Bio-composites from Food-waste

Exploring the impact of waste sourced fillers from the food industry on the functional and mechanical characteristics of bio-composites for a possible application as a façade product.

Master Thesis Report

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Abstract

This report explores the potential of integrating waste-based fillers from the food waste industry into bio-composites for facade applications.
The limited use of waste materials in building products, combined with a rising demand in sustainable materials, leaves the opportunity for new fully bio-based building material from underutilised by-products. The approach involves integrating organic waste as granular filler into polymeric composites.
The methodology consists of a literature review and three experimental phases: identifying and evaluating various food waste sources for the use as fillers, optimizing grain size and composition of the recipe, and assessing the best-performing filler combinations in facade panel designs regarding sustainability and structural merits.

Spent coffee and walnut shells were identified as promising fillers, while the shells of cacao beans, de-oiled coffee grounds and cherry pits did not perform well as fillers. The walnut shell composites, especially those with 55% filler of a blend of different grain sizes, resulted in the most promising balance between of mechanical properties and filler content.

The results indicate that walnut shell-based composites exhibit promising structural characteristics and a lower carbon impact compared to conventional facade materials. However, further research is required to explore their potential in other applications. This project illustrates the viability of using bio-composites with waste-based fillers in building products, presenting a sustainable alternative to traditional materials.

Acronyms

BMC - Bulk moulding compound; **C2G** - Cradle-to-gate; **EOL** - End of life; **PHA** - Polyhydroxyalkanoates; **PLA** - Polylactic Acid; **PP** - Polypropylen; **SLS** - Serviceability Limit State; **TPS** - Thermoplastic Starch; **WPC** - Wood-plastic composite

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1. Introduction

In the first chapter the topic is introduced and an overview of relevant parameters of this thesis are given. It formulates the research framework, methodology, and the objectives of the study and discusses the reasoning for the choice of topic.

1.1 Context

Vision: Using Waste in Building Products

What if the "waste" we generate as a society could be viable material for building houses?
In the pursuit of circular value chains, the integration of waste into the building industry is a topic that is fascinating and holds a large promise for addressing several modern sustainability challenges.

With the need for more environmentally friendly building materials, one of the challenges is the limited availability of renewable material sources due to the high demand and slow regeneration.
Due to climate conditions and geographical limitations, a local production of natural growing materials is not always possible thereby resulting in long transport distances.
Therefore one of the biggest challenges of the 21st century is to build with less, to use the resources at our disposal and to apply them in a smart way.

If we could make building products from waste, we could mitigate the need for waste treatment, reduce waste that goes in landfills or is incinerated and gain building mass without burdening the environment with the extraction of virgin grade materials and the emission of greenhouse-gases associated with the process.

But which waste can we use, how can we integrate waste into building materials and what can we make with it? There are likely many answers to these questions. This project will explore one possible way by the investigation and selection of a number of local waste flows and the systematic exploration of how to apply them in practise in a composite facade panel application.

Introducing Bio-Composites

Bio-Composites first emerged in 1908 in an attempt to make a material from lignocellulosic fibres and bio-based resin (Jawaid & Abdul Khalil, 2011).
The broad field of bio-based composite materials has a large potential for customisation and material choices tailored to the applications needs, which is why, since the 80s, the development of composites from partially or even fully bio-based sources has gained traction for many industries (Riedel et al., 2001).

In the search for low carbon and resource efficient materials, bio-based composites have the advantage that, unlike other bio materials, they can include smaller scale organic material like chips, fibres or powders which enables the use of local waste material, leftovers from production or residual flows from processes outside of the construction industry, which is ideal for this projects pursuit to utilise local organic waste.

The employment of organic by-products instead of mined or farmed new material is also advantageous economically and can reduce the cost of a composite significantly (Rodríguez et al., 2018).

Which waste could be used?

The abundance of different waste-producing sources in the anthropocene is huge. To find a fitting source for the integration into composites, the waste has to be solid matter, granular or fibrous and locally available.
After a screening of the Dutch waste landscape, two sectors emerged: the textile industry and the agriculture-food sector.
After some consideration the bio-based waste from the agri-food sector became the subject of investigation (further explained in section 2.7).

The Application

Building products have a wide range of different requirements on either their mechanical properties, functional performance or aesthetic value, depending on which role they fulfil in a building.
Alone within the layers of a facade, each layer fulfils specific demands. Applying a new material to its full potential requires balancing its properties with the demands placed upon it, as well as having a repair or replacement plan that aligns with the building product's durability and the accessibility of the installation.
In this project the waste based bio-composite is designed to be used in rain-screen facade panelling, which requires high functional qualities. With a possible evaluation on the usefulness of the proposed composite in this context, more use-cases might be considered in the future.

1.2 Research Framework - Research Gap

Defining the Research Gap

Waste use in Building Products:

The use of construction waste and reclaimed materials has long been practised in the building industry, including the direct reuse of building components and the integration of crushed waste concrete or masonry brick into new building elements.
Less explored is the use of other waste sources. Even though some possible options are discussed in studies (Welink, 2014, Erkliğ et al., 2016, Raut et al., 2023), the field leaves room for further exploration.

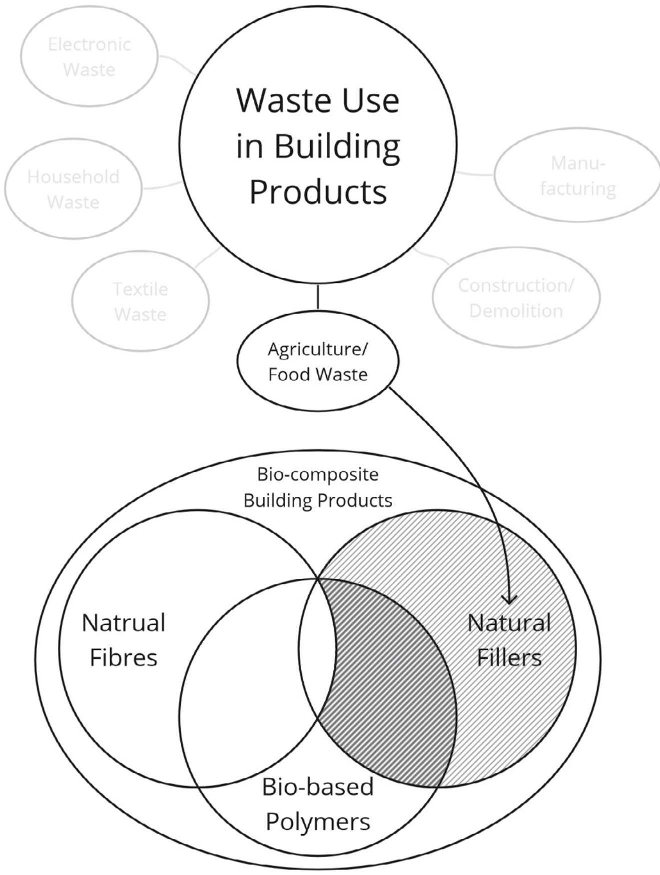
Research on Bio-composites:

Polymeric composites area composed of a matrix which contains fibre reinforcement, granular fillers or both. A material can be calle bio-composite when the ingredients are partially or fully derived from bio-based matter.
While there is abundant research focusing on natural fibre reinforcement in composites (Ho et al., 2012; Jawaid & Abdul Khalil, 2011; Ramesh et al., 2017) and considerable development in new bio-plastics (Clark & Macquarrie, 2002; do Val Siqueira et al., 2021; Murawski et al., 2019), there remains a significant gap in research concerning bulk fillers within composites.

Bulk fillers hold substantial potential to impact the carbon balance of materials, as they often constitute a significant portion (about 40-65%) of mass (American Composites Manufacturers Association, 2016). Conventional bulk fillers, such as minerals that are added into polymers and elastomers, are readily available and cost-effective. However, they typically contribute to resource depletion and environmental damage through their extraction processes and can not always be sourced locally (Pukánszky, 2001).
To overcome this, fillers form organic waste might be viable solution.

Renewable Material sources:

Of further concern is the limited extent of knowledge about fully bio-based composites that do not rely on any mineral fillers or synthetic matrices. Many established materials like wood-plastic composites (Sommerhuber et al., 2017) or laminated particle boards achieve only partial renewable material origin due to their adhesives or fossil based polymer matrix.

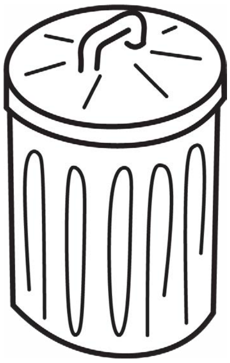


In summary, the incorporation of waste material in building products leaves room for exploration.
With substantial gaps in the roadmap for bio-composites within the building sector, waste based filler present a significant opportunity for further development.

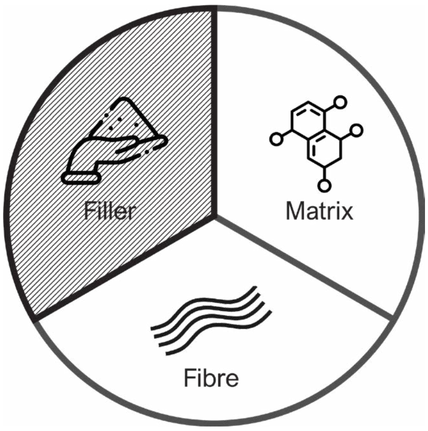
In research and practise, there is plenty of development of natural fibre based composites but no focus on the use of bio-based granular fillers, even though there is a large potential for improved sustainability of the product. This is mainly due to inexpensive mineral alternatives.
Therefore the aim of this project is to develop a fully bio-based material targeted at specific applications, such as facade panelling, with a primary focus on incorporating waste-based fillers.

1.2 Research Framework - Focal Points

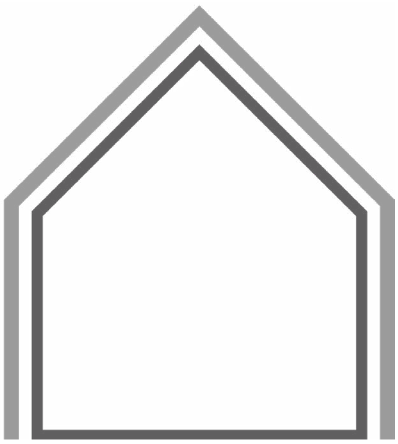
Source Focus: Waste
With resources becoming rarer, utilising waste material addresses both environmental and economic concerns. By re-purposing waste materials with less or no economic value into higher applications the residual properties of the material are utilised instead of wasted and therefore their life-cycle is extended. At the same time, by absorbing a waste-stream the reliance on virgin resources is minimised and new revenue is generated while contributing to a circular value chain.



