding PLAX A samples before testing.

Material	facesheet thickness <i>mm</i>	core thickness <i>mm</i>	core weight <i>gr</i>	overall dimensions <i>mm x mm</i>	overall thickness <i>mm</i>	overall weight <i>gr</i>
PLAX A1	1.95	-+ 11.0	107	200 mm x 75 mm	15	145
PLAX A2	1.2	-+ 13.5	141	200 mm x 75 mm	15.9	178
PLAX A3	1.3	-+ 15.0	140	200 mm x 75 mm	17.6	177
PLAX A4	1.35	-+ 13.0	90	200 mm x 75 mm	15.7	137

TEST II

The specimens were laminated using a two-component epoxy glue to ensure strong lamination, allowing the testing to focus on the material strength rather than the binding strength. A total of five specimens were produced. Compared to others, these specimens have greater core thickness, as the binding process did not cause shrinkage in the materials. They are designated as PLAX B1-B4. Their relative properties are provided in the table below, and their images can be seen on the right side.

Figure 82: PLAX A1-A5



Table 13: Properties regarding PLAXB samples before testing.

Material	facesheet thickness <i>mm</i>	core thickness <i>mm</i>	core weight <i>gr</i>	overall dimensions <i>mm x mm</i>	overall thickness <i>mm</i>	overall weight <i>gr</i>
PLAX B1	2.4	21.8	108	190 x 75	26.6	178
PLAX B2	2.4	19.2	155	190 x 75	24	225
PLAX B3	2.4	17.65	184	190 x 75	22.45	254
PLAX B4	2.4	17.73	132	190 x 75	22.53	202
PLAX B5	2.4	15.94	133	190 x 75	20.74	203

3.4.3 EQUATIONS

4-Point loading Core Shear Ultimate Stress

(1) Core Shear Ultimate Stress $F_{\text{shear_Ultim}} = \frac{P_{\text{max}}}{(d+c) b}$

(2) Core Shear Yield Stress $F_{\text{shear_yield}} = \frac{P_{\text{yield}}}{(d+c) b}$

(3) Facing Bending Stress $\sigma = \frac{P.S}{3t(d+c) b}$

" $F_{\text{shear_Ultim}}$ = core shear ultimate strength, MPa,
 $F_{\text{shear_Ultim}}$ = core shear yield stress, MPa,
 P_{max} = maximum force prior to failure, N,
 t = nominal facing thickness, mm,
 d = sandwich thickness, mm,
 c = core thickness, mm ($c = d - 2t$)
 b = sandwich width, mm"

Reference: ASTM C393, 202

Simple Beam with PLs Equally Spaced

(4) Stress $\sigma = \frac{My}{I}$

(5) Strain $\epsilon = \frac{\sigma}{E}$

(6) Shear Transverse $\tau = \frac{V_{\text{max}}}{A}$

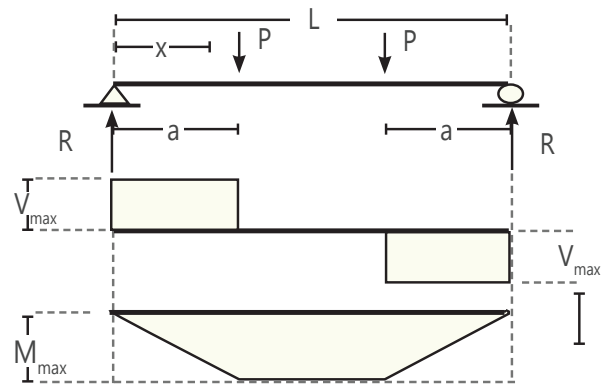
Simple Beam with PLs Equally Spaced

(7) Max Shear $R = V$

(8) Max Moment $M_{\text{max}} = P.a$

(9) Max Deflection $\Delta_{\text{max}} = \frac{P.a (3L^2 - 4a^2)}{24EI}$

Reference: StructX.com, Simple Beam, Two Point Loads Equally Spaced



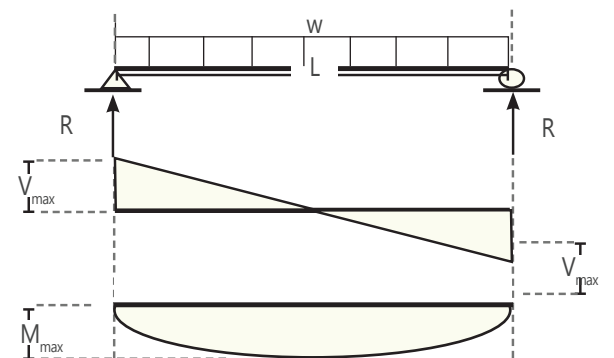
Simple Beam with PLs Equally Spaced

(10) Max Shear $V_{\text{max}} = \frac{wL}{2}$

(11) Max Moment $M_{\text{max}} = \frac{wL^2}{8}$

(12) Max Deflection $\Delta_{\text{max}} = \frac{5wL^4}{384EI}$

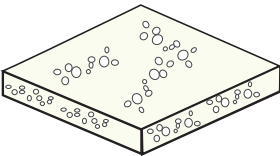
Reference: StructX.com, Simple Beam, Simple Beam with PLs Equally Spaced



chapter 4
RESULTS

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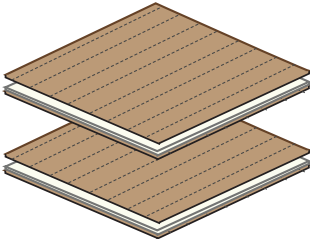
Results of the materials that are experimented and tested



4.1

core

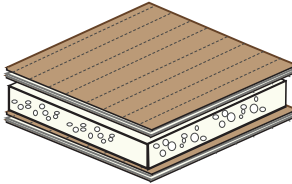
EXPERIMENT



4.2

facesheet

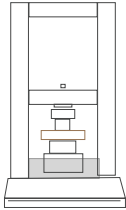
PRODUCE



4.3

composite

LAMINATE



4.4

testing & analyse

TEST

4 | RESULTS

The results of each produced material in phase I are compared with their provided specifications. The materials are compared based on their bio-based content, recycled content, consumability (whether any food-grade material is used), price, ease of production, shrinkage after production, and strength. These results are derived from literature research, and the strength of the material is determined through comparison without the use of testing equipment.

It appears that the foamed PLA, AGS01 (Agar-agar/seaweed), and WOOD01 (wood/alginate) samples exhibit the highest strength among them. Since a thermoplastic resin, PLA, is used and the bio-polymer of WOOD01 (alginate) and AGS01 (agar-agar) is still food-grade, the PLA option has been chosen as the best possible option for phase I: core material phase. Therefore, for the production of the sandwich material, PLA has been selected.

4.1 CORE RESULTS

Table 14: Comparison between all produced samples. First stage is regarding the core material used baking powder for foaming, second section is regarding using heat to produce and while section is regarding using bio-materials and drying them.

ID		Bio based	recycled content	consumable	easy production	shrinkage**	strength**
1	PLA	Full	Full	no		not observed	
1*	PLA-L	Full	-	no		not observed	
2	PHA	Full	-	no		not observed	
**	W-PLA	Full	Full	no		not observed	
3	POP	Full	-	partially		slightly	
4-5	ALG	Full	-	partially		observed	
6	ALG-CaCO3 I-II	Full	-	partially		observed	
7	ALG-CaCO3 II	Full	-	partially		observed	
8	ALG-HONEY	Almost Full	Almost Full	partially		observed	
9	ALG-H-FLAX	Full	Full	partially		observed	
10	AG-SEA	Full	Full	partially		observed	
11	AG	Almost Full	Almost Full	partially		observed	
12	AG-ALG	Almost Full	Almost Full	partially		observed	
13	SAWD I	Almost Full	2/3	partially		slightly	
14	SAWD II	Almost Full	2/3	partially		slightly	
15	SAWD III	Almost Full	2/3	partially		slightly	

* The foaming agent - baking powder- excluded from the content.

** Price is quite changeable. Therefore, a bar is used for estimation. As PLA recycled, the price is not included for the material.

*** Not technical measurements are taken. Therefore assumptions are made.



Figure 83: Final images of biobased samples for the core material.

4.1.2 PLA Results



Figure 87: Foamed PLA samples

The lamination results are presented along with their respective images and analysis. The lamination of four samples is shown in the image on the right. Even though, at first there were five samples to be laminated, the PLA-A4 sample has failed during the lamination, shrunk significantly and the facesheet had damages making it ineligible for testing.

Method :200gr PLA + 30 gr Baking powder
 Total: :10 sample produced (5 for PLAX A; 5 for PLAX B)

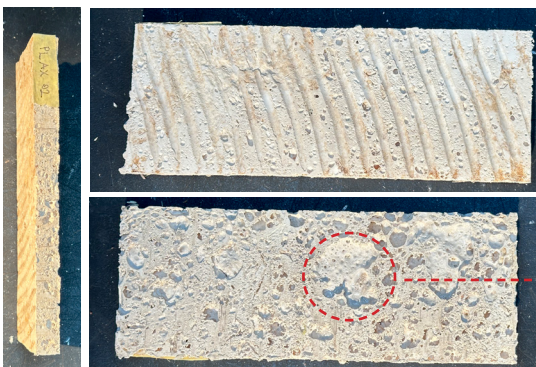


Figure 84: Close-up look of the specimen PLA A2

large cellular structure

This specimen is the heaviest between all, however it also has slightly more thickness.

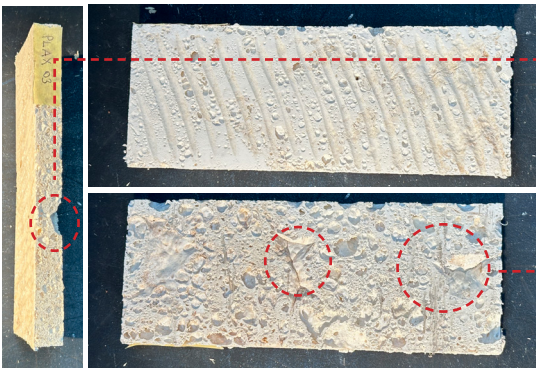


Figure 85: Close-up look of the specimen PLA A2

cellular gaps are on the edge.

non-foamed parts.

Even though this specimen does not have large foamed structure, the non-foamed part can lead to unequal structure. Additionally, foam on the edges might cause some load fails.

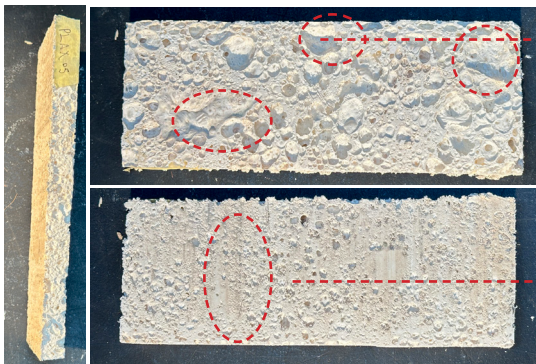


Figure 86: Close-up look of the specimen PLA A2

large openings

These slight linear lines are due to the cutting of the

Sample 5 is much lighter than the others and has larger gaps. This is due to the amount of baking powder used in the production of the material.

4.2 FACESHEET



Figure 88: Cut facesheet samples

In this section, the lamination results are presented along with their respective images and analysis. The lamination of four different approaches are given. The first approach is regarding resin consolidation of thermoset biobased epoxy while all the other three approaches are film stacking method of thermoplastic PLA resin.

1. Resin infusion technique : Bio-based Epoxy + Flax
2. Film stacking technique | Method I : PLA + Flax
3. Film stacking technique | Method II : PLA + Flax
4. Film stacking technique | Method III : PLA + Flax

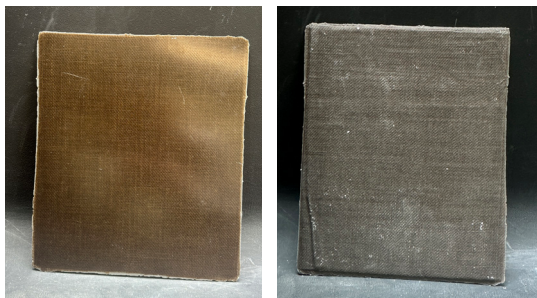


Figure 89: Bioepoxy/Flax sample

4.2.1 EPOXY - FLAX

The resin infusion technique has been used for this material. In general there are no error occurred except a very small one, which is the flax fibers not being ironed beforehand which caused an not-very-flat surface on the back side. Beside, the resin has follow quite great through the surface and the front face of the lamination has a very smooth surfaces. Additionally, materials is strong, even though mechanical testing havent conducted.

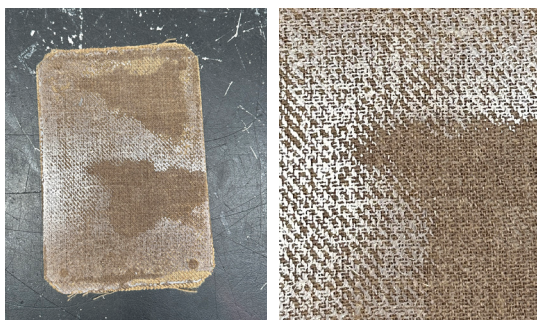


Figure 90: Flax/PLA Method I samples

4.2.2 PLA - FLAX | Method I

The resin film stacking technique has been utilized. Several errors were encountered during the process. Firstly, the PLA did not melt properly in the press machine. This could be attributed to factors such as the pressure of the machine (6 bar), the short duration of pressure (8 mins), and potential issues with the mold not applying pressure properly. Later on, the material was subsequently cured in the oven for 2hrs, and the outcomes are depicted in Figure 142. However, there were still issues as the PLA did not uniformly flow through the flax fibers.



Figure 91: Flax/PLA Method II samples

4.2.3 PLA - FLAX | Method II

Failure has been observed regarding excessive PLA extruding from the surface. The initial fiber mass fraction ratio was set at 60-65%. However, after the pressing process, it was observed that the machine allowed PLA to leak from the material without proper impregnation. It was calculated that approximately 200g of PLA leaked outside, visible on the left side of Figure 143. Additionally, since the PLA did not laminate properly, the failure in the flax can be observed on the right side of Figure 143. These gaps render the material vulnerable to moisture.



Figure 92: Flax/PLA Method III samples

4.2.4 PLA - FLAX | Method III

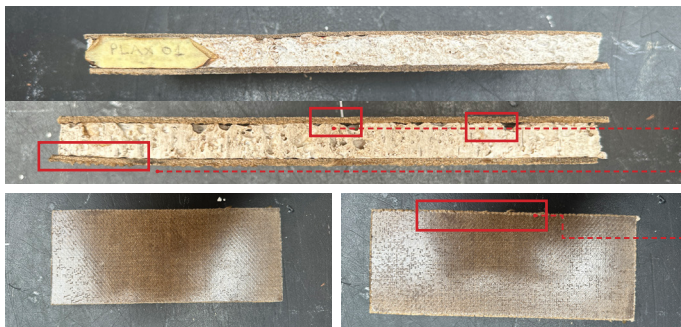
For this approach, the same method is utilized. However, this time a different pressing equipment is used. Since the mold has yielded better results compared to the first two approaches of the film stacking method, the mold approach is chosen again. However, there were no proper molds to be used. Therefore, a simple baking steel plate is used. Later on, two heavy steel plates are placed on top of the plate to apply pressure. The process did not result in many failures and was rather easy and less labor-intensive. A fiber mass fraction of 50% is achieved, but there was still a slight excess of material.

4.3 LAMINATION RESULTS

The results occurred in the lamination/binding stage of the facesheet and the core material is given. In summary, the lamination process faced challenges including shrinkage of the foam core due to applied pressure and adhesive failure from insufficient pressure. When heat was applied, material failure occurred, due to excessive

Variability in lamination quality was observed. A sample with high fiber volume ratio and mold pressing showed strong bonding properties. However, the stronger lamination has been observed with two component epoxy binding.

4.3.1. Heat gun

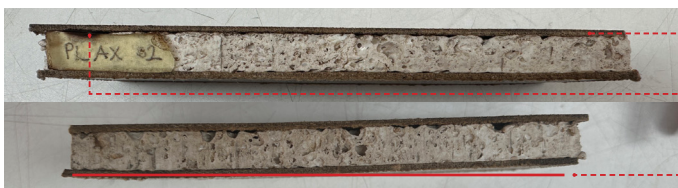


- ▶ prone-to-fail edges
- ▶ shrunk on the edge due to pressure.
- ▶ slight damage on the fibers

PLAX A1

This lamination comparatively bonded better than the other samples. However, there are still slightly prone-to-fail corners, as well as parts that have shrunk due to the pressure applied to the material.

Figure 93: Close-up look of the specimen PLAX A1.

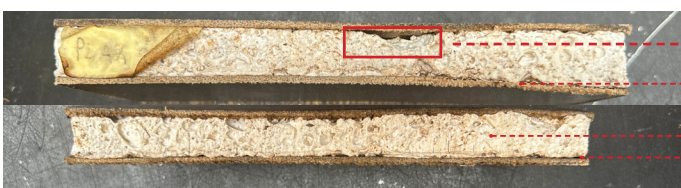


- ▶ slightly shrunk fibers
- ▶ not well bonded
- ▶ non-linear

PLAX A2

Exhibits some non-linear on the surface conditions due to the lamination results and the pressure applied during the bonding stage. Some fibers seem to be pressed too much.

Figure 94: Close-up look of the specimen PLAX A2

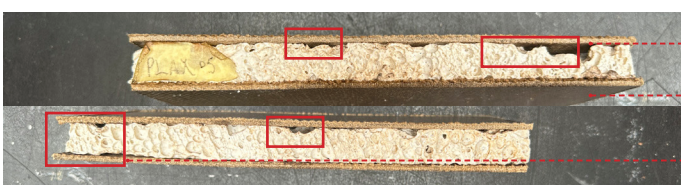


- ▶ prone-to-fail edges
- ▶ delamination and slight damage on
- ▶ shrunk on the edge due to pressure.

PLAX A3

This specimen exhibits some non-linearity on the surface as well; however, it is less pronounced than in the previous specimen. Additionally, this specimen has edges that are prone to failure, although not to the same extent. In the corners, poorly

Figure 95: Close-up look of the specimen PLAX A3



- ▶ prone-to-fail edges
- ▶ fiber-to-fiber delamination.
- ▶ shrunk on the edge due to pressure.
- ▶ not-well bonded

PLAX A5

This specimen is the lightest among the samples and has a less dense cellular structure. Pressure has caused this material to exhibit non-linear surfaces. Additionally, significant edges prone to failure can be observed throughout the left side of the figure, as well as poorly laminated surfaces and some fiber-to-fiber delamination.