Material Focus: Fillers
Bio-composites are usually composed of three mayor ingredients: The polymer matrix and fillers, and/or fibres. This study focuses on the granular bulk fillers.
Bulk fillers mostly are used to reduce price of composites and increase the dimensional stability (Hammiche, 2022).
Depending on the medium and application, additives bulk fillers can make up a significant portion of the composites weight and volume and therefore have a large impact on the materials sustainability and price.



Application Focus: Facade
For the application of engineered bio-composites, many building products are imaginable.
In this project the goal is to create a material for rain-screen facade panelling. In a functionally layered building envelope, the out-most facade cladding with non-structural demands presents a fitting used case for this experimental material exploration.
Moreover, the choice of facade panels aligns with the effort of introducing bio-based aesthetics into the urban environment.



1.2 Research Framework - Problem Definition

Problem Statement

With the construction sector contributing 39% to global carbon emissions (Crawford, 2022), there is a critical need to reform the industry by developing sustainable building products and integrating circular material flows.
As a result the demand for natural resources in construction rises, which makes the exploration of alternatives to virgin-grade materials become more relevant.

Exploring plant-based bulk fillers for bio-polymer composites offers a promising opportunity to address these challenges and might lead to low carbon material alternatives to conventional products.
Leveraging waste streams could give new purpose to currently unused by-products, conserving other resources.

The problem statement can therefore be phrased as the following:

> “ ***The use of organic waste sources as a resource efficient option for bulk-material in bio-based composites remains under-explored. Additionally, the feasibility of bio-based matrix/filler composites in a matching functional setting has yet to be established.*** ”

Research Questions

This research focuses on the discovery and implementation of waste-based bulk material as a filler in bio-based composites. The main goal is to develop a partially waste-based composite, fit for the use in rain-screen façade panelling. By research by design, waste options are experimentally tested optimised and evaluated on their functionality, circularity and architectural potential in a composite.

The Main Research Question is:

> “ ***How to integrate waste-based fillers into bio-based composite façade panels?*** ”

Secondary questions are:

- Which waste **materials** are available and useful for the use in a composite facade application?
- How does the material **recipe** influence mechanical and functional properties of the bio-composite?
- How do the **manufacturing** method and design choices factor in?
- What **limitations** for the design process are imposed by the material choices?
- How does the resulting facade product compare to established products on a functional and circular level?

1.2 Research Framework - Scope

Scope of Research

Material Potentials and Limits:
With the investigation of waste-based sources for such fillers and the experimental exploration of parameters of implementation and design, the hope is to find the best balance within the objectives of functionality, sustainability and architectural demands.

Function:
The approach of designing for the application of a rain-screen facade panel aims at making function based choices for the engineered material. The goal is to explore the benefits, limitations and options for adaptation of the newly composed material.

Ethical Use:
With the goal to develop smarter materials and building products that fit into a circular economy (see section 2.2), the two main concepts of sustainable development in construction should be followed:

"*1. Resources are not to be used at a rate that depletes the supply long term.*
2. Residue should be generated at a rate no higher than what the natural environment can assimilate."

(Clark & Macquarrie, 2002)

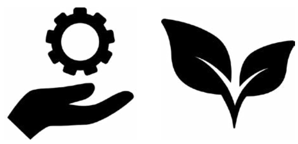
The investigation of possible waste-based filler materials is limited to materials that have no "better" alternative use and are sourced as local as possible to reduce emissions in transport.

Objectives

The quest of this thesis is to find promising waste-flows by established selection criteria based on literature and concept development.

For a selection of waste materials, their usefulness and compatibility as a composite filler material is being evaluated.

Next several parameters in the material design stages are fitted to yield the best results in terms of functionality, feasibility and sustainability.



The narrowing down of the material selection in each step and the adjustment of parameters in the material composition will lead to the "best" engineered material within the boundaries of this project. Additionally, the process allows for insights into universally applicable rules for the use of waste materials in composites and ways of implementation.

This research intends to probe whether a selection of waste flow qualifies for the use in an engineered bio-composite that can be used in façade panel applications.

Boundary Conditions

- A **selection** of waste-flows has been made based on capacity of this project and by availability of the resources.
- The research is limited and directed by **available methods** of production and materials.
- Some factors and calculations are **simplified** to give a reasonable indication for effective decision making.

1.3 Methodology

Literature Research

The literature research is divided in three parts and is the base for the choice of materials that are used, as well as for the design of experiments.

The first part includes the general relevance of bio-composites and previous studies on waste-based and other bio-based fillers.

Secondly, by identifying mayor sources of organic waste in the Dutch context, the structures of industrial waste production and a priority scheme for use-cases and waste sources potentials for the planned application are defined and selected for further investigation.

The final part of the literature review focuses on the application as facade panelling. The tests for the experimental phase are chosen by the desired properties for the panelling. Topics of interest are studies on bio-based fillers regarding their performance with varying size, volume and in relation to the composition with the matrix. Also, the methods of manufacturing and testing are looked at and how they could influence the resulting product.

Experimental Testing

In three experimental phases were undertaken to explore three different objectives (see experimental layout). Each phase has specific evaluation criteria based on the objective. Based on the outcome of the experiments of a phase, in each step the number of choices is narrowed by the results of the previous steps.

Assessment Criteria

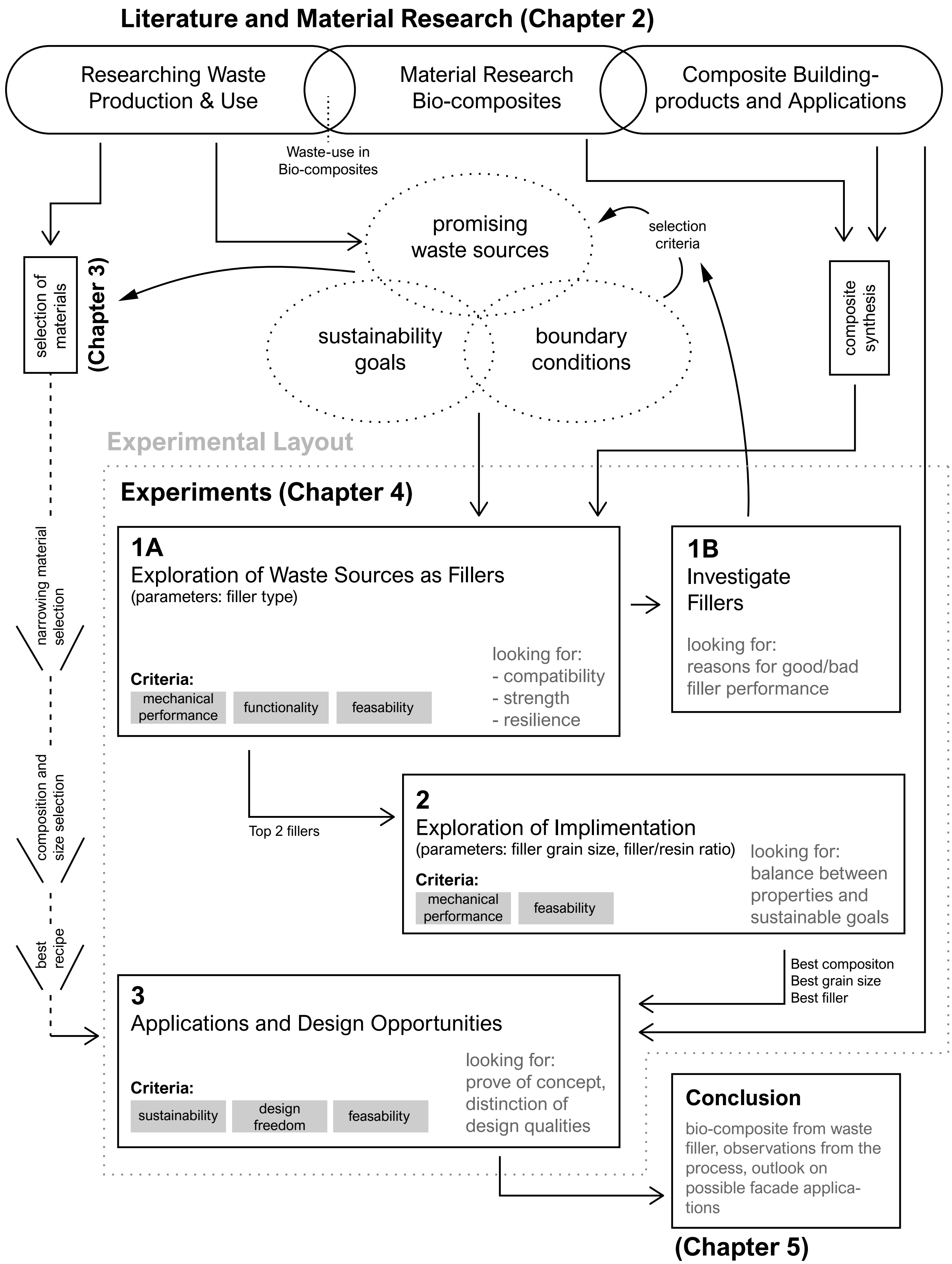
The success of each experimental phase is evaluated by phase specific criteria.

The goal of the first phase is to evaluate alternative fillers in terms of their functional and mechanical properties in a composite.
The composite variants are compared to other materials, that are commonly used in facade cladding.
No discrete benchmarks for facade panelling is used, to avoid a restriction of the material exploration by early on design considerations.
Besides material properties, the different fillers are ranked by their ease of processing.
The selection for phase 2 is decided by the best performing composites (mechanically and functionally) and overall good processing characteristics of the fillers.

The second phase criteria aims to find a good balance between the material strength and the optimum of waste-based content. In a two step process, where first the filler size and then the ratio between resin and filler are investigated. The final recipe for the next step is chosen by finding the optimum between both objectives, filler load and strength.

In the last phase, the material is evaluated on its ability to be shaped in 3D and possibilities in design and detailing are reviewed. A comparison to other conventional (non-bio-based) material options is made, in which the carbon emissions C2G and the overall feasibility of the proposed application are assessed.

1.3 Methodology - Research Flow



1.3 Methodology - Experiments

Experimental Layout

Choice of Material

From the previously investigated material sources, a selection is made and the material is acquired.

1A
Exploration of Waste Sources as Fillers
(parameters: filler type)

Creation of matrix/filler samples with respectively one waste-based filler.

Testing: visual inspection; mechanical testing for bending strength, impact resistance and water absorption and frost resistance
Result: Reasoned elimination of unsuccessful probes. Evaluation of different filler materials for their usability in this bio-composite applications.

1B
Investigate
Fillers

Further investigation of the filler material to reason with the results of 1A.

Testing: microscopic analysis of filler powder, measuring of density, and hydrophilic properties (contact angle testing), microscopic analysis of 1A sample fractures.
Result: Understanding of material behaviour and resulting consequences in further testing

2
Exploration of Implimentation
(parameters: filler grain size, filler/resin ratio)

Production of samples from promising materials with same matrix but with variation of filler sizes and volumes in proportion to the matrix.

Testing: Mechanical testing including bending, impact resistance, visual inspection
Result: Evaluation of different composition variation and identification of the highest performing material, filler sizing and composition with matrix and fibres combination.

3
Applications and Design Opportunities

Phase 3 aims to compare the outcome composite of Phase 2 in a exemplary facade panel setup with other common materials.
Additionally the possibilities for 3D shaping are demonstrated.

Testing: 3-point bending of a 3D shaped sample for comparison to sheet material, testing processability and design options in small experiments as needed
Result: Façade panel proposition and identified dependencies between design and material choices.

1.3 Chapter Conclusion

Chapter Conclusion

Bio-based composites offer a large potential for more sustainable building solutions, but they would benefit from the replacement of virgin-grade constituents with waste material constituents.
This thesis aims to explore the potential of waste-based fillers in bio-composites. Through literature research and three tranches of experimental design exploration, the most promising of different waste-based filler options, as well as a way of implementation into a composite, are proposed. Besides the type of waste used, the parameters are the filler particle size and the ratio in which the filler is added to the composite.
The final product is a rain-screen facade panelling from the resulting engineered bio-composite, of which the potential for structural design and architectural use are evaluated.
Finally the product is compared with other conventional products of the same application type to evaluate where the bio-composite places within the build environment regarding sustainability, feasability and the circular economy.

2.
Literature Review

The literature review is divided in three mayor parts. The first sections covers the synthesis of bio-composites and how they are positioned within the circular economy.
The second section identifies major sources of organic waste in the Netherlands and evaluates their potential as fillers in composite materials by referencing existing research.
Finally this chapter reviews previous studies on bio-based fillers, their performance, and the manufacturing methods applicable to the study. It concludes by setting the stage for the experimental phases.

2.1 Significance

Putting Waste to Use

Waste appears in various quantities, shapes, and sizes, and certain sectors hold potential for integration into closed-loop building products.

The fabric sector, presents an intriguing opportunity due to the high volume of waste and the challenges associated with recycling. Post-consumer fabric fibres could be utilized as reinforcement in bio-composites, enhancing material strength and utility.

Similarly, the agri-food sector stands out due to its consistent waste generation, bio-based origins, and potential for later organic degradation of building products. Additionally, this sector holds substantial national relevance within the Netherlands, given the prominence of the food production and processing industry.

Consequently it was decided to focus on the agri-food sector, although the potential use of waste fabric in composites remains an interesting and promising avenue for future exploration.

Waste in Composites

Polymer composites can incorporate secondary smaller particles, which make them a good choice for integrating waste or by-products of agricultural, forestry, or food processing industries. This also makes them provide a high degree of adaptability, allowing manufacturers to tailor material properties to specific application requirements and overcome shortcomings that might arise through the use of secondary materials.

Bio-Composites

Bio-composites have gradually become more popular since the 80s. Diversity in adaptability and design made them promising replacement for high carbon materials in the aviation and automotive industry as lightweight interior components (Riedel et al., 2001), in the bio-mechanical industry for medical prostheses and in the packaging sector (Correa et al., 2019).

Depending on the formulation bio-composites can be moulded into complex shapes, integrated with other materials, or engineered to meet specific functional and aesthetic requirements (Shanmugam et al., 2021).

Bio-composite Building Products

Currently the building industry knows various partially bio-based composites and more are being developed (figure 1-4). Amongst them are wood-plastic composites (WPC) that are sold in extruded form as outdoor floor-boards or chip-boards for interior applications which classically are made of wood fibre or chips that are bonded with a polymer adhesive.
The company NPSP, who assisted with the experiments in this thesis is developing and producing polyester and furan-resin based bio-composites, aiming for facade application with higher levels of resilience and durability (Nabasco 8010).
With rapid urbanisation and high demands in the bio-based sector, the market potential for bio-composites is large (Shanmugam et al., 2021).

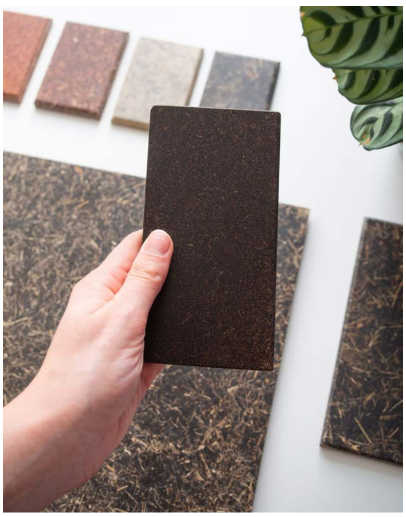


figure 2: Bio-composite with brewery waste, (source: circularmatters.com)

figure 1: Example for bio-composite, (source: npsp.nl)

figure 3: Mixed biomass composites (source: Godavari Biorefineries, NaturoMer)

2.2 Bio-Composites in the Circular Economy

Circular strategy

The R-strategies defined in the EU action plan of 2020 promote three separate circular approaches: The development of smart energy efficient materials, solving the end-of-life scenario of a products life-cycle and the prolonging of a products lifespan (European Commission, 2020).

The approach of this thesis is to further the development of a bio-composite with a low global warming potential i.e with low embodied energy.

Strategy R2: Reduce
It identifies with the strategy R2 'Reduce' by aiming to narrow the needed material flows and thereby reduce the use of natural resources. This can be done by employing secondary bio-based materials, reducing reliance on newly created material.

Strategy R8: Recycle
By association also R8 'Recycle' is of relevance for the creation of waste-based bio-composites as the raw material previously considered as waste is recycled into a higher application. The focus here lies on the identification of sources that have no better use application or alternative function.

Circularity goals of this project are the development of a material which is:

- *Fully bio-based*
- *Waste-based (as much as possible)*
- *Non-harmful in degradation*

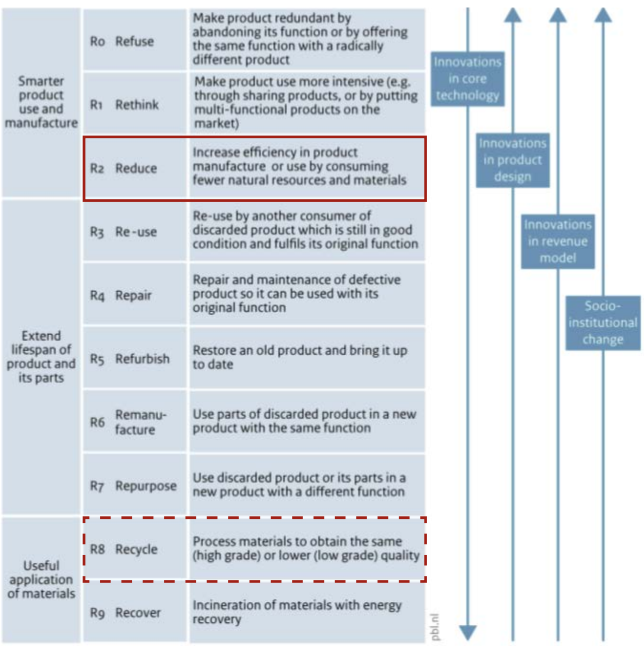
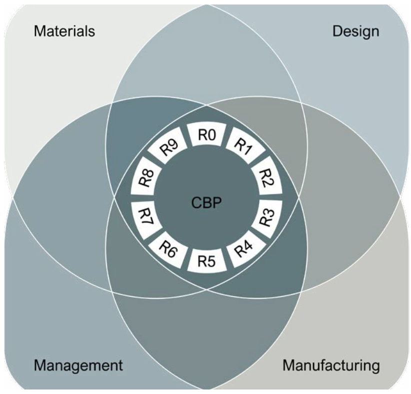


figure 5: R-Strategies (Potting et al., 2017)

Scales of consideration

In the aspiration of creating a truly circular build environment all angles from the material scale to the societal scale have to be considered.
On the canvas of circular building products, developed by the Circular Impulse Initiative of the TU Delft (CEB Hub, 2022) visualises how the four mayor scales interact with each other, where each decision made for one, holds implications for the other.



This project focusing mostly on the material scale, even though several topics in each category are influencing each other.
The filler **material** choices and investigation is focused on:

- Sourcing locally to enable short travel distances of the resources
- Sourcing bio-based with as little as possible pre-processing
- Sourcing from waste

Also important are the means of **manufacturing** which are in turn influenced by material choices:

- Optimising for the use of waste usage opposed to new material
- Preferring low-tech solutions in production
- Avoiding material that need energy intensive pre-processing

Secondary focal points lie in the **design** and **management** of the intended product:

- Choosing wast-flows of industries that have a local relevance
- Establishing possible symbiotic connections between waste producer, user and consumer.

- Designing for an application that accommodates the material lifespan and that can be replaced individually

2.2 Bio-Composites in the Circular Economy

Embodied Energy

Regarding greenhouse gas emissions and embodied energy, composites with bio-based polymer matrix and organic reinforcement perform generally better that synthetic polymer composites, as they are easier in recycling and decomposable without leaving harmful residue (Shanmugam et al., 2021).