Figure 96: Close-up look of the specimen PLAX A5.

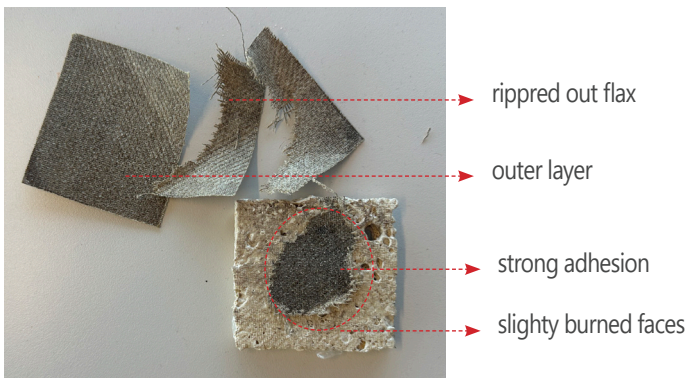


To ensure proper binding of the materials, a slight hand-applied pressure was utilized. However, this approach led to some issues. When the core was heated, it became easy to reshape the material, resulting in a shrinkage of the foam by around 30%, as the core material warmed up to a point where it could be easily compressed. Consequently, during sample production, minimal pressure was applied to avoid this problem. Nevertheless, inadequate pressure resulted in adhesive failure.



During the binding stage of the facesheet and core material, using a heat gun on the fibers caused some failures. Instead of only melting the top layer of PLA, the entire PLA in the lamination was affected. Initially, the lamination seemed fine, but the flax textile separated easily with slight pressure, as shown in Figure 123. This issue could be due to the heat gun being too strong or applied too close to the fibers, or because the fiber volume fraction was insufficient, resulting in inadequate PLA penetration through the flax fibers.

Figure 97: All PLAX A specimens



Some parts of the laminations performed better than others. For instance, as depicted in the image on the left, the flax fibers are once again separated from each other, while the facesheets are stuck to the PLA layer, suggesting that the heat gun is effective when the lamination process works properly. However, another issue arose: slight burning occurred in the facesheet material due to exposure to the heat from the heat gun, resulting in an undesirable alteration of the material phase.

Figure 98: Close-up look of the specimen PLAX C-01. Image above represents the front face while image below represents the backside of the core material.

4.3.2 Two component binder



In general, it was rather easy to laminate the materials using a two-component binder (not biobased). However, since the glue dries rather quickly, it was somewhat difficult to bind certain parts of the materials. Once there was a small gap, it could not be re-bonded because the rest of the material had already been glued. Another drawback of using glue compared to binding through PLA is that the material does not meld together, resulting in less homogeneous bonding.

Figure 99: PLAX B samples bonded with two component binder.

Lamination analyses of the heat gun approach

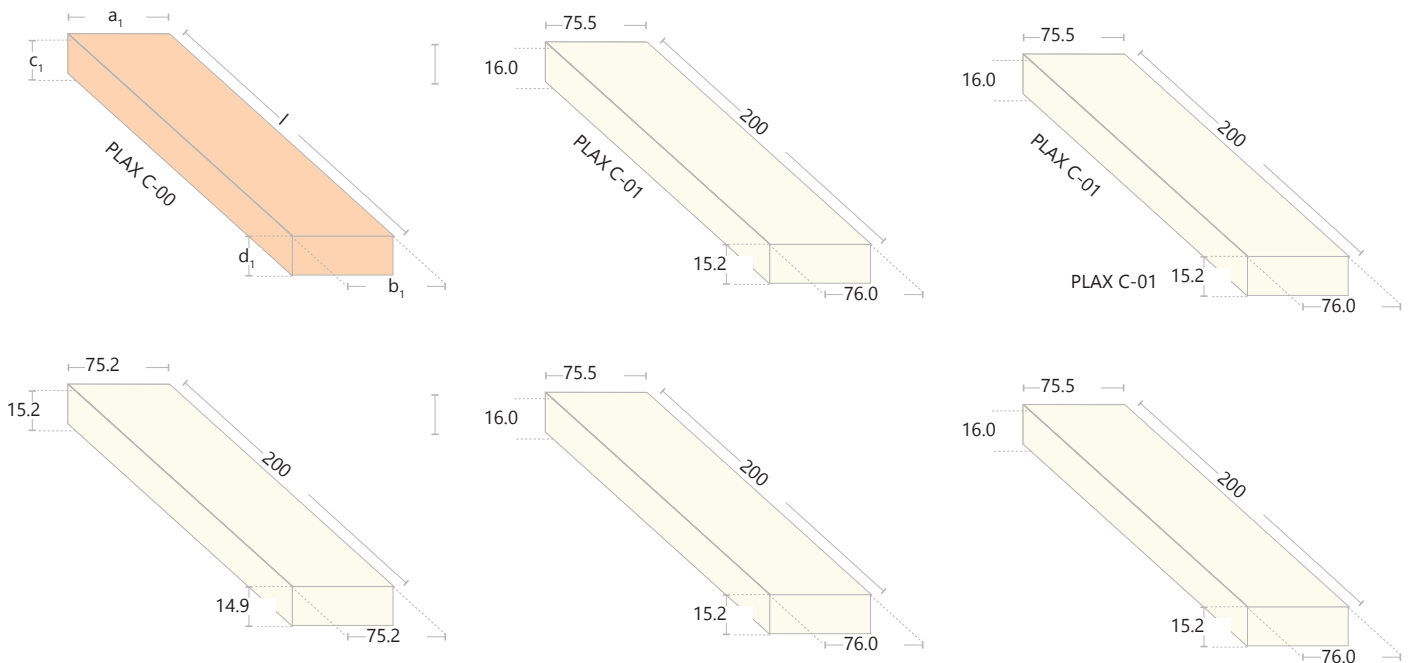


Table 15: Properties of the PLAX C-01-05 specimens before the composite production and after the binding them together.

ID	weight gr	length mm	before the binding				after the binding				shrinkage % in thickness (average)
			width (mm)		thickness (mm)		width (mm)		thickness (mm)		
			a ₁	b ₁	c ₁	d ₁	a ₂	b ₂	c ₂	d ₂	
PLAX A1	107	200	75.2	75.2	15.2	14.9	74.5	75.0	11.0	11.20	%26
PLAX A2	141	200	76.0	75.5	16.5	15.2	75.5	75.0	14.0	13.0	%15
PLAX A3	140	200	75.2	75.5	17.8	17.5	76.0	76.5	14.0	16.5	%14
PLAX A4*	100	200	76.0	75.5	16.0	15.5	-----	-----	-----	-----	-
PLAX A5	90	200	73.8	75.5	15.2	14.8	75.1	74.0	14.0	12.0	%14

Table 16: Final dimensions of the composite panel.

ID	weight gr	length mm	width (mm)		thickness (mm)	
			a ₁	b ₁	c ₁	d ₁
PLAX 01	145 gr	200 mm	75.2	75.2	15.2	14.9
PLAX 02	178 gr	200 mm	76.0	75.5	16.5	15.2
PLAX 03	177 gr	200 mm	75.2	75.5	17.8	17.5
PLAX 04*	-	-	-	-	-	-
PLAX 05	137 gr	200 mm	76.0	75.5	16.0	15.5

* for the foaming section, the foaming agent - baking powder- excluded from the content as the final product almost does not include.

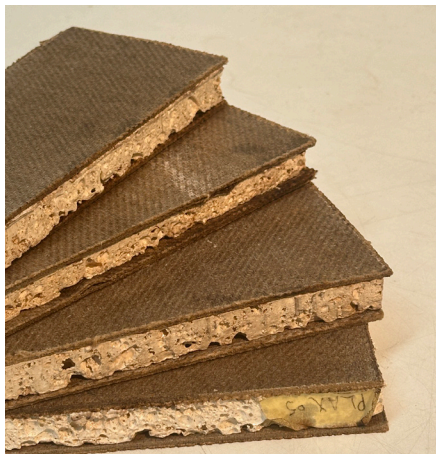
** price is quite changeable. Therefore, a bar is used for estimation. As PLA recycled from printing lab, the price is not included for the material.

*** Not technical measurements are taken. Therefore assumptions are made.

4.4 Finalized material for testing

In order to test for 4-point bending two different set of specimens are produced. Their production methods and differences are given below. The main difference is the lamination method as PLAX A does not have any binder while PLAX B has two component binder.

PLAX A



Dimensions : 200mm x 75mm
Sample amount : 4 samples
Facesheet prod. : Film stacking
Lamination : Heating gun
Test : 4-point bending

PLAX B

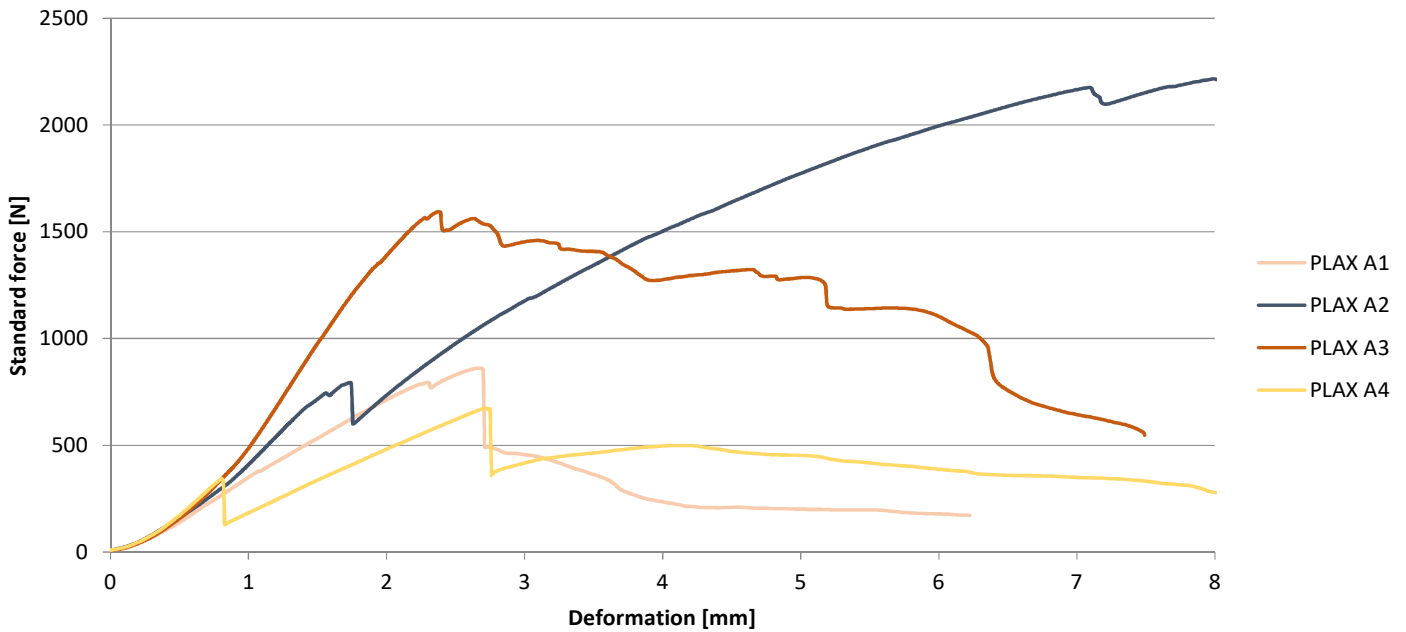


Dimensions : 190mm x 75mm
Sample amount : 5 samples
Facesheet prod. : Film stacking
Lamination : Two component epoxy
Test : 4-point bending

4.5 | MECHANICAL TEST RESULTS

As mentioned in the methodology section, at total the 4-point bending test has been conducted according to ASTM C-393 standard and 2 times with PLAX-A and PLAX-B samples.

4.5.1 PLAX A



Graph1: Load vs deflection graph of the specimens PLAX A.

ID	h_{core} mm	h_{all} mm	Mass core gr	Mass overall gr	F_{max} (N)	F_{yield} (N)	dL_{Fmax} (mm)	dL_{Fyield} (mm)	F_{shear_Ultim} (MPa)	$E_{Youngs\ modulus}$ (GPa)	$I_{estimated}$ (mm ⁴)
PLAX A1	11.1	15	107	145	861.5	738.0	2.7	2.31	0.44	2.57	14255.6
PLAX A2	13.5	15.9	141	178	2215.6	702.0	8.0	1.5	1.00	4.27	12821.1
PLAX A3	15	17.6	140	177	1594.4	1376.0	2.4	2.0	0.65	4.36	17198.6
PLAX A4	13	15.7	90	137	674.9	321.0	2.7	0.8	0.31	3.44	13201.8

Table 17: Properties of the test specimens, the ultimate load they withstood, and their corresponding calculated core shear strength, Young's modulus, and estimated section modulus.

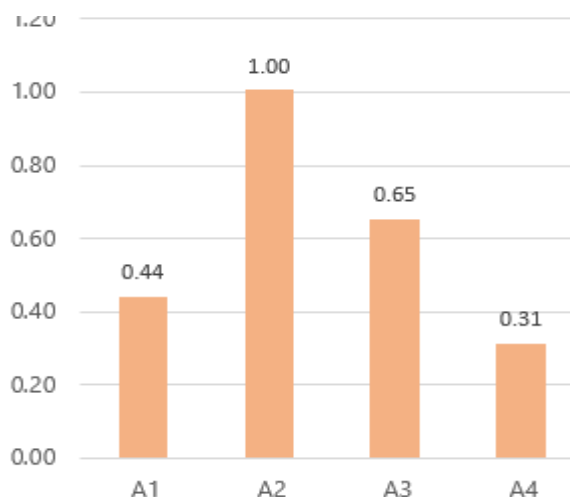


Figure 100: Core shear capacity of the sample PLAX B. (MPa)

Analyses

Most of the failures occurred due to delamination between the core material and the facesheet. Consequently, it wasn't clear where and why the failures happened, or why the testing machine stopped. Moreover, errors occurred due to the bonding with the heat gun causing fibers to separate from each other. As a result, it was uncertain whether the results were truly reflective of the material's properties or if they were significantly influenced by the delamination between the facesheet and the core. To address this uncertainty, two additional tests were conducted, which are explained in the following pages.

Close-Up look to materials

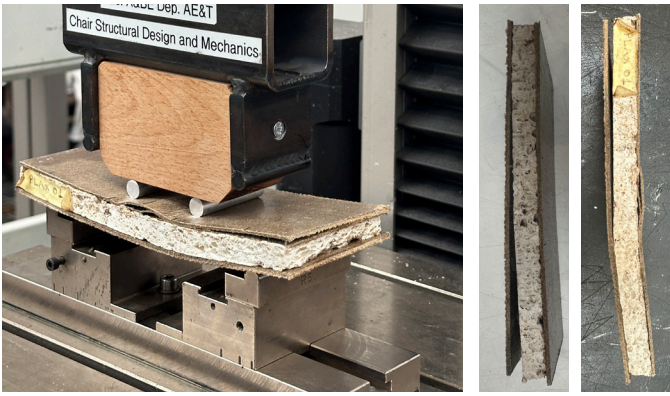


Figure 101: PLAX A1. Left, during testing. Right, after testing images

Material firstly failed due to dilamination on the fibers; as both the fibers are deattached from each others on the layer and also, the dilamation between core material and the facesheet occurred.



Figure 102: PLAX A2. Left, during testing. Right, after testing images

The material failed fairly quickly compared to the first sample. The most probable reason is primarily due to delamination from the corners, as well as between the facesheet below and the core material. Subsequently, the core material failed, and the fracture can be observed in the image above.

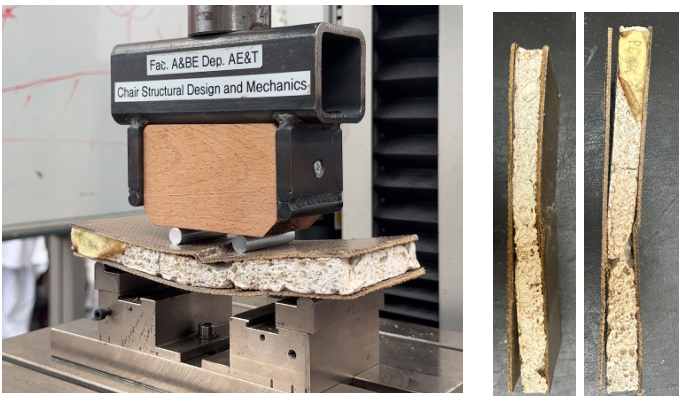


Figure 103: PLAX A3. Left, during testing. Right, after testing images

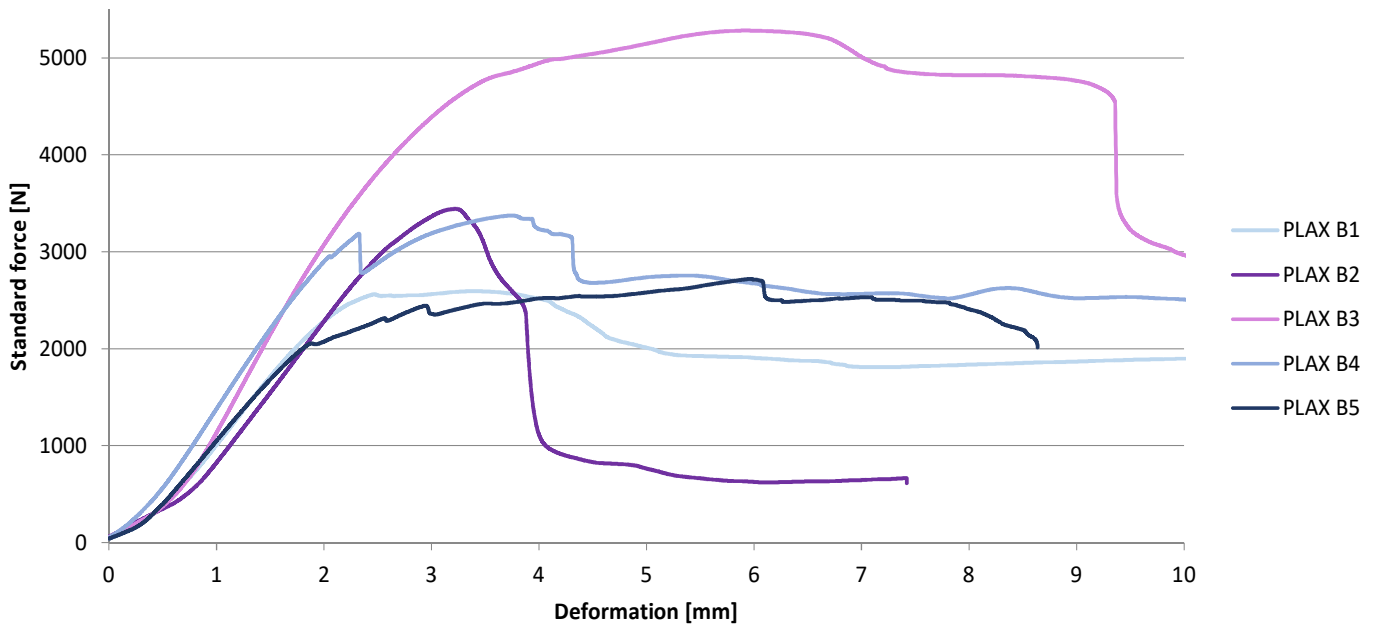
The main failiure happened on the flax fibers assuming it has been already damaged during the lamination stage, before the testing. The specimen again faced with delamination.