Matrix:
The use of a bio-based polymer matrix has a significant effect on a composites carbon footprint. A study by (Vink et al., 2003) demonstrated a decrease in Carbon emissions of 50-70% after exchanging fossil based matrix with bio-based PLA.

Fillers:
The even bigger potential in the creation of low carbon composites could the integration of bio-based and waste-based filler material.
By doing this, not only virgin feedstock and fossil resources are preserved but also carbon is bound in the fillers bio-mass.

(Singh et al., 2018) investigated the carbon impact of several plant-based fibres (jute, kenaf, flax and hemp) to the comparable production of synthetic fillers. They concluded that the organic fillers had on average an energy consumption seven times lower than common synthetic ones, at an evaluation from cultivation to gate.

These studies show that using bio-based fillers are an efficient way to reduce the environmental impact of polymer composites compared to synthetic fillers.

Other Sustainability Factors
A material focused life-cycle analysis considering cradle-to-gate includes the emissions of the raw material, processing and transport emissions (Correa et al., 2019).
Besides the embodied energy of a material, other factors play into the ecological impact. Also considered are sometimes:

- degree of fossil resource use
- land occupation (for agriculture)
- the production of particular (lasting) matters
- toxicity to humans and other organisms (Correa et al., 2019)

EOL-Prospects

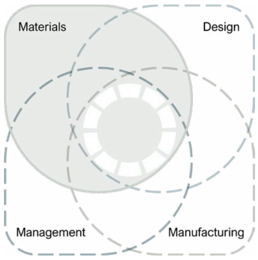
Bio-Degradation: Biodegradation refers to a chemical degradation of material by common micro-organisms, wherein various materials are converted into elements like water, carbon dioxide, and compost, without the requirement of artificial additives. This process is regulated by factors such as environmental settings, location and temperature, the nature of the material, and its use (European bioplastics e.v., 2024). Depending on the composition of a bio-based composite, it can be partially or fully biodegradable. Full degradation is a good option of closed loop recycling in the circular value chain but might have influence on the durabiliy aswell.

Mechanical recycling: A commonly used way of recycling of bio-composites is the mechanical recycling which is done by shredding the material and remoulding it, sometimes in addition of virgin plastic to maintain a high level of quality (Yang et al., 2012). The chemical degradation of matrix limits the amount of recycling repetitions. Furthermore the fillers can also degrade a high temperature, which possibly causes a drop in material performance (Grigore, 2017). The necessary energy efforts falls negatively into the balance but advantages of mechanical recycling are the low cost and possibility to add additional reinforcement of virgin matrix material which will extend the useful lifecycle of the material even though additional material is needed (Shanmugam et al., 2021).

Chemical recycling: In chemical recycling a solvent for the polymer matrix is used, which the allows the extraction of the filler materials (Yang et al., 2012) This, in theory, allows the full reuse of the filler in another application, even though the residual properties have to be reviewed. The polymer is turned to monomers or oligomers which can be used again in the production of lubricants, drilling fluids or paints (Grigore, 2017). The downsides of chemical recycling are its high costs which makes it not lucrative compared to the use of virgin grade materials (Shanmugam et al., 2021).

Energy recovery: Energy recovery of polymer composites is considered effective and lucrative as large amounts of energy can be recovered from the matrix. Still this method is not environmentally safe because of the release of toxic gases during incineration (Grigore, 2017). In terms of circular design this EOL scenario is also not preferable.

2.3 Defining Bio-Composites



Defining Bio-Composites

As shown, a composite is typically composed of three main components: The matrix, fillers and fibres (figure 6). By the choice of each of these components and the proportions of each to the others, the functional and mechanical properties can be influenced.
The constituents in a composite build a lasting chemical and/or mechanical bond (Murawski et al., 2019). The quality of the bond often determines the strength but also the durability of a composite.

Potential for Sustainability

By choosing bio-based materials for some or all of these three components, the dependency on fossil resources can be minimised and bio-degradability can be improved.
Sourcing locally decreases the emissions caused by transport of materials. The choice of raw material of each component has a large impact.
Bio-based material have the potential of binding CO2 during their lifetime. This is why organic materials with low emission in cultivation but also bio-based waste sources have a low or even negative carbon balance (Correa et al., 2019).
Bio-composites are not categorically a low carbon material class but have a lot of parameters that allow for sustainable choices.

Fillers as Focal Point

The extent of variables in the field of bio-composites is large. This is why for this project the focus is on waste-based options for filler materials.

Fillers, are normally used to reduce the price of composites and to give them more dimensional stability and also have a great potential of reducing the carbon impact by employing bio- and waste-based sources (Biron, 2013; Riedel et al., 2001; Shanmugam et al., 2021). The nature of bulk fillers, that are added to the composite as powders or smaller granular particles, allows for the integration leftovers of other processes.

Economic Potential

One benefit of bio-composites can be the economic relieve that comes with use plant-based materials. Even though additional processing steps might need to be taken into account, compared to synthetic alternatives, the overall price of especially locally sourced bio-based materials is often low. This is why using biological fillers and or fibres can reduce the cost of a composite significantly. In a study by (Rodríguez et al., 2018) the price of composite materials including banana fibre were on average 17% lower than the pure resin samples. By the use of waste materials, the cost of a bio-composite could be reduced even further since the waste materials from varying processing companies are mostly sold at minimal prices, depending on the usefulness of the by-product to other parties.
The development and production of local bio-based composite products could be beneficial outcome for both material producers and the waste producing industry.

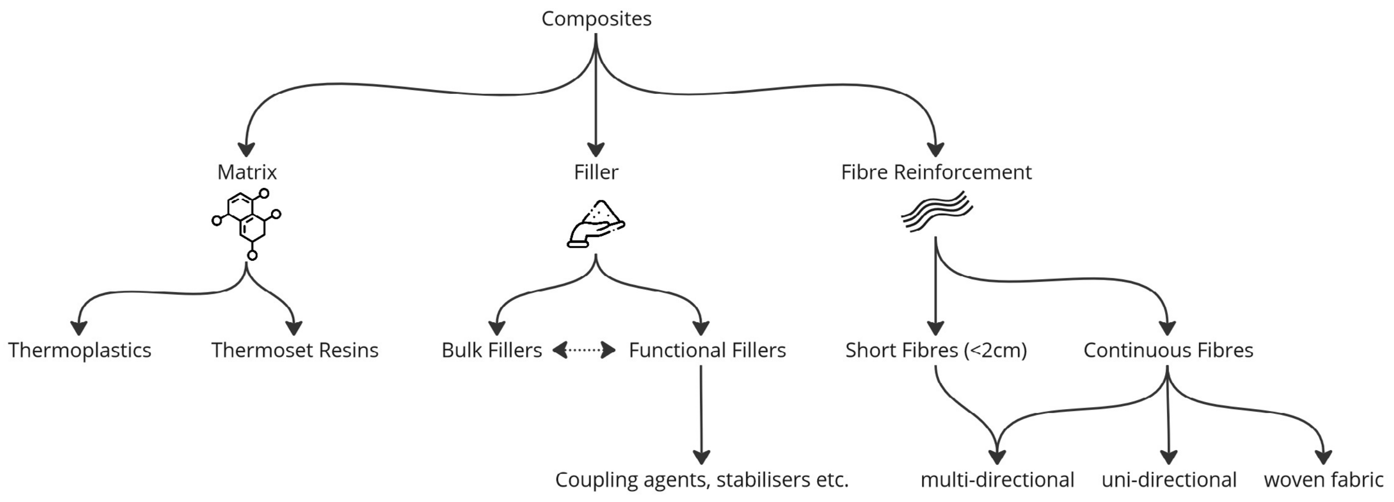


figure 6: Typical composition for polymeric composites

2.4 Bio-Plastic Matrices

Interest

The rise of public and global environmental awareness drives companies and researchers to find alternatives for petroleum-based virgin material for the production of bio-plastics. Besides the independence from non-renewable resources, the development of bio-plastics is fuelled by the need for low carbon materials and the desire for materials with new combinations of properties (Murariu et al., 2016).

Sustainable Sourcing

Bio-plastics can be categorised by source in three groups, as shown in figure 8, of which second- and third-generation polymers are optimal for a circular economy approach, because they don't employ virgin resource materials that have other valuable purposes (Tan et al., 2022).

Biodegradability

If the filler materials of a composite rely on plant-based material, the polymer matrix is the limiting factor for bio-degradation.
The term bio-degradation is used ambiguously but normally refers to the ability of a material to degrade by the activity of bacteria and micro-organisms.
If a material is rated compostable, that means it will degrade under specific humidity and heat conditions that are achieved in industrial composting plants (European bioplastics e.v., 2024).
Bio-degradability can be a desired trait in making a material choice but might also influence the durability of a product negatively if the material is not preserved correctly.

Terminology/Definition

The term bio-plastic is used to describe Polymers that are either directly derived from natural sources, like starches, gelatine, cellulose or chitin; synthesised from bio-derived monomers; or produced by bacteria or microbes (Andrew & Dhakal, 2022). Also polymers from non-renewable resources that are bio-degradable are sometimes considered bio-plastics. Ffigure 7 (European bioplastics e.v., 2024) shows the division into four sectors.

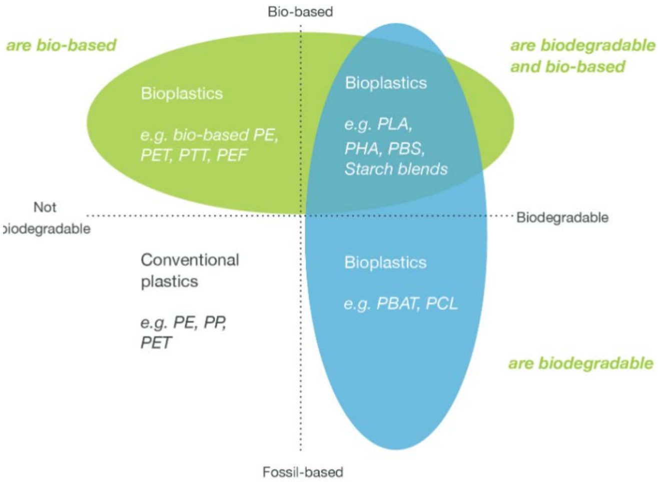


figure 7: Bio-plastics Four sector definition, based on (European bioplastics e.v., 2024)

Price

Biologically derived polymers are often a bit more expensive than synthetic plastics. PLA is around 1.5 times and PHA is almost three times more expensive than PP (Biron, 2013). This might change over time, with the development of more options and upscaled production but is currently a limiting factor to the popularity of bio-plastics at the current time (Tan et al., 2022).

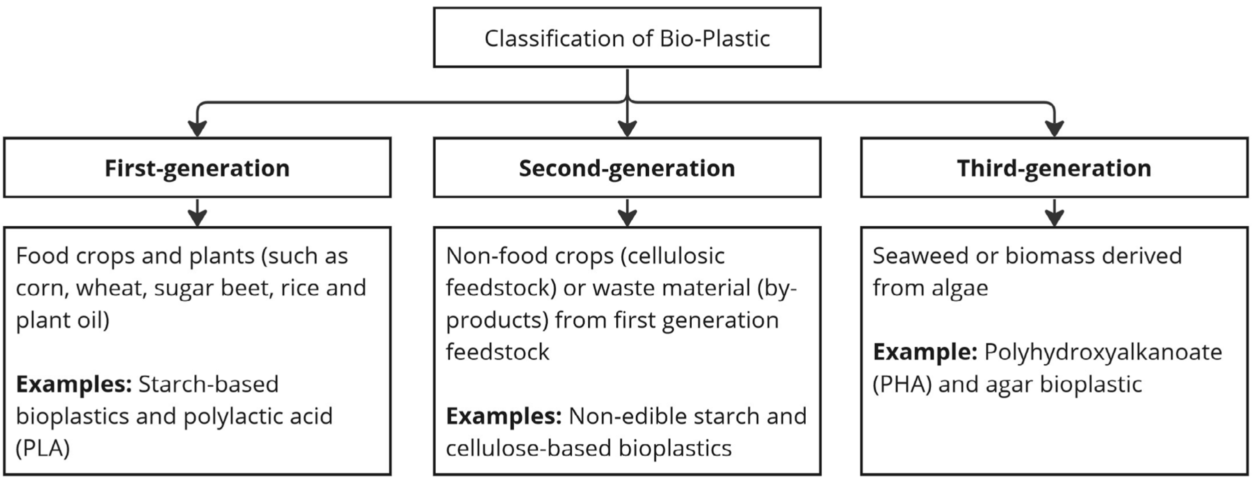


figure 8: Categorization of Bio-plastics by Material Source, based on (Tan et al., 2022)

2.4 Bio-Plastic Matrices - Thermoplastics vs. Thermosets

Thermoplastic vs. Thermoset

Polymers are divided into thermoplasts and thermosets which have a different underlying chemical structures. Thermoplastics consist of long molecule chains. Unlike thermosets they do not have any cross connections, which makes them meltable and they able to be shaped at elevated temperatures (figure 9). Thermosets are liquid resins that cure at higher temperatures. In this step the molecule-chains build crosslink connections that make thermosets resistant to heat after the curing process is finished (Brandrup et al., 1999).
Both material groups have the potential for bio-based building materials and have been used for composites with different material targets.

Benefits of (non-elastic) thermoplastics are higher impact resistances, while thermosets are well suited for high temperatures (Brandrup et al., 1999). For the use in a façade application a thermoset resin is the better choice as matrix as the heat resistance and UV resistance are desirable traits.
In table 1 thermoplastics and thermosets resins are listed, which are either bio-based, bio-degradable or both.

Recyclabiliy
In terms of recycling, thermoset resins and thermoplastics (in composites) have to be approached in different ways due to their material properties.
Most thermoplastics are re-meltable, which makes the reuse of pure material easier. Problematic is the degradation of organic fibres and fillers in the recycling process of thermoplastic based composites (Chaitanya et al., 2019).
Thermosets have on average a higher durability but are not meltable. A way to recycle them is to shred and mix them into new products. In two studies by (Xu et al., 2018, 2019) this was successfully tested with epoxydised rubber and clay composite.

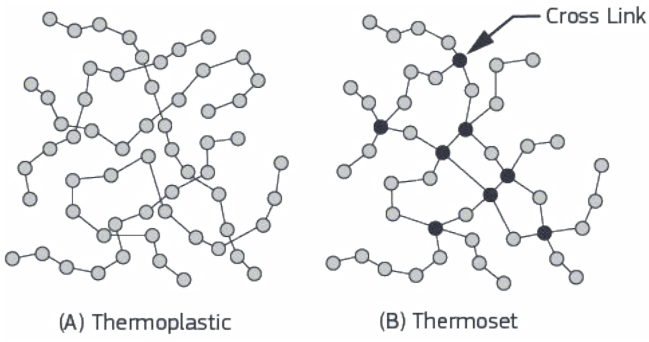


figure 9: Schematic, mollecular difference between thermoplastics and thermosets, (protolabs.com)

Name	Material-class	Bio-degradable	Renewable content [wt%]	Uses
(PTT) Polytrimethylene Terephthalate	Thermoplastic	no	35-37	residential and industrial applications, clothing fabrics
(PEF) Polyethylene Furanoate	Thermoplastic	yes	100	bottles, cups, packaging
(PBAT) Polybutylene Adipate Terephthalate	Thermoplastic	yes	100	bottles, cups, packaging, agricultural foils
(PCL) Polycaprolactone	Thermoplastic	yes	0	hot metal adhesives, shoe counters, extrusion aid
(PLA) Polylactic Acid	Thermoplastic	yes	100	packaging, bottles, films, planters, plastic bags
(PHA) Polyhydroxyalkanoates	Thermoplastic	yes	100	packaging, containers, bottles
(PBS) Polybutylene Succinate	Thermoplastic	yes	100	packaging, coats
(TPS) Thermoplastic Starch	Thermoplastic	yes	40-60	cutlery, planters, toys, foils, bags
(EP) Epoxy Resin	Thermoset	no	20-80	paints, coats, adhesives, plugs and switches, shells
(Furan) Furane Resin	Thermoset	no	100	automotive interior panels, mould sand-binder in metal-casting
(UP) Polyester Resin	Thermoset	no	0-?	pipelining, automotive parts, cookware, doors

table 1: Selection overview Bio-plastics, based on data from (Brandrup et al., 1999; Budinski & Budinski, 2002; Biron, 2013)

2.5 Fibres

Terminology: Fibre

The term fibre in the context of composites refers fibrous filler added to the composite for reinforcement to improve the materials properties, including tensile and bending strength.
Commonly used fibres in composites, like carbon fibre or glass fibres can be replaced with a wide range of animal or plant based fibres.
Fibrous fillers in this project generally are referred to as ‘fibres’ or ‘fibre reinforcement’. Fibres are not the focus of this study, but they are an important constituent of composites, so a summary of the use of natural fibres in composite is provided in this section.

Implementation

Composites can contain either continuous or non-continuous fibres as reinforcement. Depending on the natural state and occurrence of the chosen fibres, the length and layout of fibres can be predetermined.
Continuous fibres can be organised in three ways: woven, mono-directional or multi-directional as depicted in figure 10. The arrangement of fibre layers will influence how the composite material behaves and if it will have anisotropic characteristics (Kula et al.,2013).

Background

The development of bio-composites first started by adding natural fibres as reinforcement to polymers (Merhi, 2021).
To this day most (bio-)composites employ fibre reinforcement to achieve high tensile and bending properties (Riedel et al., 2021). The abundance of natural fibres (figure 6) opens up many opportunities for natural fibre reinforcements which are being explored in numerous studies. The fibres are sourced from fruit, seeds, grasses or extracted from stalky parts of plants by a process called retting, which involve the breaking down of the fibril structure into separate strands and the degradation of other organic matter (Ramesh et al., 2017).

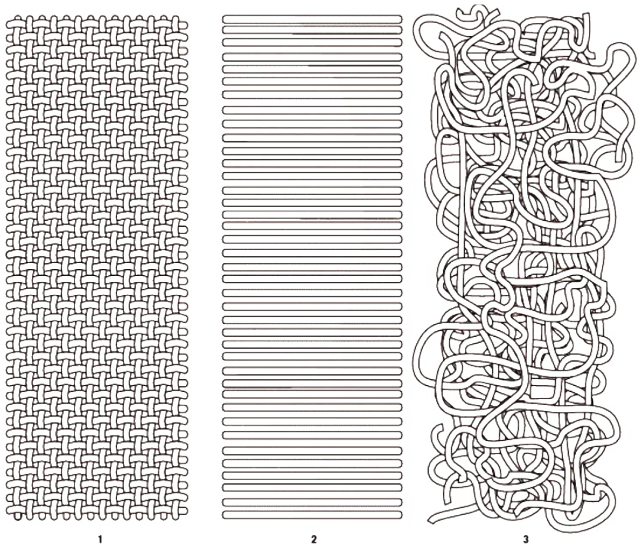


figure 10: Different types of organization of continuous fibre (Kula et al., 2013)

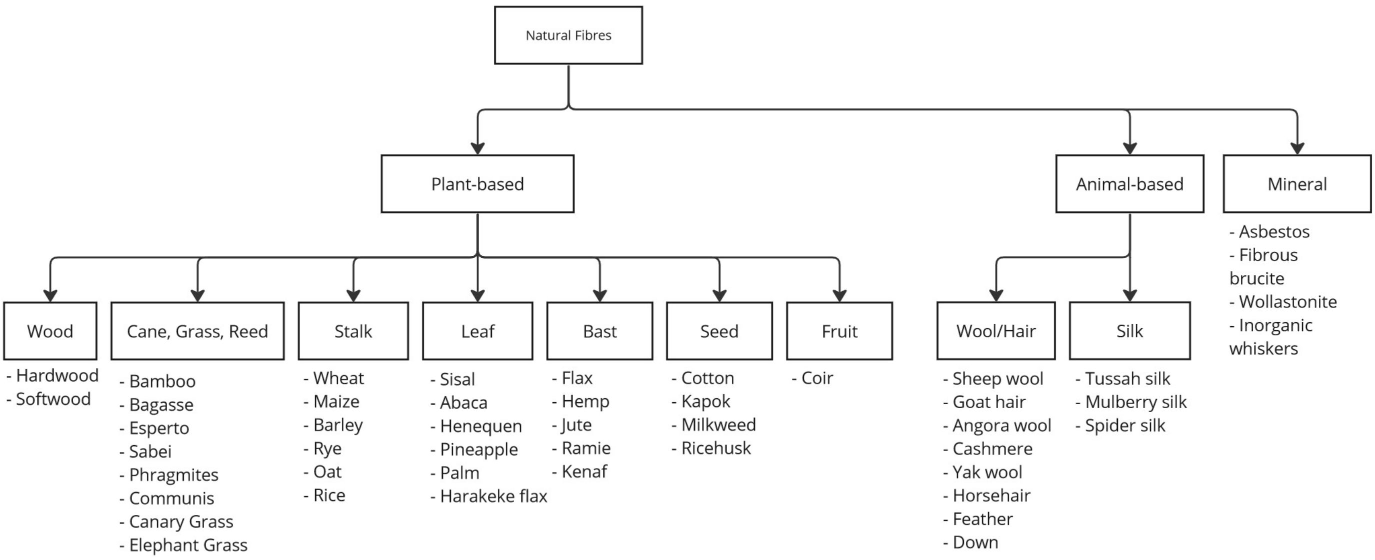


figure 11: Overview of Natural fibre sources, based on data from (Ho et al., 2012)

2.6 Granular Fillers

Functional Fillers

Functional fillers are typically added to composites in smaller quantity (<5%) to achieve a specific material characteristic or to increase the ease of processing. (American Composites Manufacturers Association, 2016).