Figure 104: PLAX A4. Left, during testing. Right, after testing images

The speciment failed in the testing result as the material did not break but rather experienced a huge bending that can be seen through the Figure 167 in the below images. In turn, the speciemient ended up not having results on the shear yielding capacity of the material. As in the previous samples, this sample also delaminated and more than the others.

4.5.2 PLAX B



Graph2: Load vs deflection graph of the specimens PLAX B.

Table 18: Properties of the test specimens, the ultimate load they withstood, and their corresponding calculated core shear strength, Young's modulus, and estimated section modulus.

ID	h_{core} mm	h_{all} mm	Mass core gr	Mass overall gr	F_{max} (N)	F_{yield} (N)	dL_{Fmax} (mm)	dL_{Fyield} (mm)	F_{shear_Ultim} (MPa)	$E_{Youngs\ modulus}$ (GPa)	$I_{estimated}$ (mm ⁴)
PLAX A1	21.8	26.6	108	178	2593.4	2348.0	3.3	2.0	0.71	0.79	150007.6
PLAX A2	19.2	24	155	225	3441.9	2715.0	3.2	2.3	1.06	1.11	108518.4
PLAX A3	17.65	22.45	184	254	5284.0	4775.0	6.0	3.5	1.76	1.59	87900.3
PLAX A4	17.73	22.53	132	202	3372.0	2942.0	3.8	2.1	1.12	1.65	88893.7
PLAX A5	15.94	20.74	133	203	2720.9	2047.0	6.0	1.3	0.99	2.36	68414.4

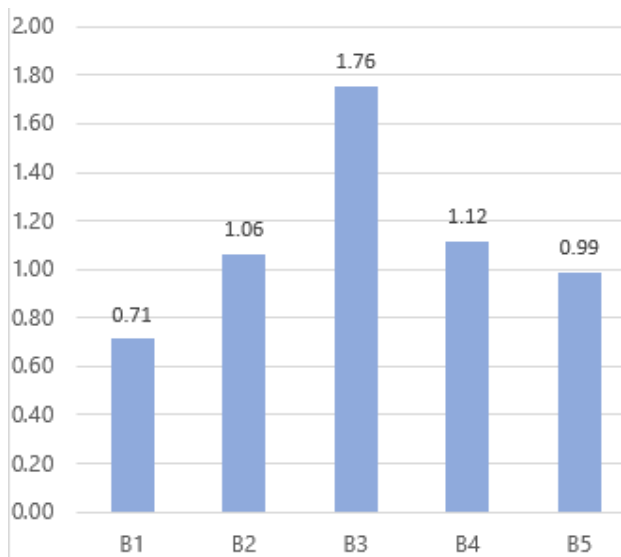


Figure 105: Core shear capacity of the sample PLAX B. (MPa)

Analyses

The five specimens showed different failure modes, which are explained in detail on the following page. The shear stress ranged from 0.71 MPa to 1.76 MPa, and the maximum load they withstood ranged from 4.77 kN to 2.05 kN, as shown in the table on the left. Except for PLAX B1 and PLAX B3, where core shear failure occurred, the results are quite similar to each other. However, some materials still experienced delamination, which made identifying the results difficult. The thickness does not necessarily correlate with higher strength; this may be more related to the cellular structure and the mass of the material.

Close-Up look to materials



Figure 106: Images of PLAX B1. Left; Image after the testing testing; Right, close up where the material has failed.

The material failed due to shear, which is the desired failure mode for the test. Due to the loading, the fibers are slightly stretched on top. During the test, no binding delamination was observed. Delamination occurred very slightly on the bottom, presumably due to the shear failure reaching the bottom part.



Figure 107: Images of PLAX B2. Left; Image after the testing testing; Right, close up where the material has failed.

The specimen firstly failue due to the binding failure . However, the core still failed. Fibers showed no damage.



Figure 108: Images of PLAX B3. Left; Image after the testing testing; Right, close up where the material has failed.

The specimen showed greater shear failure compared to other materials. Delamination was observed, which is assumed to be caused by the shear failure. Slight damage to the fibers was observed due to the loading. The core crack started from the point of load and extended to the edge.



Figure 109: Images of PLAX B4. Left; Image after the testing testing; Right, close up where the material has failed.

A different failure observed, occurring in the middle of the material, emphasizing a bending failure by having cracks both in the core and the bottom facesheet. The specimen had great bonding between the facesheet and the core material. The fibers showed slight damage at where they were loaded.



Figure 110: Images of PLAX B5. Left; Image after the testing testing; Right, close up where the material has failed.

Fiber delamination occurred on the top facesheet, assuming it has happened due the shear in the facesheet and supported by the failure in the bonding in between.

4.5.3 FAILURE TYPES

The PLAX B samples exhibited different failure modes during the 4-point bending test. PLAX B1 and PLAX B3 showed shear failure, while PLAX B2 showed bending failure with a crack on the bottom facesheet. Additionally, other materials primarily failed due to delamination and core failure.

1. Shear Failure on the core
2. Shear Failure on the facesheet
3. Bending Failure
4. Lamination failure

Shear Failure | on the core (Desired failure)

The purpose of the test was to check the core shear properties of the sandwich panel. Therefore the desired failure type was the shear failure on the sandwich core. This failure type mostly on the PLAX B1-B3. The images below shows the shear failure of the specimens. PLAX B1 (failed at 2.6 kN). Failure happen within the material, while the crack on PLAX B3 went further leading delamination between core and the facesheet (failed at 5.3 kN).

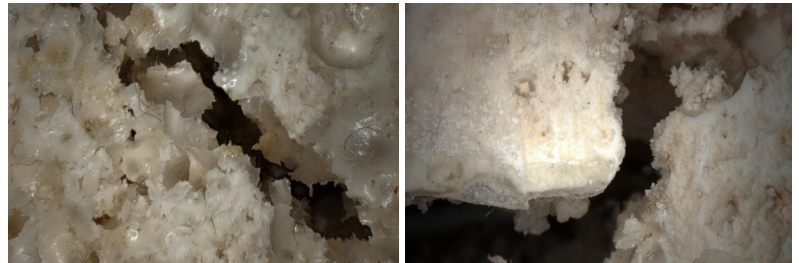
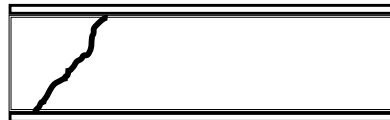


Figure 111: PLAX B1 and PLAX B3 respectively, and the

Shear Failure | on the facesheet

PLAX B4 and PLAX B5 failed due to shear failure on the flax fibers. The images below shows the shear failure happened in the flax fibers of the specimens. PLAX B4 (failed at 3.3 kN). and PLAX B5 by also having delamination between core and the facesheet (failed at 2.7 kN).



Figure 112: PLAX B1 and PLAX B3 respectively, and the failure on the

Bending Failure

Another failure type that has been observed is the bending failure. As it can be seen from the below images, the material failed from the maximum bending point by leading to facesheet (fiber break) at the bottom point. This specimen, PLAX P4, is the only specimen that showed crack on the facesheet, and it failed at the load of 3.37 kN.

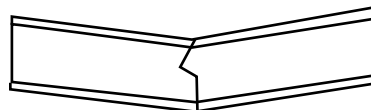


Figure 113: Load vs deflection graph of the specimens PLAX A.

Lamination failure on the sandwich panel

These below failure shows the failure happened due to the delamination between facesheet and core resulting the binding material, the epoxy, failed. Between all the materials, the PLAX B2, PLAX4 and PLAX B5 showed the highest epoxy failure, while for PLAX B3 the epoxy failure resulted after the failure on the core as the shear failure.

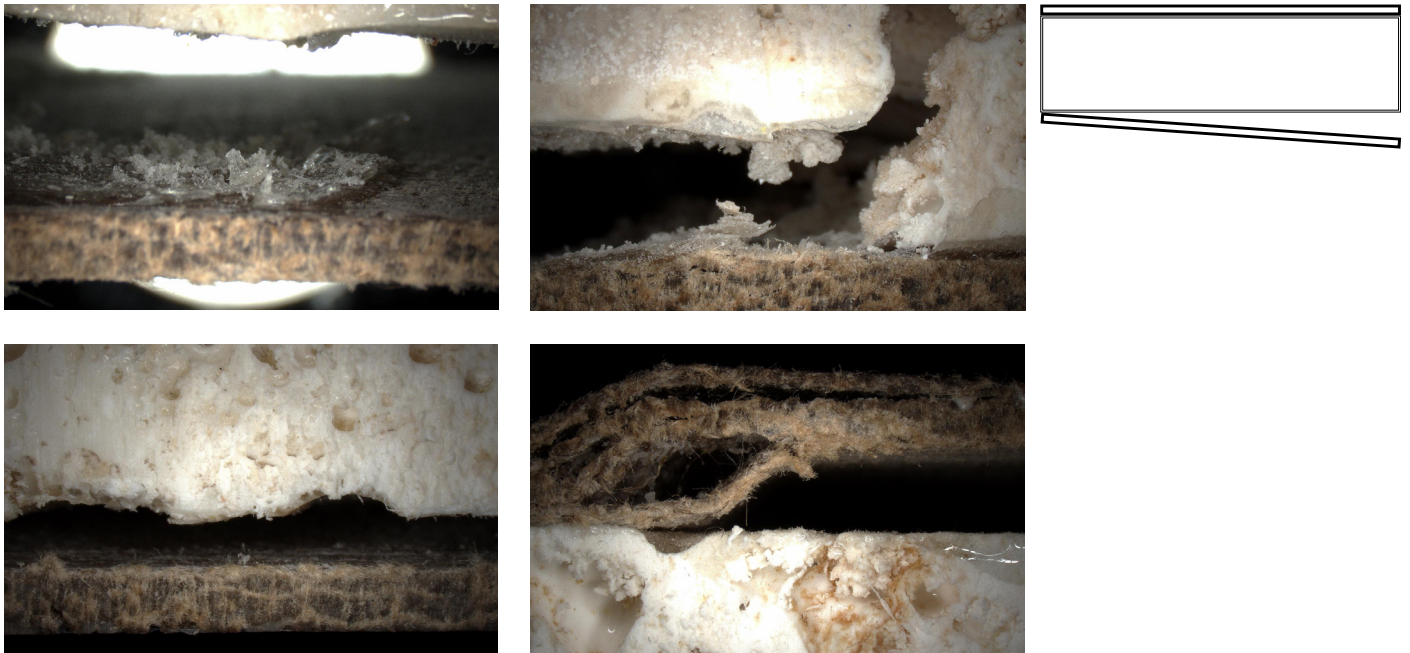


Figure 114: Microscope images showing the delamination between facesheet and the core material. Respectively; PLAXB2, PLAX B3, PLAX B4, PLAX B5

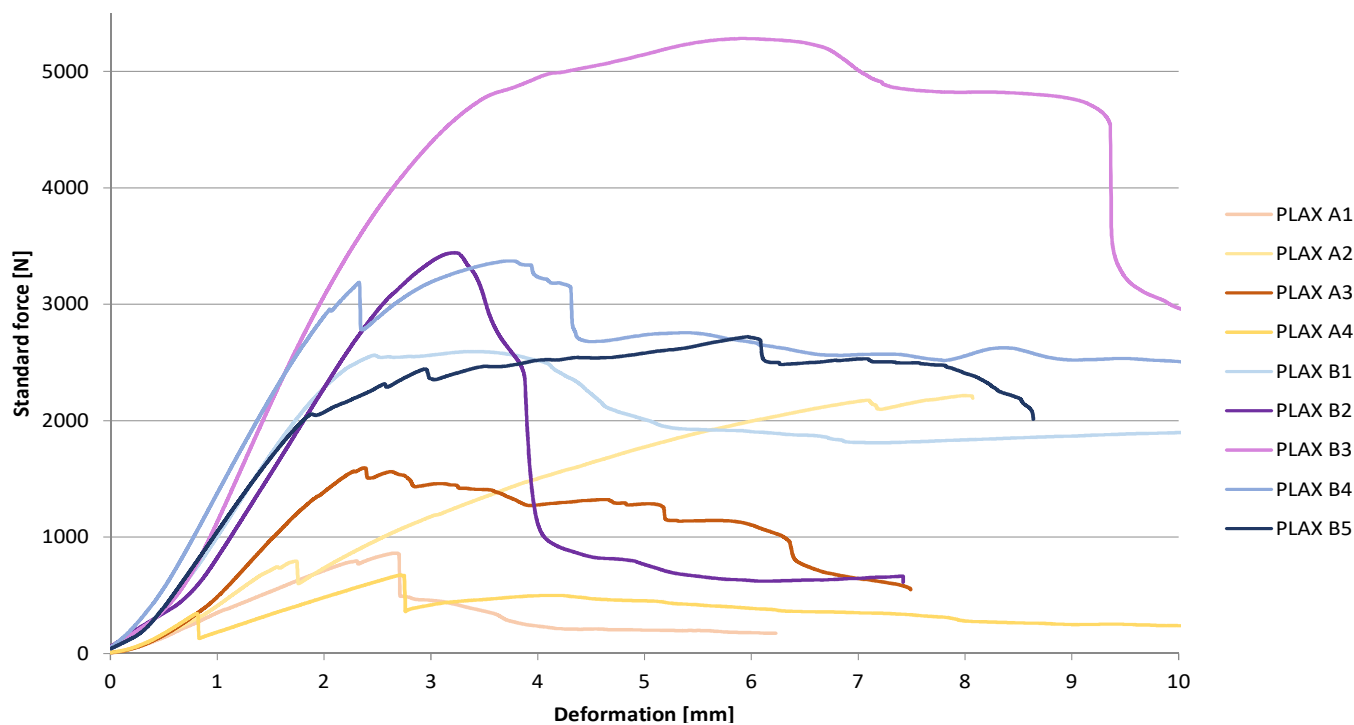
Further investigation on the core material

The images below show further microscope analyses to understand the behavior of the core material after the material is melted and foamed with baking powder. The material is showing variety of foaming results, while some parts are showing a closed cell structure, many of the foaming features shows open cell structure.



Figure 115: Microscope images showing the cellular structure of the foam material

4.5.4 COMPARISON BETWEEN BOTH TEST



Graph3: Load vs deflection graph of the specimens PLAX A.

ID	h_{core} mm	h_{all} mm	Mass core gr	Mass overall gr	F_{max} (N)	F_{yield} (N)	dL_{Fmax} (mm)	dL_{Fyield} (mm)	F_{shear_Ultim} (MPa)	$E_{Youngs\ modulus}$ (GPa)	$I_{estimated}$ (mm ⁴)
PLAX A	13.2	16.1	119.5	159.3	1336.6	784.3	3.9	1.6	0.6	-	11799.0
PLAX B	18.5	23.3	142.4	212.4	3482.4	2965.4	4.5	2.2	1.1	1356.7	111520.4

Table 19: Tabulated properties and calculated results of the specimens as their averages.

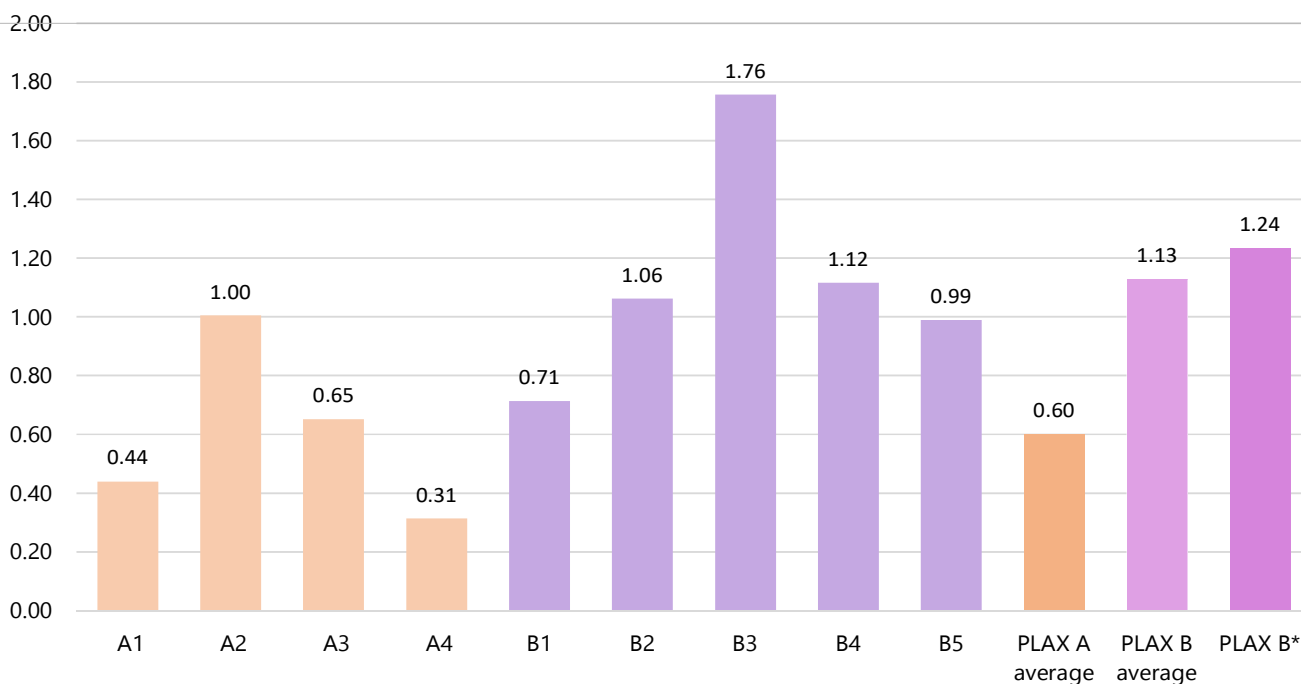


Figure 116: Core shear strength comparison of the PLAX A1-A4, PLAX B1-B5, PLAX A average, PLAX B average and PLAX Bcore

4.5.5 DECISION REGARDING THE RESULTS

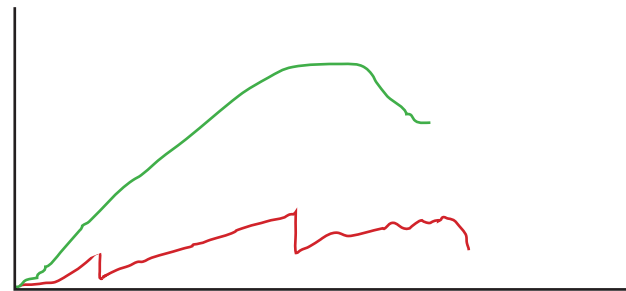
Average of the shear strengths

The both specimen has an average of shear quite differently, while the PLAX A has an average of 0.6 MPa, the PLAX B specimens are having 1.1 MPa average, as well as PLAX B*, which refers to the average of the core failed specimens are 1.24 MPa.