Functional fillers are typically used to achieve on of the following goals:

- **Colouring** *(pigments, colourants)*
- **Fire resistance** *(bromine, chlorine, borate and phosphorus)*
- **UV resistance** *(ultraviolet absorbers, stabilizers)*
- **Electric conductivity** *(metal powder, carbon particles)*
- **Ease of processing** *(waxes, oils, clay, silica)*

Functional fillers can be natural or synthetic. The choice of additives for bio-composites should align with the sustainability goals. For a bio-degradable product no additives should be added that do not degrade naturally or release toxic compounds in degradation.

figure 12: Example pictures for additives (left to right), Colorant (polyfill.com), Linseed oil (indiamart.com), Nanoclay (attogene.com)

Common Bulk Fillers

Bulk fillers are commonly used to reduce the composite price, as they are the most inexpensive ingredient. Bulk fillers also usually improve the dimensional stability, leading to less shrinkage in the moulding process (Tan et al., 2022). Depending on the application and composite type fillers might account for about weight 40-65% (American Composites Manufacturers Association, 2016).
The implementation of bio-based bulk fillers has therefore the potential for impacting the products sustainability significantly.
These are the bulk fillers most commonly used in building products:

- ***Calcium carbonate*** (mineral) - derived from limestone, marble or seashells
- ***Kaolin*** (mineral) - mined clay is one of the most common mineral bulk fillers.
- ***Alumina trihydrate and Calcium sulphate*** (mineral) - frequently used for their flame and smoke retarding properties and low cost.

(Pukánszky, 2001)

figure 13: Calcium carbonate rich stones (source:daswell.com)

Bio-based Bulk Fillers

Bio-based bulk fillers have emerged as a popular way to increase the bio-based content of composites, while benefiting from low weight and low material prices. Research has been conducted on various options including nut shell powders, fruit pits and bone dust (see section 2.7). Biochar (which is biomatter that is burned without oxygen, in a process called pyrolysis) is currently also a popular material for research as it also can serve as functional filler (Tadele et al., 2020).
However there is a lack of research on bulk fillers applied for the use in building conducts.

Many studies about bio-based fillers are focused in film material for packaging and medical appliances.

Waste as Bulk Fillers
Similar to bio-based bulk filler in general, the research on the use of waste matter it limited, also considering that often no distinction is made between by-product “waste” and cultivated sources. Still in some papers specific waste materials are specified (Erkliğ et al., 2016; García-García et al., 2015; Gutiérrez-Macías et al., 2021; Wechsler et al., 2019).

2.6 Granular Fillers

Material Requirements for Fillers

If a material is useful in an application as filler is subjected to several parameters that target both the material chemistry as well as the way of integration. Factors can be:

- the fillers surface-texture
- porosity
- grain size
- grain shape
- chemical structure
- filler/matrix ratio

(Senthil Muthu Kumar et al., 2020)

For these parameters no ideal exists but the success of the material is dependent on the other ingredients, the processing methods and the desired function.

Compatibility with the Matrix

Good adhesion between filler and matrix is integral for a high performance of the composite. This can be either be achieved through either a mechanical interlock (high porosity, rough particle surfaces) or a chemical bond (can be achieved through bonding agents).
With usually hydrophobic resins, “the hydrophilic character of the filler results in high moisture absorption, poor matrix-filler interfacial adhesion, and poor filler dispersion”(Senthil Muthu Kumar et al., 2020, p.127).

Filler Size and Load

The size and load of filler particles influence the movement of polymer chains within bio-composites, with implications for the material’s mechanical properties (Senthil Muthu Kumar et al., 2020). Particularly in thermoplastic matrices this has a high impact the material stiffness, opposed to thermosets which are already restricted by cross-linking (Senthil Muthu Kumar et al., 2020).

Larger particles in the blend raise the risk of fracture due to stress concentration along particle edges. However, larger grains reduce the required amount of resin because the ratio of surface area to volume decreases with larger particles, resulting in a more efficient use of the resin matrix. The best filler volume is therefore in direct correlation to the grain size and porosity of the material.
Further studies on filler sizes and the resin-filler proportion, are referred to in section 4.2.

Hybrid Fillers
The use of several different filler types can be beneficial to achieve multiple material objectives.
Additional to adding functional additives that make up only a small amount of the overall mass, combining a bulk filler with fibre reinforcements has proven to be an effective way to benefit from each components advantages.
In the investigation of several studies, (Senthil Muthu Kumar et al., 2020) concluded that desirable traits from each filler can be combined which in his case resulted in samples with higher dimensional stiffness and tensile strength.

Section Conclusion

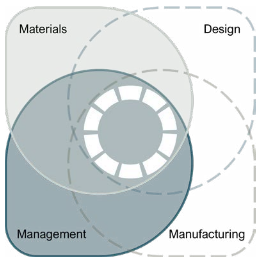
The main components of a bio-composite and their defining characteristics have been introduced.
The effect of bio-based granular bulk fillers seems to be heavily dependent on the individual material combination and integration of the material.
At the same time bio-composites leave many option for sustainable choices and a high degree of customisability.

For bio-based fillers, the compatibility with the matrix and possible other fillers or fibres has to high, which is dependant on the various factors including shape and surface texture as well as hydrophobic behaviour and chemical composition.
To achieve a high degree of waste based content, the ratio of resin to filler has to be matched with the particle sizes used, to not compromise on the resulting materials properties.

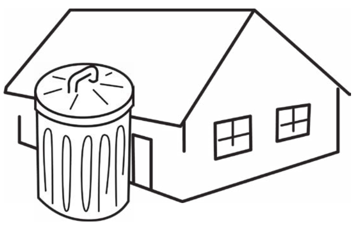
2.7 Waste as a Source

Waste as a Source

Utilising waste-flows for building products like composites is a win-win-win scenario in which not only environmental concerns are addressed but the user profits from low prices and local sources and the waste producer gets freed from their by-products with financial gain. By re-purposing waste materials with less or no economic value into higher applications the residual properties of the material are utilised instead of wasted and therefore their life-cycle is extended.

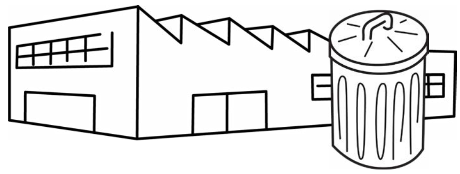


Post-Consumer Waste:



Post-consumer waste is waste of direct consumers, like kitchen- and household-waste, home electronics and textiles. In general, post-consumer waste is of varying purity and quality, and therefore is harder to utilise for the building industry.
Still, where collection and sorting schemes are in place, post-consumer waste can be a valuable resource for a range of materials.

Industrial Waste:



Industrial waste is not contaminated by consumers and the steady production processes can be a permanent high-quality source of fillers. Some of the most relevant waste-producing industries and consumer waste sources in the Netherlands include:

- **Agri-food Sector**: Agriculture and food processing industries generate substantial organic waste, including crop residues and organic waste, with the Netherlands being the second largest food exporter worldwide (Government of the Netherlands, 2023).

- **Construction and Demolition**: The construction sector contributes to waste through building materials, packaging, and demolition debris. In Netherlands demolition waste accounts yearly for approximately 25 million tonnes (CBS, 2020).

- **Manufacturing**: Various manufacturing processes, especially those producing electronics, textiles, and chemicals, contribute to industrial waste in the form of production residues and discarded products.

Since one of the potential objectives was a fully bio-based composite, the agricultural and food processing industry showed a huge potential. The advantages are the biodegradability, local availability and renewable sources but also some post-consumer waste sources were considered.