Discontinuity on the graph

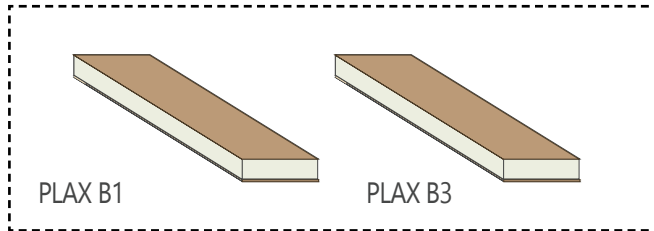
PLAX A specimens are showing more discontinuation on the graph which mostly caused due to the weak lamination between facesheet and the core material. This stands as a further reason on why PLAX B samples are resulting in more reliable results.



Result

PLAX A samples are discarded for the design stage. PLAX B1&B3 are used to calculate the core shear strength. However for some values, the whole average of PLAX B are taken.

DECISION REGARDING THE RESULTS



Failed in core shear

As mentioned in the previous pages, the PLAX B1 and PLAX B3 failed in core shear. Therefore, their results are taken into account to calculate the shear capacity to design the proposed panel.

ID	h_{core} mm	h_{all} mm	Mass core gr	Mass overall gr	F_{max} (N)	F_{yield} (N)	dL_{Fmax} (mm)	dL_{Fyield} (mm)	F_{shear_Ultim} (MPa)	$E_{Youngs\ modulus}$ (GPa)	$I_{estimated}^*$ (mm ⁴)
PLAX B1	21.8	26.6	108	178	2593.4	2348.0	3.3	2.0	0.71	0.79	150007.6
PLAX B3	17.65	22.45	184	254	5284.0	4775.0	6.0	3.5	1.76	1.59	87900.3
PLAX B*	19.73	24.53	146	216	3938.68	3561.5	4.67	2.77	1.24	1497.15*	53822.4

Table 20: Finalized properties of the materials.

Load Type	Layer	Thickness (mm)	Mass (kg/m ²)	Weight (kN / m ²)	Weight (kN / m ³)
Facesheet	4 layers	2.4	2.45	0.024	10
Core	-	19.7	10.08	0.099	5

4.5.6 Comparison between PLA and conventional core materials

Table 21: Comparison between different core materials for sandwich panels. Reference; Edupack 2023

Material		Material Properties			Primary Production			Material Recycling			
		Price	Shear Strength	Flammab.	Embodied energy	CO2 footprint	Water usage	Recycle	Downcyc.	Biodegr.	Renew.
		€/m ³	Mpa		MJ/kg	kg7kg	l/kg	YES/NO	YES/NO	YES/NO	YES/NO
	PLA	3700	27-43	Flammable	45	2.3	20	YES	YES	YES	YES
	Foamed PLA	700-1500	1.25	Flammable	45	2.3	20	YES	YES	YES	YES
FOAM	PU (0.062)	600	0.39-0.49	Flammable	100	5.1	295	NO	YES	NO	NO
	PU (0.128)	1250	1.1-1.29	Flammable	100	5.1	295	NO	YES	NO	NO
	PU (0.6)	5875	10.3-12.6	Flammable	100	5.1	295	NO	YES	NO	NO
	PP Foam	1.84	6.0-7.01	Flammable	80	3.35	120	NO	YES	NO	NO
	Phenolic Foam	694	0.2-0.5	Self-extinguish.	98	6.1	155	NO	YES	NO	NO
	Polyetherimide (closed)	6635	0.79-1.45	Self-extinguish.	234	18.95	515	NO	YES	NO	NO
	PES Foam	6505	0.35-2.1	Self-extinguish.	230	17.5	600	NO	YES	NO	NO
	Polyetherimide (0.11)	8100	1.31-1.45	Self-extinguish.	234	18.95	515	NO	YES	NO	NO
	Polyethylene terephalate	2195	0.8-2.32	Flammable	88	5.1	400	NO	YES	NO	NO
	Polyetherimide (rigid)	8350	0.6-4.8	Flammable	330	28.1	600	NO	YES	NO	NO
	Expanded PS	84	0.055-0.50	Flammable	108	3.01	451	NO	YES	NO	NO
	PVC foam (0.030)	450	0.1-0.11	Self-extinguish.	85	5.5	450	NO	YES	NO	NO
	PVC foam (0.20)	3000	2.33-2.42	Self-extinguish.	85	5.5	450	NO	YES	NO	NO
PVC foam (0.40)	6000	5.25-6.0	Self-extinguish.	85	5.5	450	NO	YES	NO	NO	
HONEYCOMB	Aluminum (0.016)	437	0.37-0.41	Non-Flammable	425	27.5	1200	YES	YES	NO	NO
	Aluminum (0.037)	1000	1.17-1.38	Non-Flammable	425	27.5	1200	YES	YES	NO	NO
	Aluminum (0.147)	4000	6.42-7.09	Non-Flammable	425	27.5	1200	YES	YES	NO	NO
	Aramide paper/phenolic	1500	1-2.43	Self-extinguish.	325	16.5	480	NO	YES	NO	NO
	Aramide paper/phenolic	6000	4.19-4.63	Self-extinguish.	325	16.5	480	NO	YES	NO	NO
	Glass polyimide	7000	1.28-1.41	Self-extinguish.	300	21.8		NO	YES	NO	NO
	Glass polyimide	17000	4.59-5.07	Self-extinguish.	300	21.8		NO	YES	NO	NO
	Impregnated Paper	350	0.28-1.09	Slow-burning	110	3.1	1450	NO	YES	YES	HALF
	Polycarbonate	2200	0.59-1.36	Slow-burning	215	12	170	YES	YES	NO	NO
	Polyetherimide	6250	1.28-1.41	Self-extinguish.	405	28.8	525	YES	YES	NO	NO
Polypropylene	250	0.55-0.8	flammable	150	3.9	39	YES	YES	NO	NO	
NATURAL	End-grain Balsa (0.095)	2545	4.24-5.18	Self-extinguish.	71.6	0.373	700	NO	YES	YES	YES
	End-grain Balsa (0.25)	790	1.55-1.90	Self-extinguish.	71.6	0.373	700	NO	YES	YES	YES
	Cork Board (0.25)	2046	0.8-1.1	Self-extinguish.	153	1.47	700	NO	YES	YES	YES

Recyclable, biodegradable, renewable
 Non-Recyclable, Non-biodegradable, Non-renewable

Recyclable, Non-biodegradable, Non-renewable
 Non-Recyclable, Biodegradable, Renewable

Table 22: Comparison between different core materials for sandwich panels. Reference; Edupack 2023

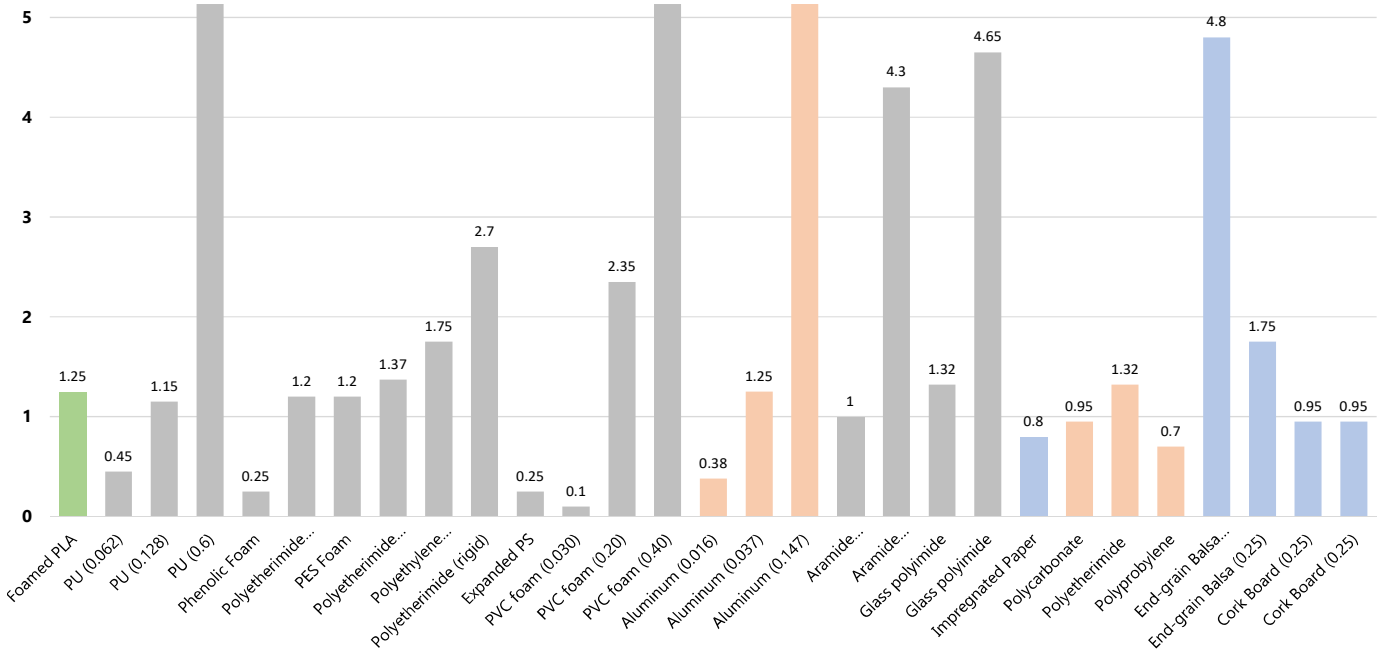
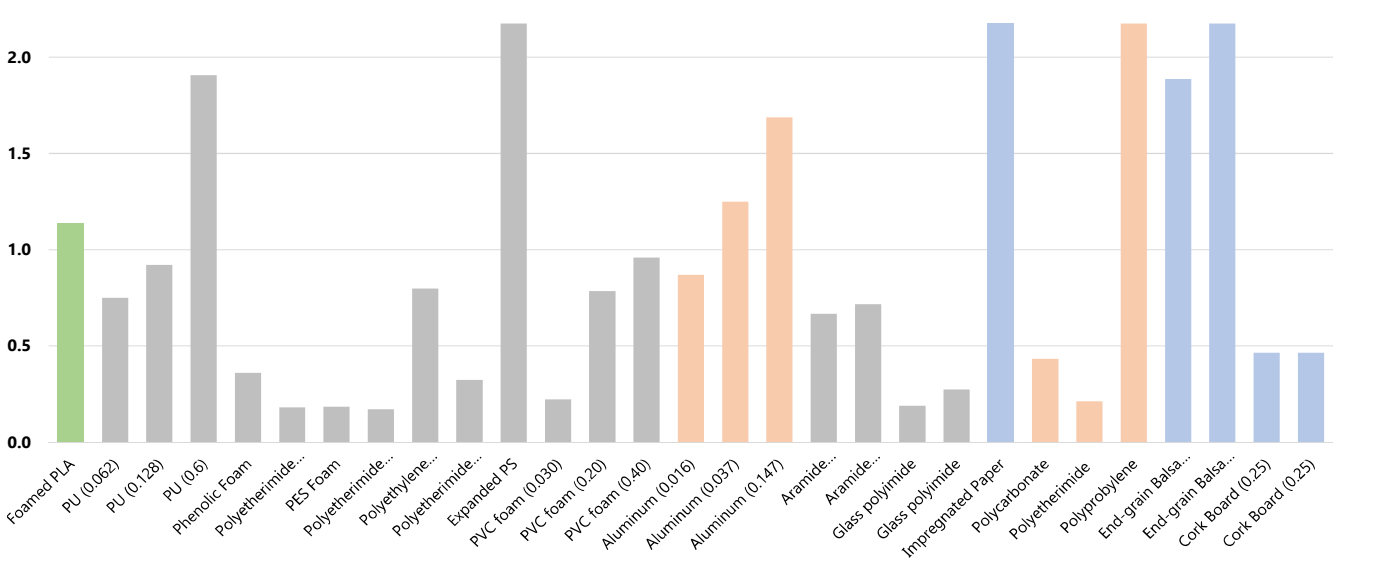


Table 23: Comparison between different core materials for sandwich panels. Reference; Edupack 2023



Shear strength comparison | table above

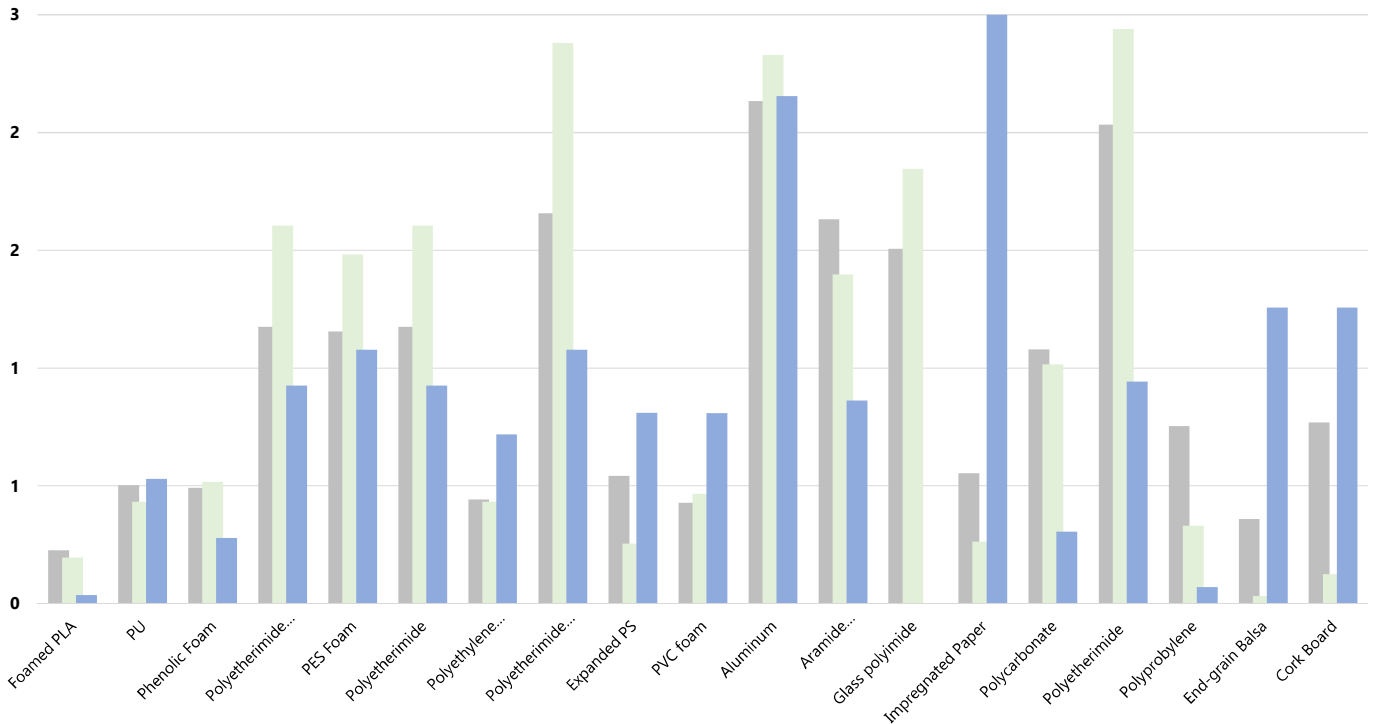
The table shows the shear strength of different materials, indicating that the 'Foamed PLA' core exhibits comparatively strong shear properties, similar to PU (0.128) or regular Polyethylene and PES foams. It shows higher values compared to PU (0.062), cork board (0.25), and polycarbonate. However, foamed PLA shows lower values compared to some materials such as PU (0.6), PVC (0.40), and Aluminium (0.147), which are already quite strong for residential floor applications.

Price/Shear strength ratio comparison | table below

The table shows the price-to-shear strength ratio as an assumption of material cost. The reasoning is that thicker materials tend to be stronger, making the comparison a significant evaluation, despite the ratio being influenced by factors other than just thickness. Foamed PLA falls within the mid-range, placing it neither very expensive nor very cheap. However, since the material is not currently in use, this affects its price, and the material thickness can vary according to requirements.

Embodied Energy
CO2 carbon footprint
Water Usage

Table 24: Comparison between different core materials for sandwich panels. Reference; Edupack 2023



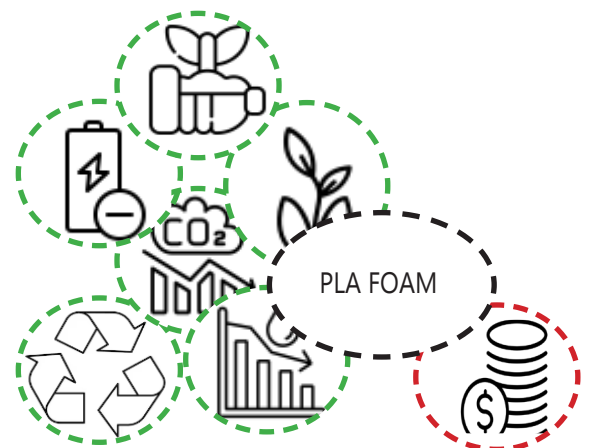
Production stage comparison

The table above presents production-related data for the core materials, referencing Edupack 2023. The first column lists the embodied energy (kg/kg), with PLA having the lowest value. The second column shows the CO2 footprint. While PLA has a low CO2 footprint, cork and balsa have even lower carbon footprints compared to PLA.