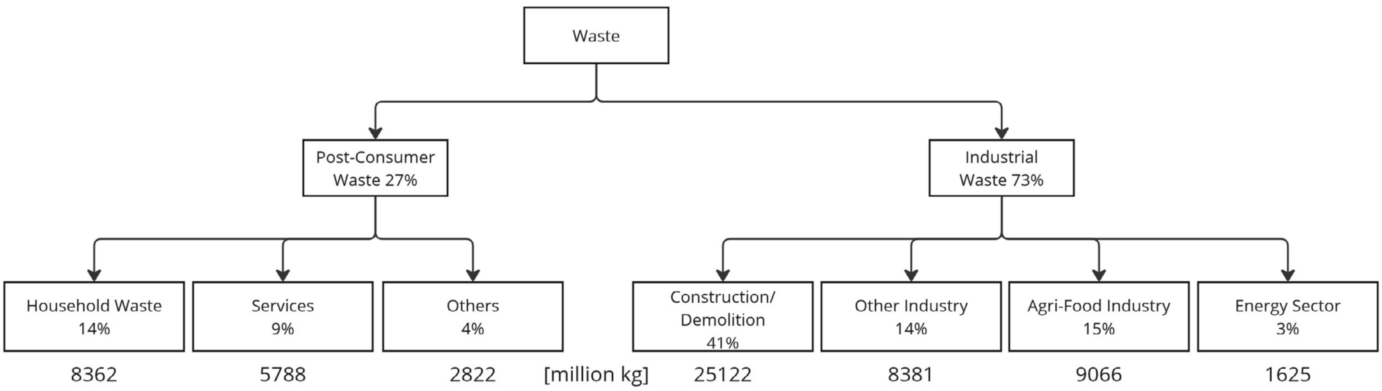


figure 15: Overview of waste-producing sectors of the Netherlands, based on (CBS, 2020)

2.7 Waste as a Source - Industrial Food Waste

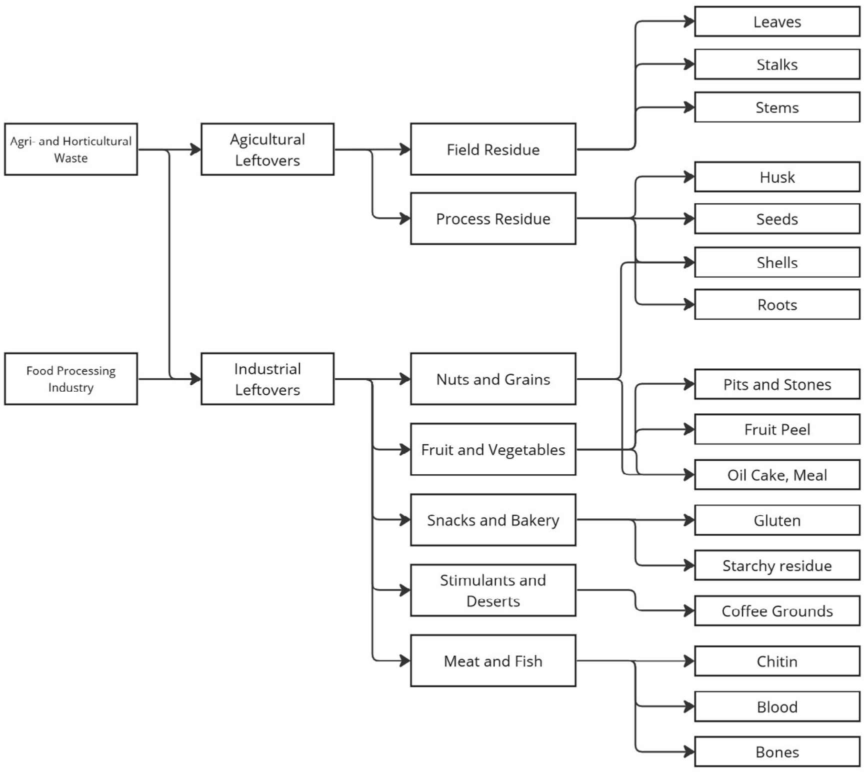


figure 16: Overview of industrial, horti- and agricultural waste-streams

Agri-food waste in the Netherlands

The Netherlands has a big food processing industry. Only second to the USA the Netherlands is one of the top food exporting countries worldwide (Government of the Netherlands, 2023).
Besides the growth and export of crops, the even bigger industry is the import, processing and re-export of food products. The main sectors of that industry are: vegetable and fruit (including ready-made foods), cocoa and fats, soy, sweets, snacks and soft-drinks, dairy, flour, meat, bakery products and flower bulb cultivation (Welink, 2014).
The waste production of agriculture and the food processing industry together is an estimate of 9 million tonnes (CBS, 2020).

Use-case Priorisation

In the agri-food sector almost all by-products have secondary uses or alternative applications. To get an idea if the intended use of these by-products is better than another, we can refer to the policy by the PBL Netherlands Environmental Assessment Agency that introduced an updated scale on preferable ways to treat organic waste products (Rood et al., 2017). Here two schemes give an indication on which process to favour based on produced outputs (Moerman´s Ladder) and the volume of a waste-stream and its potential value generation (Value Pyramid). Using food waste material for building products would fall into the category of 'raw materials for industry (bio-based economy)', meaning it falls into the middle range of the list (figure 17).

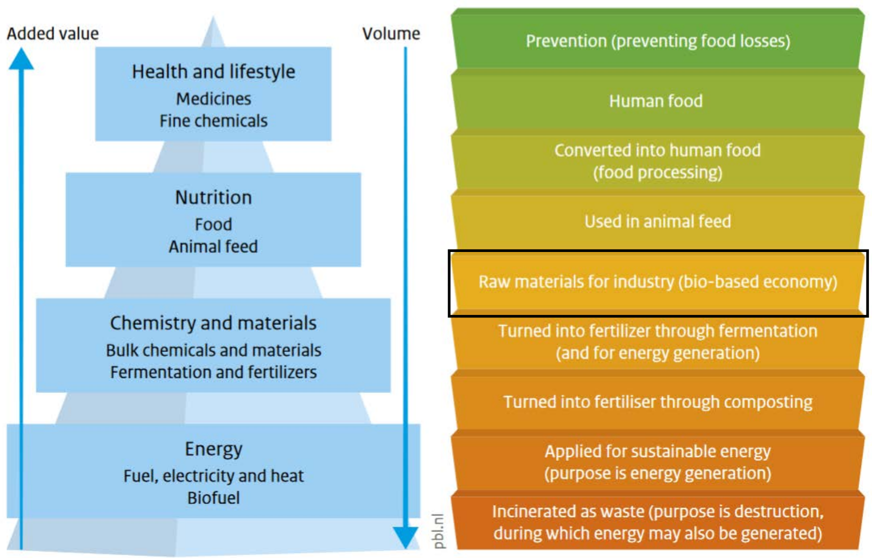


figure 17: Value Pyramid and Moerman's Ladder (Rood et al.,2017)

As a consequence of the PBLs guideline, the focus for the selection of materials to consider as source for bio-composites lies on industry by-products that have no possibility of human consumption and no or little significant value as animal feed.

2.7 Waste as a Source - Industrial Food Waste

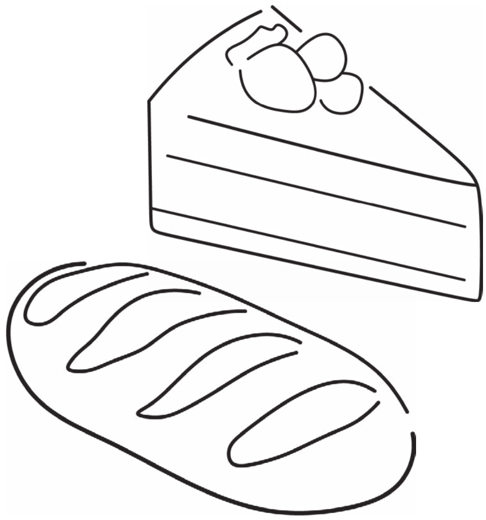
Fruit and Vegetables:

Fruit and Vegetable waste both in agriculture and the food processing industry can be a variety of products. The main by-products that are being produced are greens and leaves, roots, pits and fruit peel. Many by-products from this category are well suited for animal feeding and the production of fertiliser through fermentation (Raut et al., 2023)

Fruit pits from stone fruit like peaches and cherries, which are extracted in the process of canned products and jams can be used in gardening, as polishing grit for pressure washing and energy generation. Most stone fruit pits consist of an inner stone and an outer shell. The inner stone can be utilised in the production of cosmetics but often the whole pit is thermally recycled due to its high calorific value (Wechsler et al., 2019). To save on labour costs, many pre-processed fruits are pitted in their countries of origin. A local source for fruit pits could be from local businesses that process their own harvest or rejected fruit that accumulates in packaging and sale of large scale suppliers.
The start-up "Fruitleather Rotterdam" used this source to make leather imitate from rejected or unsold mangoes fibre. The Netherlands has a limited potential for the production of fresh stone fruit due to the climate. Still cherries, plums are being cultivated locally on a medium scale with about 1090 hectare of stone fruit trees (CBS, 2017) .

Flour, Snacks and Bakery Products:

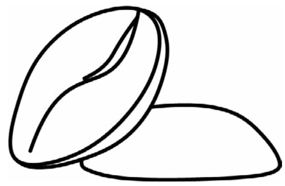
Waste form industrial bakeries and firms producing snack food are rejected ingredients and products filtered out by quality assurance like potatoes, waste dough, cookies, chips. The major by-product of many processes are corn gluten and starch. Yearly about 1000 tonnes of starch are produced which are not graded for human consumption. The rejected foods and starchy residues are utilised as animal feed or fermentation (Welink, 2014).
The corn gluten, due to its good nutritional value is considered a high value animal feed, which is ranked higher that the aim of this project on the Moerman's ladder. As a natural polymer, the overproduction of starch can be utilised with the production of bio-plastics like PLA or TPS which in recent years is being investigated intensively (do Val Siqueira et al., 2021).



2.7 Waste as a Source - Industrial Food Waste

Coffee:

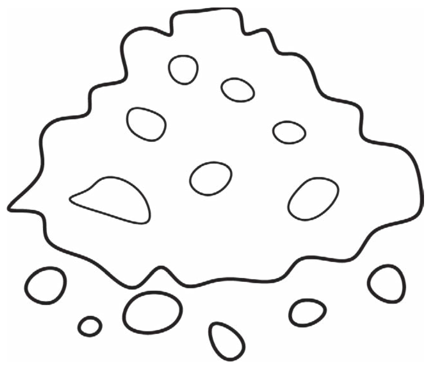
Coffee is one of the medium sized markets in the Netherlands of which about 23% are instant coffee products (Statista, 2023). Waste from coffee processing consists mostly of rejected beans, membranes from roasting (which contain mostly cellulose, lignin hemicellulose, protein and moisture) and spent coffee grounds from the production of instant coffee and coffee products like sweet drinks or deserts.
These waste products are used for composting and the production of biofuel (Welink, 2014). Coffee grounds can be sourced both industrially and from consuming businesses like coffee chains, offices and hospitals.



In a study (García-García et al., 2015) tested a PP matrix with 20wt% spent coffee grounds as filler. The results showed a slight increase in flexural modulus and better thermal stability (indicated by the increase of onset degradation temperature compared to pure PP. Furthermore, they treated the coffee-grounds for achieving hydrophobic behaviour (silanization) which led to a remarkable reduction in water uptake of the composite compared to a wood fibre reinforced composite with the same load of filler.