However, this value assumed to not include the CO2 capturing of flax. When the reduced is made PLA is stated to have 0.5 kg/kg CO2 (Morão & De Bie, 2019). The last column shows the water usage during production, with PLA requiring the least amount of water at 20 l/kg. Overall, PLA has one of the most sustainable production footprints compared to conventional materials.

Shear strength comparison | table above

The table shows the comparison between Foamed PLA and conventional core materials within three categories as foam, honeycomb and natural material. When all results are compared with each other, PLA stands as the only material (negotiable for balsa and cork) that can be recyclable as it is. Additionally, for the production of PLA the amount of energy needed is the lowest among all, as well as the water usage. when it comes to carbon footprint, the material has very low footprint and stands as the 3. best on the list after corck and balsa. In terms os shear strength, as mentioned before, the material has





4.5.7 Test results summary

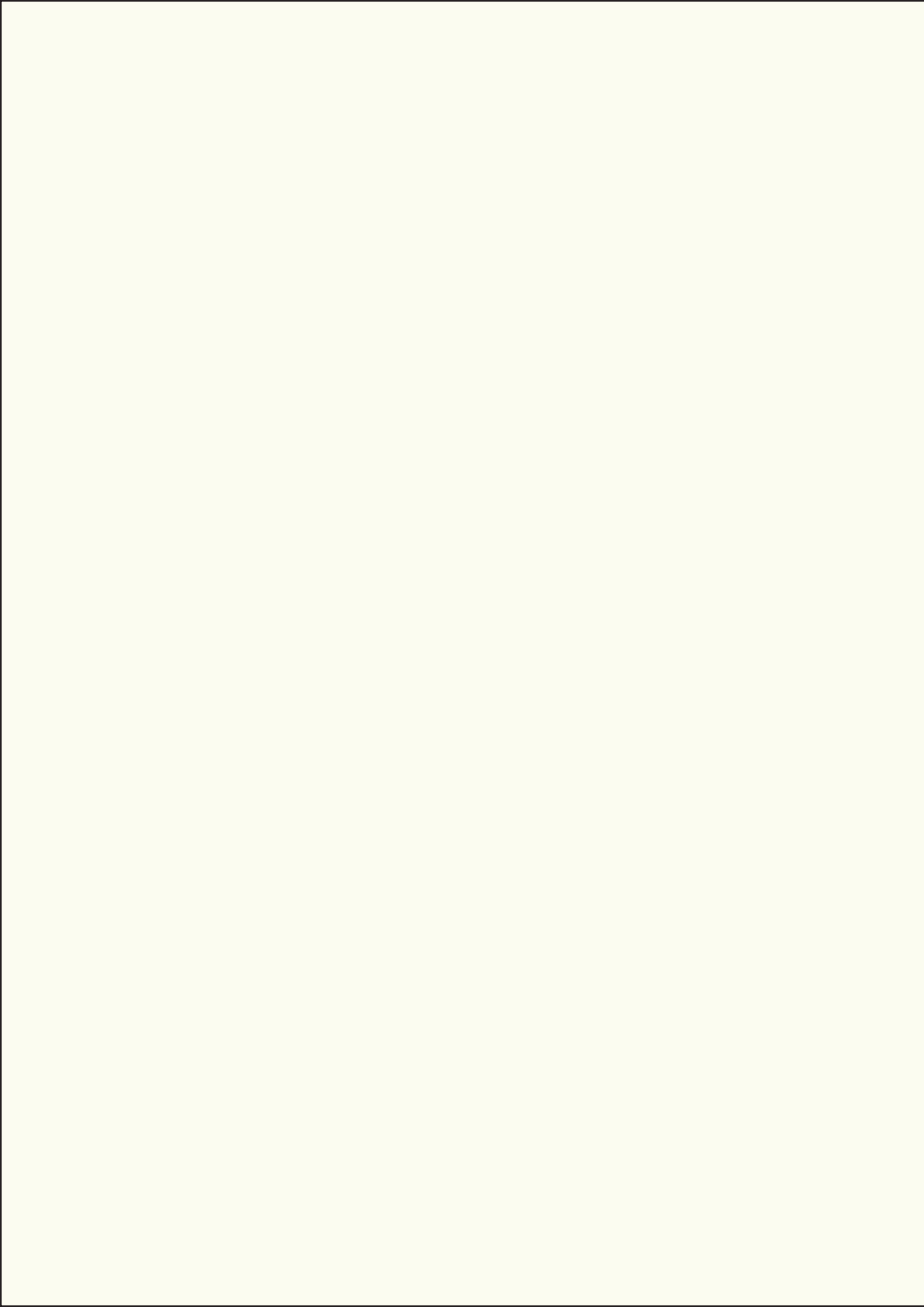
$*F_{max}$ N	F_{yield} N	dL_{Fmax} mm	dL_{Fyield} mm	$**E_{modulus}$ GPa	$***I_{optimized}$ mm ⁴	$F_{core\ shear\ ult}$ MPa	$M_{bending}$ nmm	$\sigma_{facing,bend.}$ MPa	
3938.68	3561.50	4.67	2.77	2.4	53822.4	1.24	98467.07	4.67	
length mm	width mm	$h_{facesheet}$ mm	h_{core} mm	$h_{overall}$ mm	$m_{acesheet}$ gr	m_{core} gr	$m_{overall}$ gr	$****W_{core}$ kN/m ³	W_{core} kN/m ³
190	75	2.4	19.7	24.5	35	144	216	5	10

* For all the results and values, except the E modulus, the PLAX B1 and PLAXB3 (which are apparently failed in the core shear) are considered and their average value is tabulated in the table above.

** For the E modulus of the average value of the all specimens are considered.

*** To calculate the section modulus, the material has been optimized considering the E modulus of separately the facesheet and the core material; which assumed to be Efacesheet 1.7GPa; Ecore 3GPa.

**** The weight of the core is 5 kN/m³ (509.86 kg/m³), however during the design stage the materials shear force it receive is quite less than it can take. Therefore a conclusion has been made is the core material can be



chapter 5

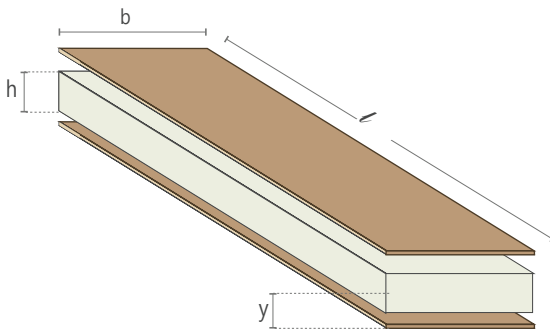
DESIGN & PRODUCTION LINE

81 - 91

5.1 DESIGN CALCULATIONS

The design stage starts with the calculations of the proper core thickness and the facesheet thickness. For this purpose, an Excel file has been designed to calculate the minimal thickness for the core. During the calculation phase, many assumptions have to be made in order to reach an accurate estimate. These estimations are also provided in the last section of the results.

The span of the material ideally prospected as 5m x 1m to compare with a conventional concrete floor system. Therefore, the thickness of the materials is calculated for a loft that can accommodate this span length. At the end of the analysis, it has been found that a facesheet of 6 layers, each 0.0036 m thick, and a core material thickness of 0.15 m satisfy the given load for an area's residential floor design.



- l_{span} : 5 m
- b_{width} : 1 m
- h_{core} : 0.15 m
- h_{total} : 0.1872 m

- Facesheet : 10 kN / m³
- Core : 2.5 kN / m³*
- Core Shear Cpt: : 1.24 MPa
- $I_{sandwich}$: 0.000918*
- $E_{sandwich}$: 1.36 GPa

Design Verification

Load Type	Type	Load
Dead load	Self weight	10 kN / m ² x 0.0036 x 2 + 0.18 x 2.75 kN/m ³
	Floor finishing	0.75 kN/m ²
	Partition	0.5 kN/m ²
	Total	5.45 kN/m²
Live load	Imposed load	2 kN/m ²
	Total	2 kN/m²

Load combinations

$$W = 1.35 \times DL + 1.5 \times LL$$

$$W = 1.35 \times 5.45 \text{ kN/m}^2 + 1.5 \times 2 \text{ kN/m}^2 = 5.45 \text{ kN/m}^2$$

Simply supported beam

$$V_{\max(\text{end})} = w \cdot l / 2$$

$$V_{\max(\text{end})} = (5.45 \text{ kN/m}^2 \times 5 \text{ m}) / 2$$

$$M_{\max(\text{center})} = w \cdot l^2 / 8$$

$$M_{\max(\text{center})} = (5.45 \text{ kN/m}^2 \times (5 \text{ m})^2) / 8$$

$$\sigma_{\text{sress}} = My/I = 17.04 \text{ kN} \times 0.0936 / 0.000918 \text{ m}^4$$

$$\Delta_{\max \text{ deflection}} = 5 \cdot w \cdot l^4 / 384 \cdot E \cdot I$$

$$\Delta_{\max} = \frac{(5 \times 5.45 \text{ kN/m}^2 \times (5 \text{ m})^4)}{(384 \times 2409857.9 \text{ kN/m}^2 \times 0.000918 \text{ m}^4)}$$

$$= 75.3 \text{ kN/m}^2 \leq 1240 \text{ kN/m}^2$$

$$= 17.04 \text{ kN}$$

$$= 1736 \text{ kN/m}^2 \leq 15000 \text{ kN/m}$$

$$= 0.0199 \text{ m} \leq 0.020 \text{ mm}$$

SATISFIES!

	F _{max}	F _{yield}	dL at F _{max}	dL at F _{yield}	length	h _{overall}	h _{facesheet}	h _{core}	width	A _{surface}	Mass core	Mass facesheet	Mass overall	S _{support distance}	a _{load distance}	F _{core shear ultimate}	F _{yield}	σ _{max} (f)	σ _{facings bending}	Elonga Modulus (E _{0.05} $E_{0.05}$ / (24.dL))	I _{optimized}		
	F _{ultimate}		mm	mm	mm	mm	mm	mm	mm	mm ²	gr	gr	gr		mm	Mpa	Mpa	Mpa	N/mm ²	Mpa	mm ⁴	mm ⁴	mm ⁴
PLAX	8618	738.0	2.7	2.31	200	15	195	111	75	15000	107	19	145	150	50	0.44	0.00	12.66	11.28	2368.95	213.53	6273.03	12795
PLAX	2215.6	702.0	8.0	15	200	15.9	12	13.5	75	15000	141	18.5	178	150	50	1.00	0.00	43.47	41.87	5401.67	384.43	4872.83	10130
PLAX	1594.4	1376.0	2.4	2.0	200	17.6	1.3	15	75	15000	140	18.5	177	150	50	0.65	0.00	25.37	25.08	5895.35	527.34	6483.93	13507
PLAX	674.9	3210	2.7	0.8	200	15.7	1.35	13	75	15000	90	23.5	137	150	50	0.31	0.00	12.27	11.61	4204.98	343.28	5227.79	10798
PLAX B1	2593.4	2348.0	3.3	2.0	190	26.6	2.4	21.8	75	14250	108	35	178	150	50	0.71	0.00	5.16	14.88	705.10	114267.26	26440.20	167147
PLAX	3441.9	2715.0	3.2	2.3	190	24	2.4	19.2	75	14250	155	35	225	150	50	1.06	0.00	8.53	22.13	1001.00	78084.94	21081.60	120228
PLAX B3	5284.0	4775.0	6.0	3.5	190	23.45	2.4	17.65	75	14250	184	35	254	150	50	1.76	0.00	15.29	36.60	1440.22	60643.81	18176.51	96396
PLAX	3372.0	2942.0	3.8	2.1	190	22.53	2.4	17.73	75	14250	132	35	202	150	50	1.12	0.00	9.68	23.27	1490.47	61472.17	18221.16	98114
PLAX	2720.9	2047.0	8.0	1.3	190	20.74	2.4	15.94	75	14250	133	35	203	150	50	0.99	0.00	9.39	20.61	2146.50	44670.14	15222.40	75114
PLAX A																							
average	1336.6	784.3	3.9	1.6	200.0	16.1	1.5	13.2	75.0	15000.0	119.5	19.9	159.3	150.0	50.0	0.6	0.00	10.22	23.6	4932.7	367.2	5715.9	117991
PLAX B																							
average	3482.4	2965.4	4.5	2.2	190.0	23.3	2.4	18.5	75.0	14250.0	142.4	35.0	212.4	150.0	50.0	1.1	0.0	9.6	23.5	1356.7	71823.7	19848.4	111520
PLAX B																							
average	3938.68	3561.50	4.67	2.77	190	24.53	2.40	19.73	75.00	14250	146.00	35.00	216.00	150	50	1.24	0.00	10.22	24.72	1356.66	9593.15	22114.60	53822
											100.00										0.00	0.00	0

V _{facesheet}	V _{core}	h _{facesheet}	h _{core}	M _{weight}	I	b	width	h _{overall}	g	I _x	I _y	E _{facesheet}	E _{core}	I _{core}	I _{facesheet}	I _x optimized			I _{regular}	E _{optimized}	
																Ad2 _{facesheet}	total		ESHEAR	EBEND	
10	2.75	0.0036	0.18	0.567	5	1	0.1872	0.0936	0.000918	0	1700000	3600000	0.0009			3.888E-09	3.0339E-05	0.000918331	0.000546684	2734916.285	0

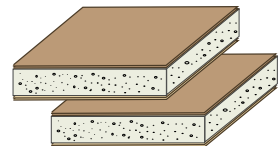
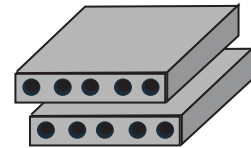
Loads					Load Combination	Line Load	SAFE			SAFE			SAFE	
Dead Load	Live Load						Shear	Bending Moment			Deflection			
Self Weight	Finish	Partition	Imposed	Inst.	F _{core shear ultimate}	V _{max} = w/212	v = V _{max} / IA	F _{tensile} / f _{esh}	M _{max} = w(l ²)/8	σ = M _y /I	δ limit (Eurocode) L/250	δ max (5.w.l ⁴)/(384.E.I)		
0.567	0.75	0.5	2	0	5.45295	5.453	1235.68	13.632	15000	17.04046875	1736.833	0.0200	0.017235633	

Figure 117: Excel documentations of the calculations

5.2 COMPARISON WITH RESIDENTIAL HOLLOW CORE

Table 25: Comparison of concrete hollow core system and PLAX sandwich floor panel. (Morão & De Bie, 2019; Edupack 2023, (Houten Kanaalplaatvloer, NIBE and Kanaalplaatvloer Inc Druklaaf, NIBE)

Materials	Required kg	Estim Price Euro	CO2 kg/kg	Recyclable	B.degrade	Rew.able
Concrete*	246	24.6	0.85	Yes	No	No
Reinf. steel	3.2	3.68	1.10	Yes	No	No
Cement	1.92	5.184	0.90	Yes	No	No
	251.12	33.464	103.5			
Flax	7.2	12.96	0.92	Yes*	Yes	Yes
PLA*	7.2	26.64	0.5	Yes	Yes	Yes
PLA	49.5	148.5	0.5	Yes	Yes	Yes
	63.9	187.38	32.2			



The PLAX slab used in residential systems is being compared with a commonly used alternative, the hollow core concrete slab, which was previously mentioned in the benchmarks section. Overall, the PLAX slab proves to be approximately 6 times more expensive than its concrete counterpart. However, it offers significant advantages: it is 4 times lighter and boasts a carbon footprint that is 3 times smaller. However, PLA has disadvantages such as a low melting temperature and flammability, whereas concrete neither melts nor is flammable. Despite these considerations as potential problems, additional layering could overcome these issues.

Moreover, PLAX's renewable and biodegradable properties distinguish it as a green material choice, enhancing its environmental credentials and positioning it favorably in sustainable construction practices.



5.3 PRODUCTION LINE

The proposed production line of PLAX floor systems is shown in the figure below. The process starts with the simultaneous production of core material and facesheet materials. Once the core is ready, the biobased profiles are attached, and the facesheet is laminated. In the final stage, the premanufactured panels are labeled and prepared for distribution. It is important to have an easy and linear process. A further step-by-step explanation is given on the following pages.

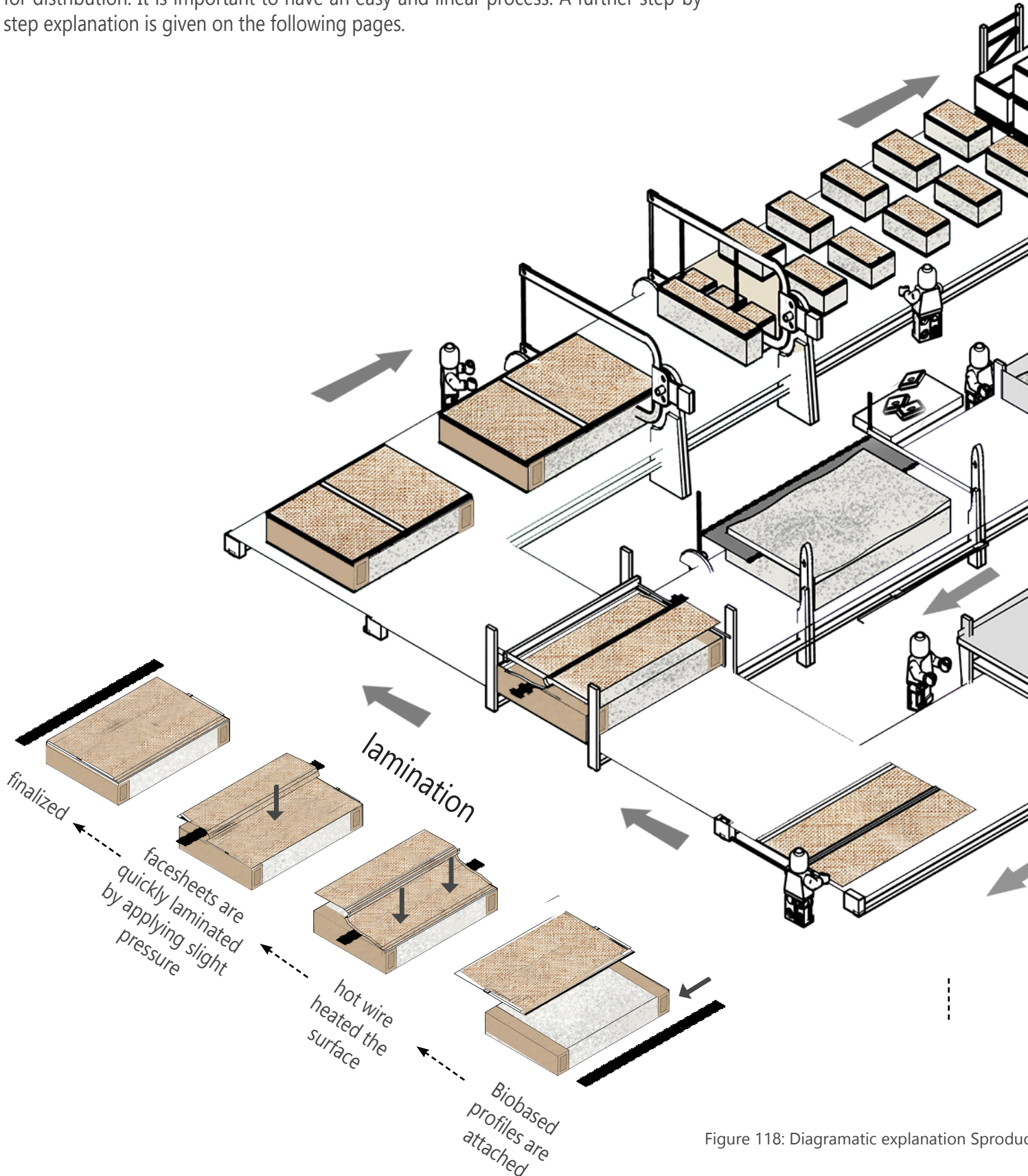
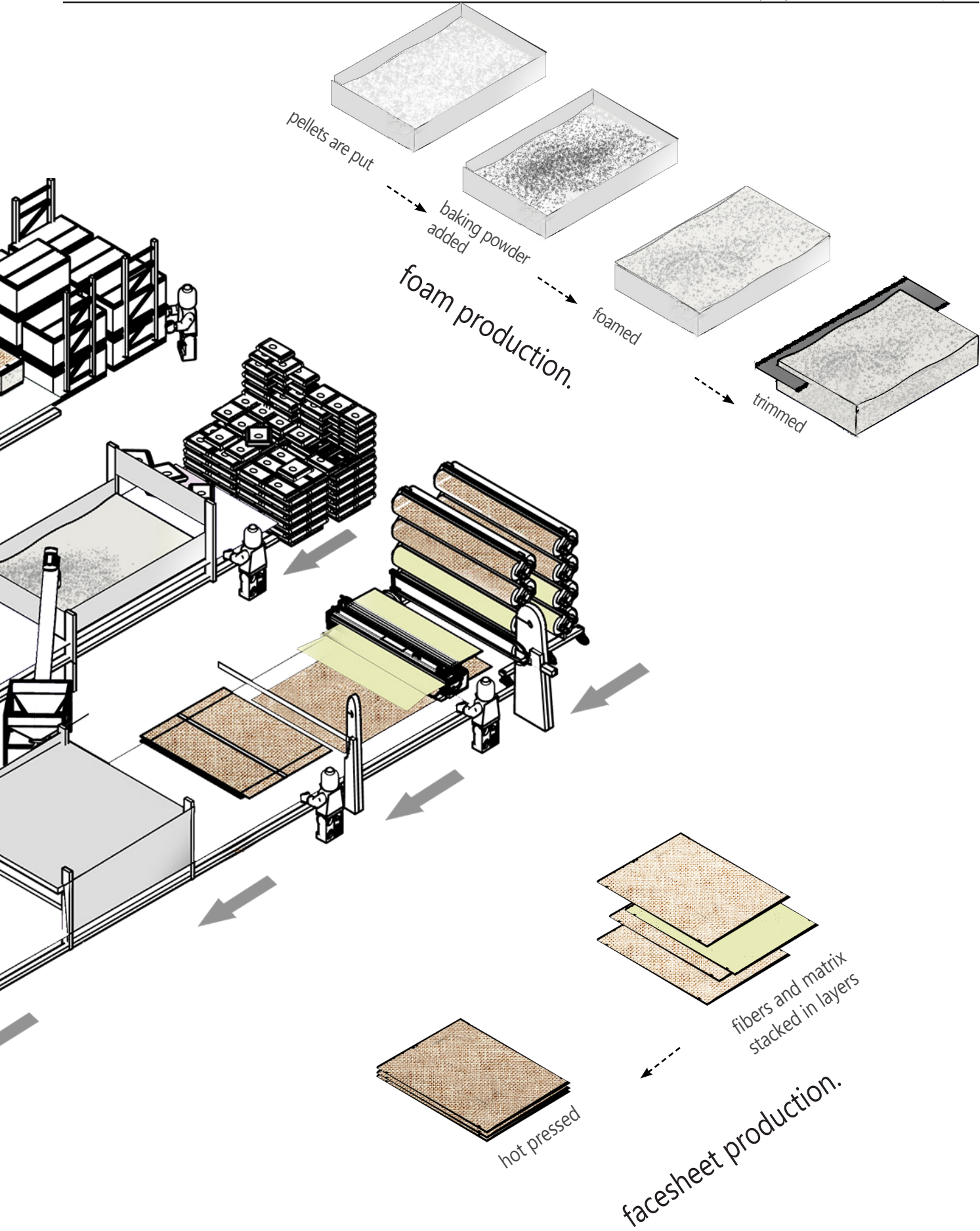
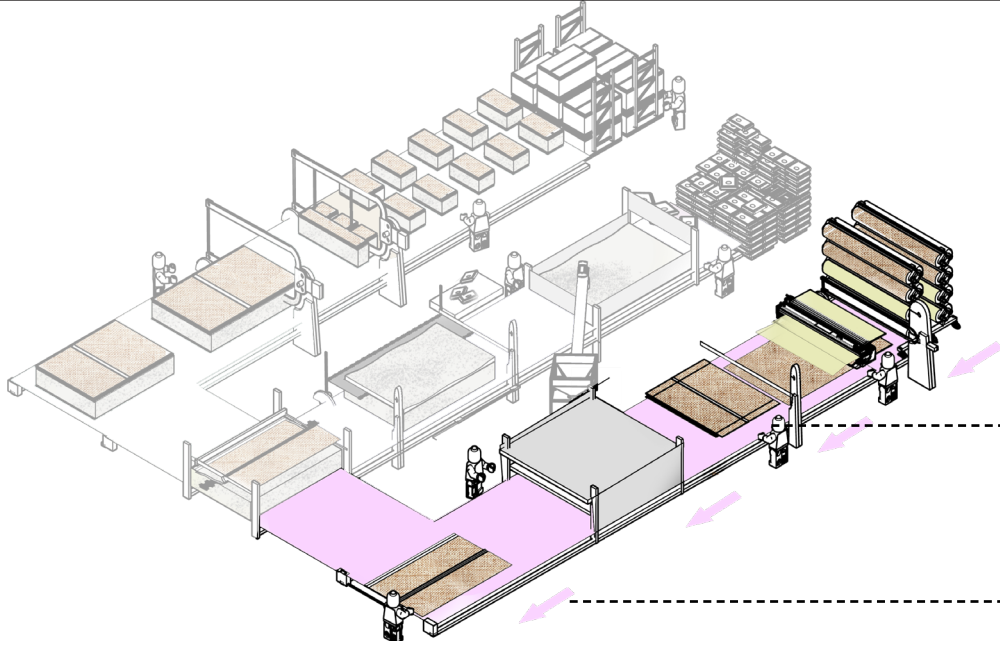


Figure 118: Diagramatic explanation Production

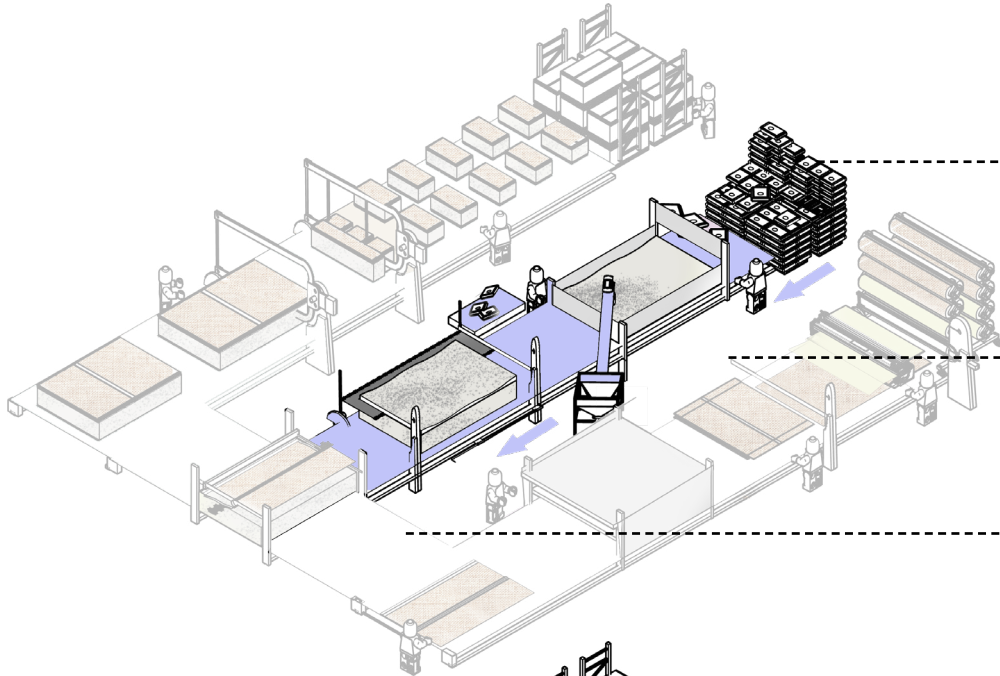


Production line for industrial applications of the PLAX products.

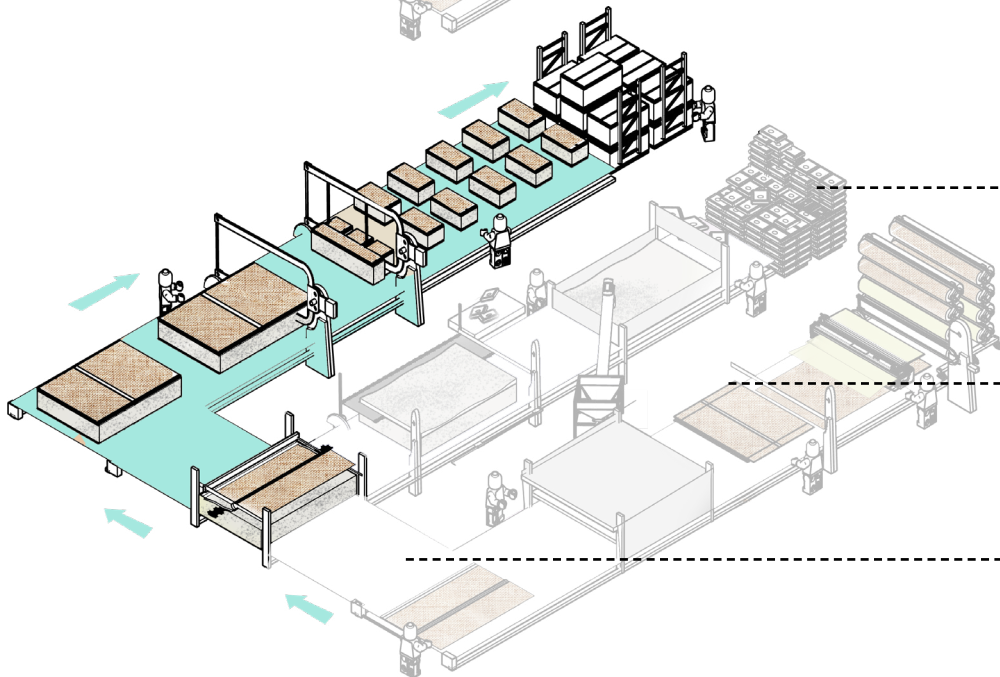
I
FACESHEET PRODUCTION



II
CORE PRODUCTION



III
LAMINATION

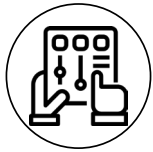




1. PLA/Flax Layering



2. Hydraulic Press



3. Control

STAGE I

The first stage of the industrialized line starts with the production of the facesheet. The layering of the stacking is arranged with the desired fiber mass ratio using flax fibers and PLA films. The materials are then pressed in a hydraulic press at 170°C, first hot and then cold pressed, for a total of 15 minutes. Afterward, the laminated sheet undergoes a quality control check.

Figure 119: Diagrammatic explanation of phase I.



1. PLA melting



2. Foaming agent added

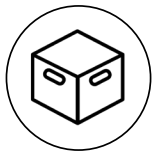


3. Cutting to shape

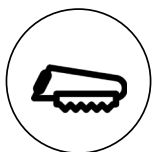
STAGE II

Stage two happens simultaneously with stage I. First, PLA pellets are placed in a large closed container with a heating plate, acting as an oven. The PLA is melted at 170°C for a while, and then the foaming agent is added to foam the material. In the third part, the material is cut into a perfect rectangular shape to create a ready surface for lamination.

Figure 120: Diagrammatic explanation of phase II.



3. Adding the profiles to the sandwich panels



2. Cutting to transport dimensions



1. Lamination with hot wire/blade and carefully laminating

STAGE III

The final stage involves laminating the products from the first two stages. First, the flax/PLA facesheet is heated to its glass transition temperature to make it more flexible for adjusting onto the core material. Then, the core material is slightly cut using a hot wire or blade to locally heat the surface without damaging the core. The facesheet is then gradually rolled onto the core with light pressure applied. Finally, the laminated materials are cut to the

Figure 121: Diagrammatic explanation of phase II.I

5.4. DESIGN PROPOSAL

Overall exploded diagram

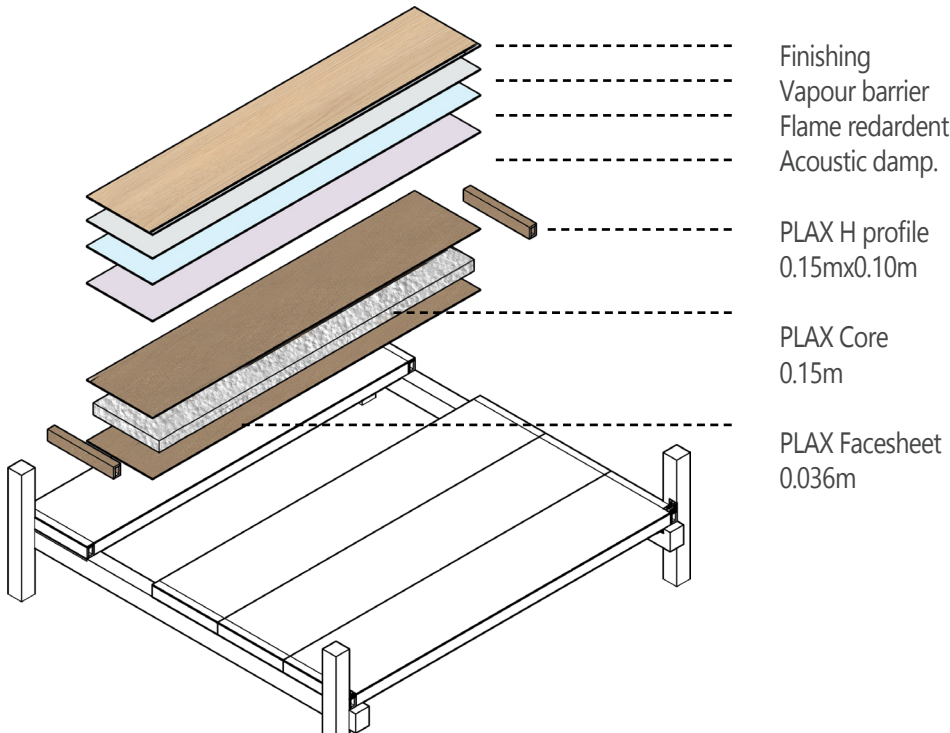


Figure 122: Exploded diagram of the proposed system with layers.

The image on the left represents the exploded diagram of the proposed design. The wood columns span 5 meters apart from each other and are supported by the primary beams. The secondary wood beams span 1 meter, equally distributed along the shorter span of the PLAX sandwich floor panels.

The PLAX sandwich floor panels include additional protective layers such as a vapor barrier, a fire-resistant layer, an acoustic damping layer, and a finishing layer.

PLAX profiles

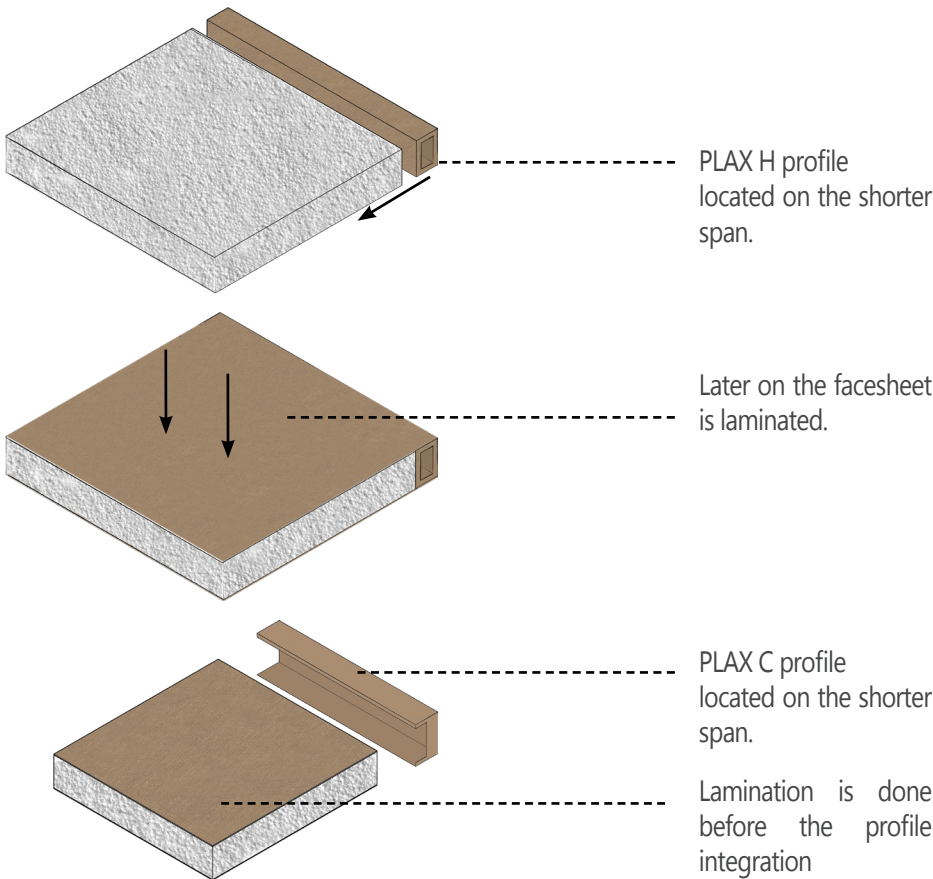


Figure 123: Proposed biobased profiles and explanations.

As the material requires additional details to attach to columns and beams or to each other, a biobased profile is introduced. This profile is referenced from a PhD project at TU Eindhoven (Hannurkar, 2023).

The profile is proposed to be manufactured as an H section along the shorter span of the panel, as seen in the figure on the left. However, different profiles can be configured, and it can be designed in various profiles such as C and L sections, as shown in the images below on the left.

To simplify the manufacturing process, the profile is attached to the core material after production. Subsequently, the flax/PLA facesheets are laminated on top of the entire panel.

Technical details

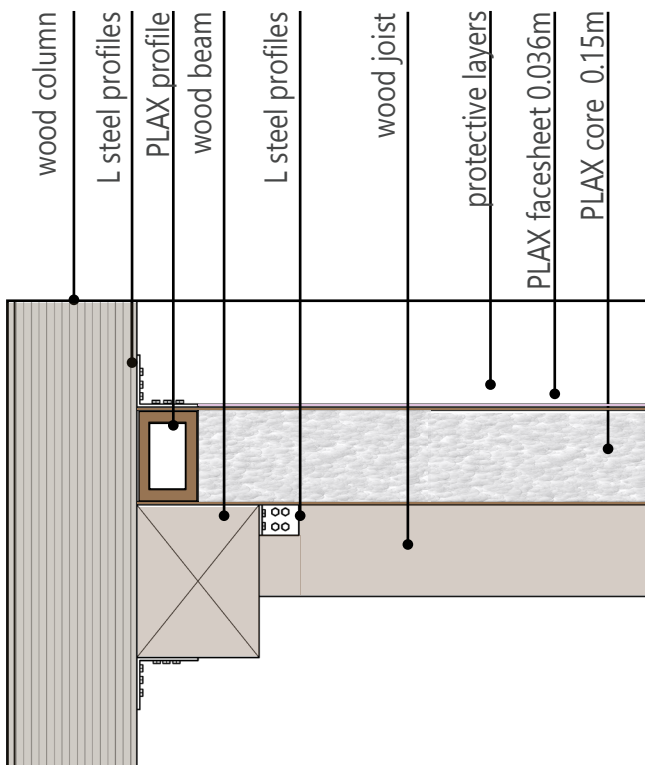


Figure 124: Column to floor detail.

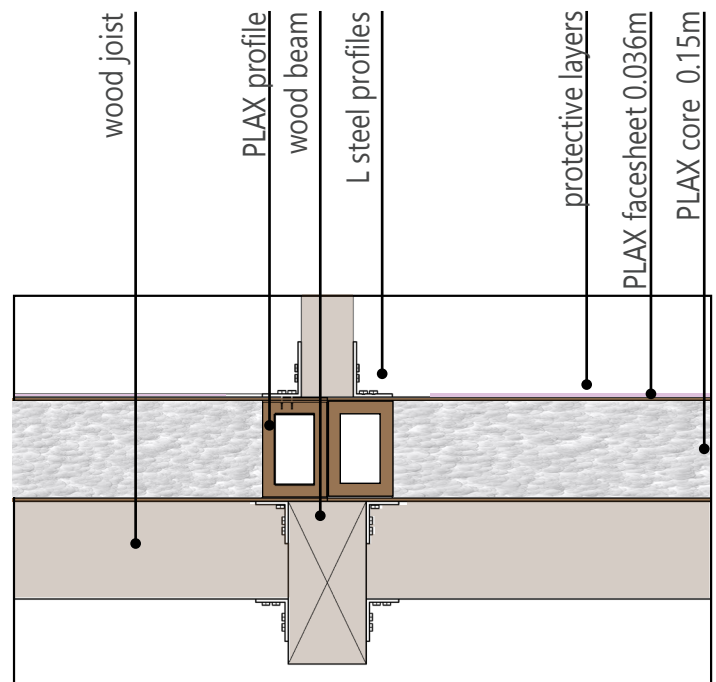
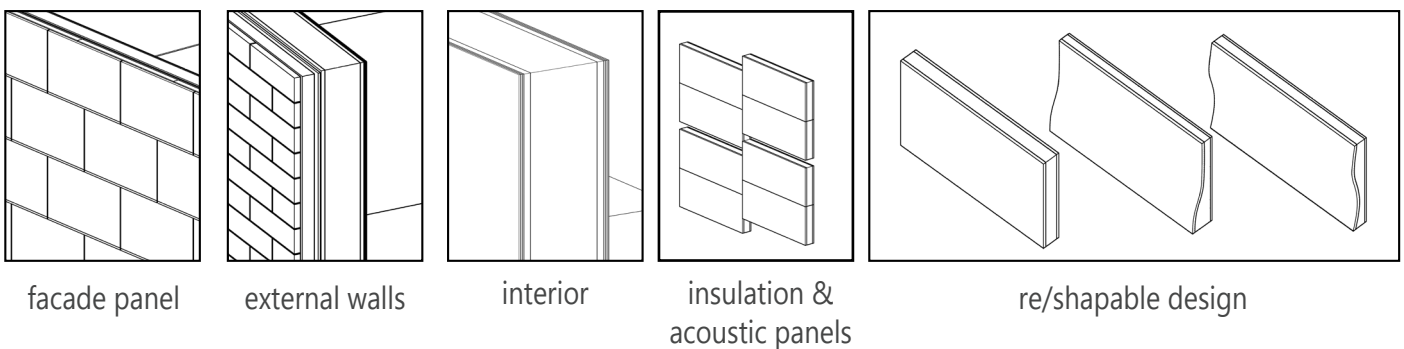


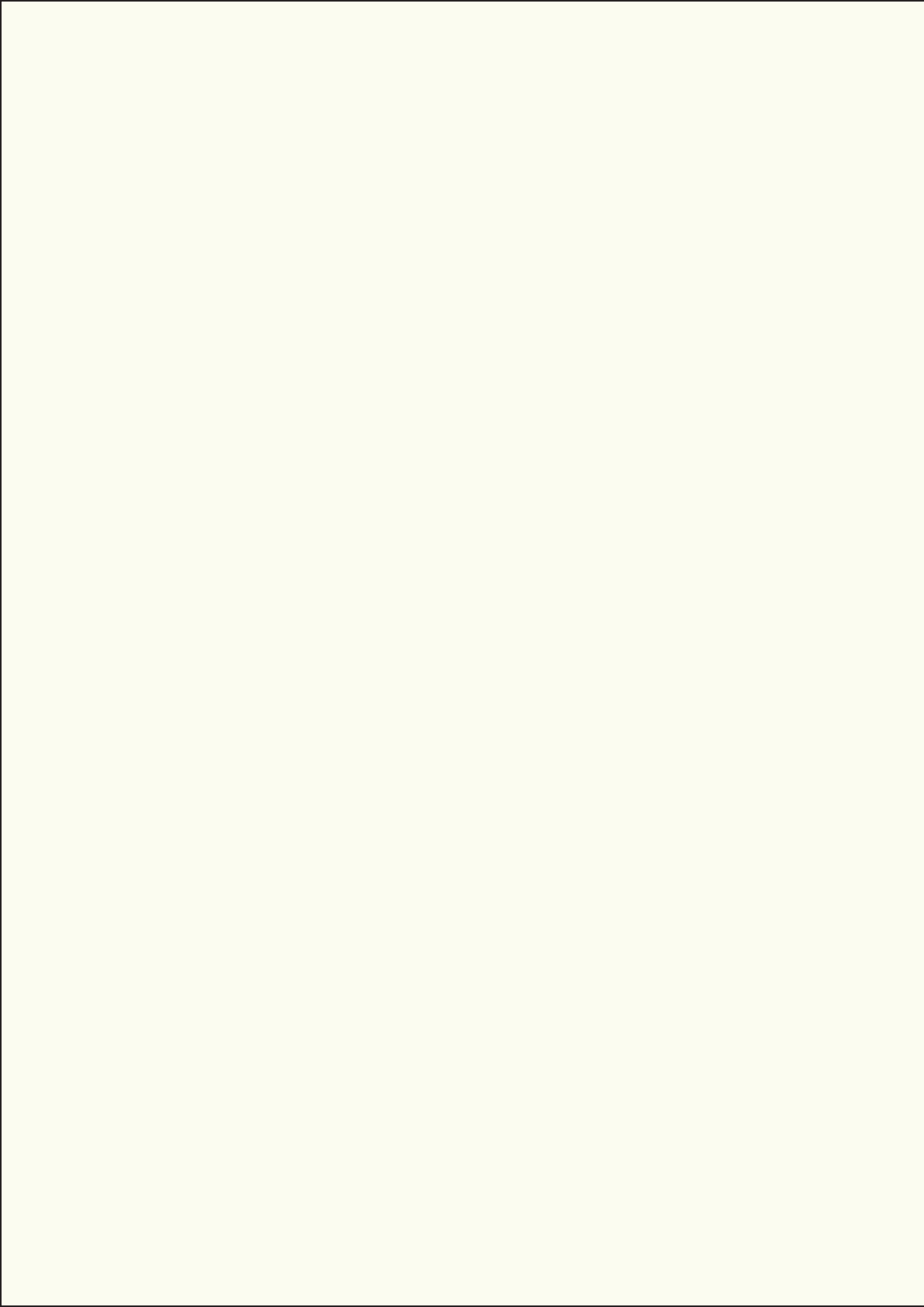
Figure 125: Floor to floor and beam detail.

6.5. POSSIBLE APPLICATIONS



The PLAX material is tested and designed primarily for potential floor applications. However, it also has potential for other uses. With additional structural tests, it could be utilized as a wall system. Additionally, it can serve non-structural purposes such as acoustic tiles and insulation materials, pending further testing. For external wall paneling, the material requires adequate protection due to its low glass transition temperature

The PLAX material is tested and designed primarily for potential floor applications. However, it also has potential for other uses. With additional structural tests, it could be utilized as a wall system. Additionally, it can serve non-structural purposes such as acoustic tiles and insulation materials, pending further testing. For external wall paneling, the material requires adequate protection due to its low glass transition



chapter 6

CONCLUSION & REFLECTION

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6.1 Conclusion on "Design by Experiment"

Design by experiment stage based on finding a novel material that can replace the petroleum based materials. For that research polymers are investigated. Polymers are classified in different categories as biodegradability and their source of origin. For the experiment materials having a source of plant based and biodegradable options are chosen, which are PLA and PHA (fully biodegradable and environmental friendly materials with a plant based and bacteria based origin) as well as the potentials of seaweed has been investigated and its polymers as agar-agar and alginate. Additionally, collected sawdust also included. Total more than 30 samples are investigated and 10 of them has been tabulated in the results section. Foamed PLA, popped corn, sawdust, agar-agar reinforced with seaweed showed great possibilities for the possible usage of being used as a core materials.



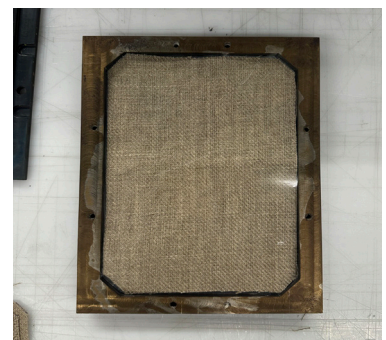
Chosen Material as PLA

As the result of the "Design by experiment" phase, foamed PLA is chosen as the material that will create the core material of the sandwich panel as it possesses the possibilities of having strong properties specifically for shear strength. Additionally, it is easy to produce, and does not require any food-grade material which means it does not take from the food industry. It is recyclable, biodegradable and has a low carbon footprint.



6.2. Conclusion on "Design by Literature"

Design based on the literature involves producing a flax fiber-reinforced composite panel to be used as the facesheet material for the sandwich structure. The methods are referenced from the literature review. Throughout the project, various production methods were investigated, and the optimal method was selected. This involves using four layers of flax with a 50% fiber mass ratio of PLA film, laminated through the film stacking method with a hydraulic hot press machine.



Method Evaluation

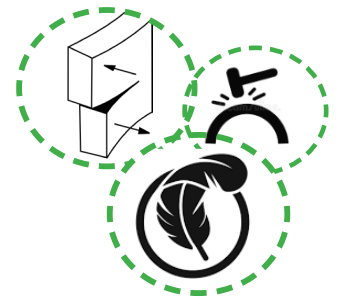
Advantages of the method: It is not labour intensive and as the press machine is considerably easy to use, the lamination process is handled easily.

Drawbacks of the method: The machine used did not have cold pressing, which is assumed the material to be laminated more equally at the end and would decrease



5.3. Conclusion on "Test Results"

Design by testing stage is realized in two stages for two different set of specimens| as PLAX A and PLAX B. For PLAX A total of 4 samples tested and those samples laminated without intruding an additional binder. PlaX B had a total of 5 samples and laminated by using two component binder in order to eliminate the chance of failure due to the binding. HOwever n real production the propal does not have an addiitonal binder. PLAX A samples showed an aeverage of 0.7 MPa shear strength capacity for the core material, while PLAX B almost doubled average of 1.1 MPa. However for the conclusion of the test results, only two samples from PLAX B considered as they are the samples showed a failure in terms of shear crack on the core. However during the calculation and design stage, the shear capacity of the material is considered quite high and less shear capacity could be enough, therefore the thickness and the mass (divided into half) optimized accordingly. For the Young modulus of the overall material, the average of the PLAX B are take

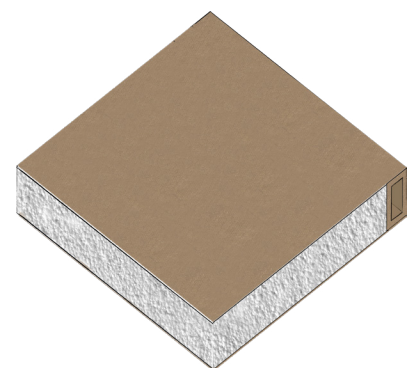


*F _{max} N	F _{yield} N	dL _{Fmax} mm	dL _{Fyield} mm	**E _{modulus} GPa	***I _{optimized} mm ⁴	F _{core shear ult} MPa	M _{bending} nmm
3938.68	3561.50	4.67	2.77	2.4	53822.4	1.24	98467.07

5.4. Conclusion on "Design"

The proposed material, spanning 5m x 1m, was compared to a conventional concrete floor system. For the required load, a PLAX slab with a 6-layer facesheet (each 0.0036 m thick) and a 0.15 m core thickness was found suitable. Although the PLAX slab is about 6 times more expensive than a hollow core concrete slab, it offers significant advantages: it is 4 times lighter and has a carbon footprint that is 3 times smaller.

However, PLA has disadvantages, including a low melting temperature and flammability, unlike concrete. These issues can be mitigated with additional layering. PLAX's renewable and biodegradable properties make it a green material, enhancing its environmental credentials and making it a viable option for those prioritizing performance and eco-friendliness in residential building



6.5 Conclusion on "Overall" properties

Foamed PLA

Source: PLA is a renewable source of fermented plant starch from corn, sugarcane or sugar beet pulp.



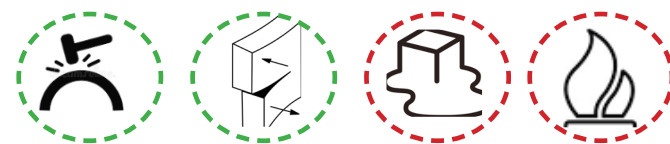
Circularity: The material stands as a circular materials as it's recyable and can be reused, downgrade and biodegrade.



Production of PLA: Production of PLA is environmental friendly, even compared with many plant/wood based products. The embodied energy is 45 MJ/kg (2 timesless then PU and 1.5 times less than naturla balsa core. CO² footprint is 2.3 kg/kg (2times less than PU but 1/5 of the balsa core), and water usage is 20 l/kg (15 times less than PU and 35times less than balsa core. Price of PLA is not very high but not very low either, as 1 m³ PLA is between 3700 Euro, 4Euro per sqm.



Mechanical properties: PLA exhibits great mechanical properties, with a E of approximately 3 GPa, a tensile and compressive strength, of around 60 MPa, and 70 MPa respectively (Edupack 2023). The calculated shear strength is 1.24 MPa, making it suitable for core applications. However, PLA has a relatively low glass transition temperature of around 53°C and a melting point of about 170°C. While these characteristics facilitate easy production without the need for high temperatures, they might limit design options due to the material's flammability. Nevertheless, if the material is not exposed to external conditions, these limitations



FLAX

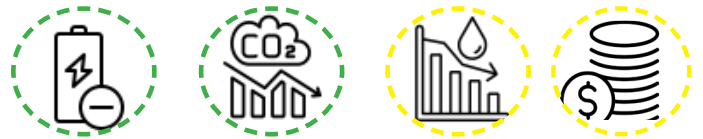
Source: Natural fiber renewable plant fibers.



Circularity: The flax is a circular material as it is fully biobased plant based material.



Production of Flax: Embodied energy is around 55 MJ/kg (similar to PLA and glulam, 12 times more than concrete and 1.5 times more than steel), and have less carbon footprint as 0.9 kg/kg (less than PLA, 4 times less than steel but 2.5 times higher than glulam), however required more water usage as 330 l/kg (2 times less than glulam). Even though for CO² footprint and energy consumption is higher for flax, the required amount of material is less for the production making it a sustainable choice.



Mechanical properties: Flax fibers exhibit excellent mechanical properties, with a Young's modulus of approximately 70 GPa, and tensile and compressive strengths of around 850 MPa and 70 MPa, respectively (Edupack 2023). For the facesheet, the referenced tensile strength is 125 MPa, and its Young's modulus is 1.25 GPa. Since the material is matrixed with PLA, it exhibits low glass transition temperature properties. Additionally, the material is considered flammable.





6.6 Conclusion on building Industry Benchmarks

Goals

Product 80%

Reduce the embodied energy by 40%, the material of the floor system. Embrace natural materials, increase recycled content, use low VOC materials, use renewable resources and carbon neutral materials.

Maintenance 14%

Decreasing the need for maintenance for three main topics as, easily detachable for reduced energy; modular and easy to maintainable pieces; longevity and efficiency.

Transport 5%

Decrease the effort for transportation by handling efficiency using smaller products to reduce energy and use local sourced materials.

Construction 1%

Ease of Construction, Favour easily constructible materials with dry connections
Maximise material utilisation to minimise waste.

End of life 1%

Prioritise materials conducive to biodegradation, avoiding chemical-laden connections. Avoid synthetic resins that hinder recyclability, proposing reuse or recycling.

Result

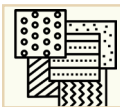
Renewable resource, low carbon materials used.

Protective layers needed.
Detachable connections are provided.
Longevity unknown.

Locally sourced materials

Pre-manufactured materials with dry connections.

Recyclable and environmental friendly end-of-life options.



6.6 Conclusion on material based benchmarks

Goals

Material Supply

Minimise material usage to prevent stock shortages, excess material usage, energy consumption, and a larger carbon footprint during production.

Climate and environmental systems effect:

Decreasing the need for maintenance for three main topics as, easily detachable for reduced energy; modular and easy to maintainable pieces; longevity and efficiency.

Product Life Span

Durability: material with an extended lifespan to ensure longevity.

Strength-to-Weight Ratio

Lightweight High-Strength Material: Choose a light material with high strength to minimize weight and material usage while maintaining structural integrity.

End of life

Renewability and Biodegradability: Material's renewable sources and biodegradability at end of life. Environmental impact from extraction to disposal.

Result

Lightweight material, with less material production.

Easily detachable connections with biobased profiles.
Longevity unknown.

Protective layers needed.
Longevity unknown.

Lightweight.
Great ratio for facesheet
Not very high ratio for core.
Further test needed.

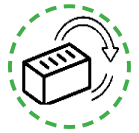
Recyclable and environmental friendly end-of-life options.

6.7 CONCLUSION

The world is currently facing a significant global warming issue, with a high carbon footprint, and the construction industry stands out as one of the major contributors to a significant percentage of carbon emissions. This is primarily attributed to the usage and production of materials. Upon closer examination of buildings, it becomes evident that floor systems constitute a substantial portion of the construction within buildings. Essential structural components, such as concrete and steel, along with small-scale building materials used across diverse applications, are major contributors to high carbon emissions. These materials are primarily non-bio-based, emit unhealthy gases during production, and have limited sources. Therefore, the research gap arises as "What are fully-biobased structural materials?"



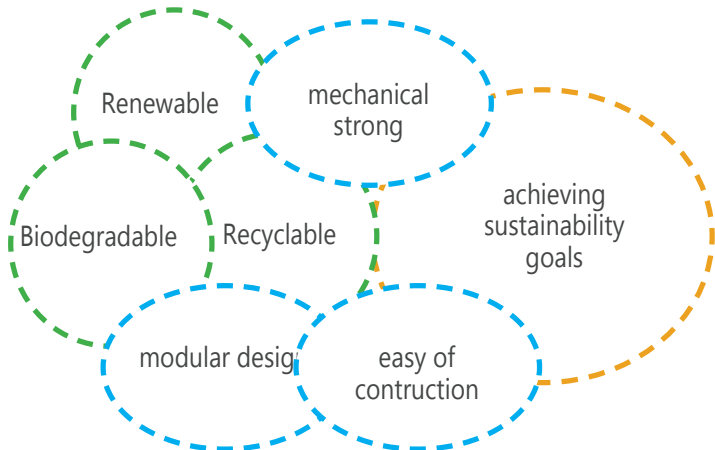
Research Framework: To address the research gap, the approach towards building materials must shift towards the investigation of "**green materials**" and mechanically capable of resisting necessary loads. Green materials is referred as materials that are fully-biobased, recyclable and biodegradable. "Sandwich floor" panels stands as a promising building component type to go further than the conventional materials. Therefore the research question formulated as



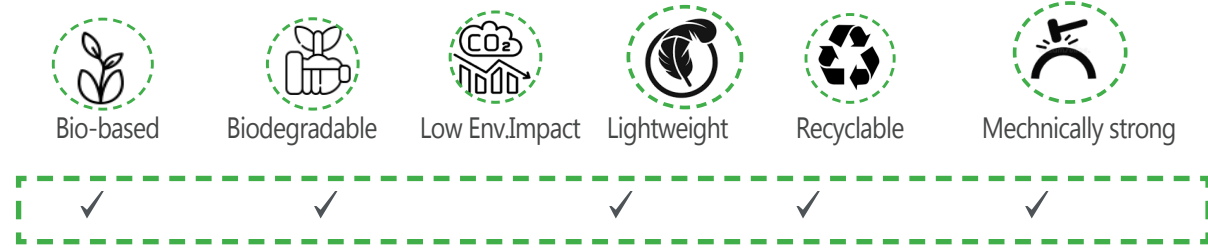
"Could a novel biobased sandwich flooring outperform conventional flooring systems"

To answer the research question, a research methodology is formulated as 3 stages;

- 1. Design by experiment :Novel material finding as the core materials.
- 2.Design by literature :Production of a biobased facesheet
referencing the literature review.
- 3.Design by testing :Confirming and analyzing the results
- 4.Design from findings :Desinging through results



- 5.Turnign back to research question :
"Could a novel biobased sandwich flooring outperform conventional flooring systems"



- 6. Conclusion
YES, a novel biobased sandwich flooring outperform conventional flooring systems.

6.8 FUTURE WORK

The research holds a vast opportunities to be research as a future work.

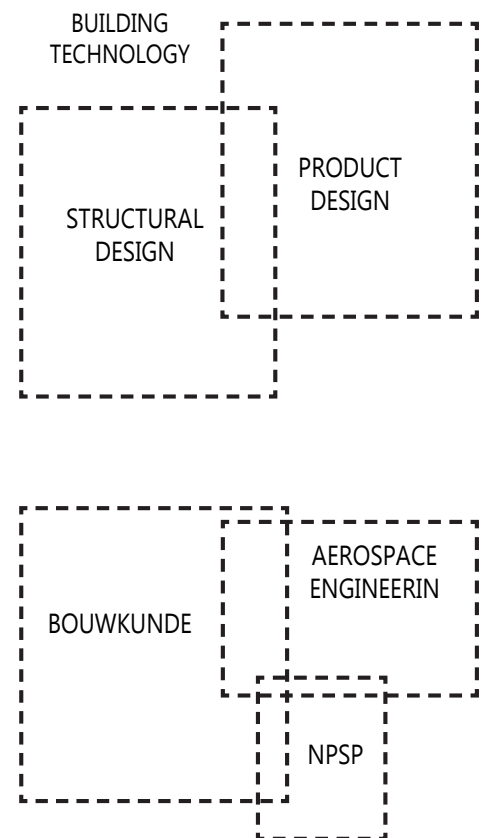
- Introducing an easy laminating method and testing it to evaluate the performance of the material with the most optimal "fully-biobased" approach.
- Conducting separate tests for the core material to understand its shear properties, as well as for the facesheet's flexural properties to obtain more accurate results without assuming certain values.
- Performing more tests to validate the results for large span of the panel. Additionally, have different mechanical tests to explore the potential of using the material as different load-bearing building components such as columns, beams and wall systems.
- Investigating the acoustical and thermal insulation properties of the core material.
- Advancing the design idea with the proposed biobased profile to achieve a more easily detachable and pre-manufactured system that can be attached to various building types.
- Conducting a "Life Cycle Analysis" to assess the longevity and durability of the material. Additionally, developing end-of-life scenarios, as the material is recyclable and has the potential to be reused. Testing recycled materials will provide insights into how the material performs after recycling and the extent to which it can be upcycled.

6.9 REFLECTION

Academic Reflection: This thesis project aims to address a research gap in the current literature concerning green, natural reinforced composites that are lightweight, biodegradable, and mechanically capable of withstanding the required load for a floor system. The topic, 'PLAX: Bio-based Floor System,' is positioned within two different chairs in the Building Technology studio, Bouwkunde: structural design and mechanics, and product design. While both chairs are closely related to material choice, the structural and mechanical chair aims to design a floor system capable of withstanding loads properly with great tensile and compressive strength, proven by further testing of the product. More emphasis is placed on the product in terms of methodology/testing choice and the efficient design of the floor system. For the product design part, the focus lies within Building Technology and the department's previous research.

Production mostly occurs at Aerospace Engineering, Bouwkunde and NPSP. This sometimes leads to minor issues such as difficulties in scheduling arrangements. On the other hand, interdisciplinary collaboration has made the project more collaborative. Personally, engaging with individuals from different backgrounds has increased my understanding of the project's objectives, the differences between various industries, and the possibilities of composite materials. Results highlights that they are many options that can be investigated as a bio-based option to reduce the carbon emission as well as to replace the petroleum based materials.

The process demonstrates a clear purpose and end goal, focusing on environmentally friendly materials, interdisciplinary collaboration, upcycling, and bio-based materials. There are significant opportunities for innovation in green materials, further collaborations, and industrial adaptation. However, limited equipment access and non-linear progress due to insufficient methods have posed challenges. Despite these, the overall process has been quite efficient.



Sociocultural Reflection:

The research aimed to develop a potential floor system made of green materials by means both biobased and biodegradable having non-toxic and renewable resources, with mechanical properties equal to or better than traditional materials. Throughout each phase, the most possible and sustainable approach has been tried to be adapted. To align with the sociocultural and sustainability goal, the product is aimed to pass through benchmarks of different approaches in Europe as well as UN Sustainable Development Goals:

UN Sustainable Development Goals:

- Goal 9: Build resilient infrastructure, promote inclusive and sustain. industrial. and foster innovation"
- Goal 12: Ensure sustainable consumption and production patterns"
- Goal 13: Take urgent action to combat climate change and its impacts."
- Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable develop."
- Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and

LETI 2023

- Avoid: Avoid to usage of petroluem based products.
- Shift: Shift to sustainable and environmental friendly products.
- Improve: Improve the building industry and wellbeing of the people.



"A new way for architecture":
Only biobased materials: IS IT A POSSIBILITY?

*shifting the
architecture!*

Throughout any phase of the thesis research the sustainable and circular approach is tried to be adapted. The main focuss of the project was to identift product lifecycle, efforts are made to minimize carbon emissions, thereby promoting healthier environments and offering local, long-term cost-effective solutions. This initiative is also a step towards reducing the risk of global warming and achieving net-zero emissions. Therefore utilizing not only biodegradable or renewable but an approach to both is an important to step to be taken. This approach needs some shifts in the architectural approach effective socio-cultural structure of the current conditions to lead healthier environment as well as to raise awareness of the necessary shift in architecture towards "green construction industry".

Refuse Non-Biobased Materials

Refusing all non-biobased materials may not be realistic immediately. However, it is a promising approach and one that we need to adopt.



Make it affordable

Initially, these approaches might be costly due to the limited availability of non-industry-based materials. However, this is believed to be a short-term problem. As biobased materials become more readily available, their accessibility will also increase, as they do not require extensive processing.



Adapt

Adapting to a fully biobased approach might present some challenges, such as requiring thicker building components. Initially, this might seem difficult since some current materials allow for thinner structures. However, this should not be a significant problem if sociocultural adaptations occur.



Improve

As with any approach, the fully biobased method can be improved. After adopting this approach, there is always room for further enhancement. Therefore, materials can be improved in terms of efficiency, strength, and properties.

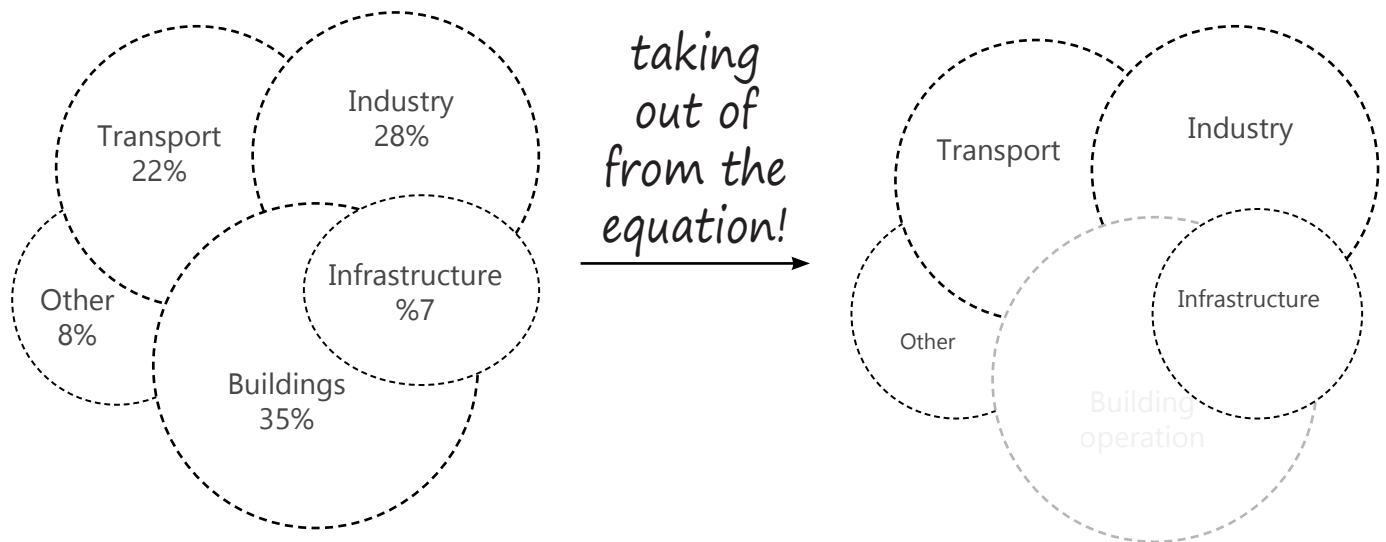
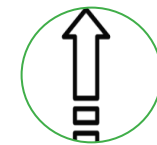
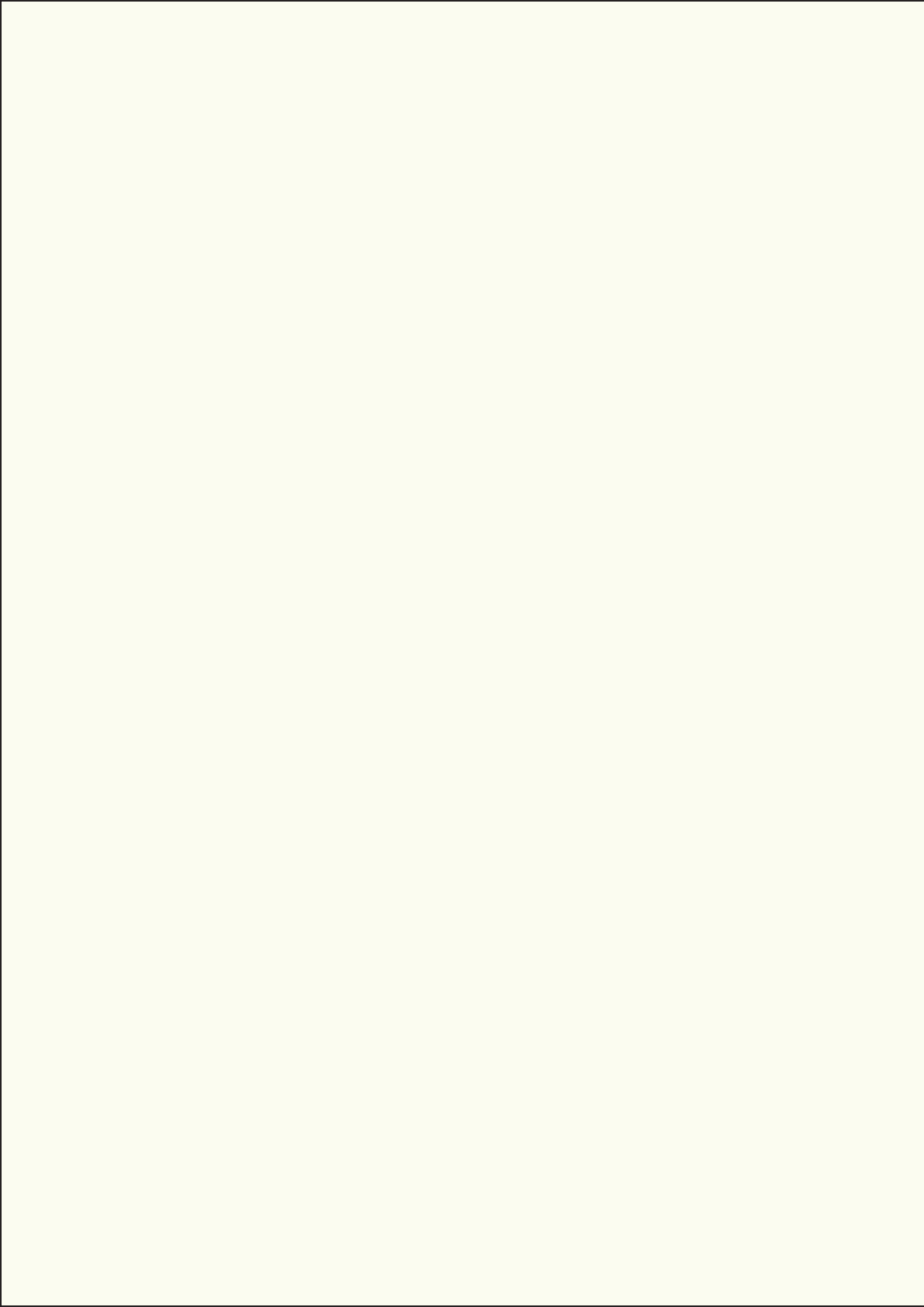


Figure 126: Carbon emission by industries. Left side; industry based percentages. (Why Buildings, Architecture 2030; ISA; Statista)

Going green, increasing sociocultural awareness.

As a result of the research, the possibilities of bio-based materials have been explored. Although some approaches might show difficulties in adaptation at first, this is not necessarily negative, as every change involves a challenging adaptation process. Additionally, the research highlighted the potential of a fully bio-based environment, which leads to healthier, carbon-neutral settings, thereby addressing the urgent problem





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