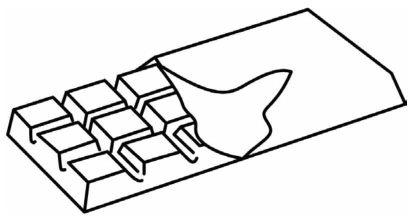
Bleaching Earth:

Bleaching earth is a fossil kaolin clay, used as adsorbent for colouring pigments in vegetable oil. After it is saturated, it gets discarded. For use in an alternative application the absorbed oils have to be extracted, which are then used for fuel. The bleaching earth can then be used as a sand substitute in concrete production (Welink, 2014) Since the bleaching earth is not bio-based and requires several processing steps before being considered for building products, it got eliminated from consideration for this research project.



Cacao:

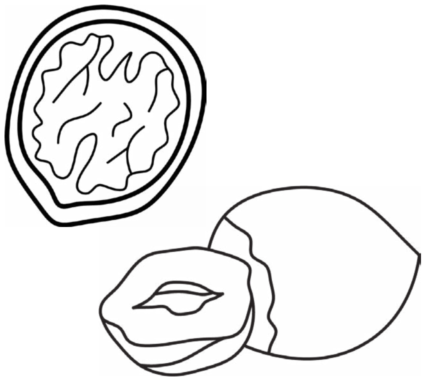
With 1.1 billion kg of cacao beans in 2018, the Netherlands are the largest importer of cacao beans worldwide, most imports come from the Ivory Coast and Ghana (CBS, 2018). In the producing country the beans get extracted from the fruit, they get fermented and dried. In the Netherlands the beans get roasted, winnowed and crushed. The residual materials from the cacao processing are the shells and small amounts of fatty acids which can be used in cosmetics, soap and paints. The shells are utilised as solid fuel pellets and soil improver (Welink, 2014). These applications can be considered lower than the use in bio-composites on the Moerman's ladder and cacao shells are therefore well suited for this project in regards of circularity efforts.



2.7 Waste as a Source - Industrial Food Waste

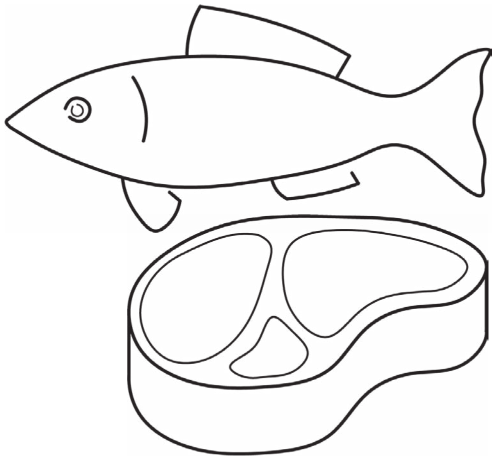
Nuts:

Nuts, same as stone fruit are imported to the Netherlands mostly pre-processed (shelled) (Nuts & Dried Fruits Statistical Yearbook 2022/23). Since they are still and interesting source for filler material in bio-composites they are still considered in this investigation. Local sources for varying nut shells are possible even though the potential to use this material without long transport ways might be higher in producing countries.
Nut shells as a source for fillers in particleboards have been studied in several investigations (Shejkar et al., 2021, Ahlawat et al., 2018) with related results to the use of stone fruit pits. Higher dimensional stiffness and better absorption and swelling properties are an advantage of the material but come with a gradual reduction in bending strength with rising filler content.



Meat and Fish Industry:

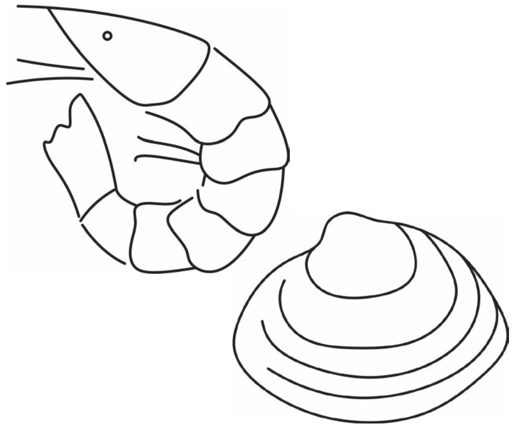
The meat and fish industry appears promising as resource, since it has steady production rates and several waste materials like bones and feathers, which both are is mostly made up of creatine might be interesting materials to explore.
By the European regulation for animal by-products of 2009, most waste products from slaughterhouses are classified as category 1, which disqualifies the waste from application in building products. This extends to areas where fruit or vegetable waste might be contaminated by animal waste, so factories that process both meat and plant-based foods, for example for ready-meal production are disqualified as a source for any kind of waste stream for this or similar endeavours.
The use of bone or chitin waste material might still be possible with proper treatment in a processing plant certified according to the regulation (European Commission, 2009) but the treatment might significantly increase the price for such materials.



2.7 Waste as a Source - Industrial Food Waste

Seafood:

Crabs and shrimp are fished in the northern sea of the Netherlands, Denmark and Germany. Due to high costs of the peeling process with Dutch food safety regulations (refrigerated peeling conditions and high labour cost) the peeling has been almost exclusively outsourced to Morocco (Mooijer-Volendam, 2024).
The old tradition of the fishermen's families hand-pealing the shrimp as a communal activity is not practised anymore since the 1990 (at least not in larger quantities for resale). An alternative source for animal-based chitin could be the post-consumer waste from seafood restaurants.



Conslusion

Concluding can be said that agricultural and food processing waste in the Netherlands has a high potential for functioning as a sustainable source for filler material in bio-composites though some materials have better ways of alternative uses according to the Dutch guidelines regarding bio-waste.

The selection of cherry pits, spent coffee grounds, cacao bean shells and walnut shells was made based on the availability for this project and because of promising properties or origin.

Wastestream	**Origin**	**Benefits**	**Disadvantage**
Stone Fruit Pits	jam, preserves and dessert production. waste produce	high hardness, no better use-cases, studied before	most imports are pre-processed, local sources have limited size
Bleaching Earth	vegetable oil production	no better use-cases, similar to common mineral fillers	not bio-based, intensive pre-processing needed
Spent Coffee	local cafe businesses, instant coffee industry	available in large quantities, studied before	possibly leftover soluble constituents
Cacao Bean Shells	chocolate processing industry	under utilised, specific local industry	brittleness
Starchy Waste	bakery products and snack production	large quantities available	inconsistent quality, better use-cases
Nut Shells	local farming and processing	studied before, high hardness, no better use-cases	most imports are pre-processed, local sources have limited size
Animal bones	butchery, meat and fish processing	no better use-cases	contamination, restrictive regulations
Crab shells, Seefood waste	sea food restaurants, fishing industry (not local)	no better use-cases	restrictive regulation, limited local availability

table 2: Overview of Considered Waste-flows

2.8 Target Application

Defining the Application Type

By focusing on rain-screen facade panels, the thesis not only addresses a new challenge for polymeric composites but also leverages the advantages of functionally layered building envelopes. This approach promises to showcase the potential of bio-based materials in high-demand applications.

The challenge is whether we can substitute traditional building materials, which either depend on non-renewable resources (like synthetic polymers and metals), have a high carbon footprint (such as aluminium), or rely on heavily demanded organic sources (like wood). The aim is to discover a material that competes functionally with conventional ones while offering sustainability benefits through the use of renewable resources, waste utilization, and a low overall carbon footprint.

Opposing the historically popular mono-layered wall systems, modern façades mostly make use of layer systems in which each layer has a specific purpose: weather protection, insulation, load transfer, installation, moisture barrier etc. (Klein, 2013).
The advantage that this gives us, is the flexibility of designing each layer to correspond to its specific function and to make selective replacements at eol for each individual layer.
Therefore, in this project, the outermost layer must address the following requirements:

- Protection from **precipitation** (rain, hail, snow)
- **Heat and UV** barrier (shielding the main facade from direct sunlight and providing a ventilation layer)
- Aesthetic **appearance** (significantly influencing the building's perception)
- Resistance from **impacts**

So how can we leverage the strengths of bio-composites to meet the challenges of exterior facade cladding?

Geometry
Rain-screen cladding is commonly made from sheet materials, but it also supports intricate design possibilities. Its flat form is well-suited to moulding techniques used for composites, which involve minimal shrinkage and allow for serial production with single or multiple moulds. This moulding process enables the creation of complex shapes and designs.
Based on the chosen production method, medium to large pieces up to 1,5 x 1,5m are producible (Masri et al., 2021), so anything from a small tile to large panels are possible. For a fitting size, design should account for the material strength and stiffness but also keep a suitable serviceability in mind, with allows for replacements without being wasteful.

Implementation
To install rain-screen panels, the pieces usually are secured on a substructure via a hook system, fasteners or bolts. Depending on the properties that the composite displays a variety of design options are suitable.
To bridge the gap between panels, they might overlap, interlock or an additional piece might be added.

Life-Span
In figure 18 average life spans of different layers of the building envelope is illustrated. For the building skin an average lifespan of 20+ years is allotted.
The durability of bio-composites can vary greatly based on formulation and design. Since no extensive investigation of the long term durability of a panel can be made here, we can only evaluate the feasibility and sustainability at theoretical life-span (see section 4.3.3), which is to be validated in further research.

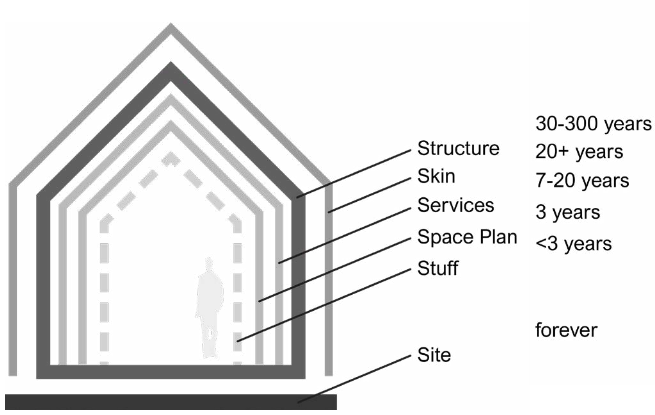


figure 18: Scheme of the shearing layers model, based on (Brand, 1994)

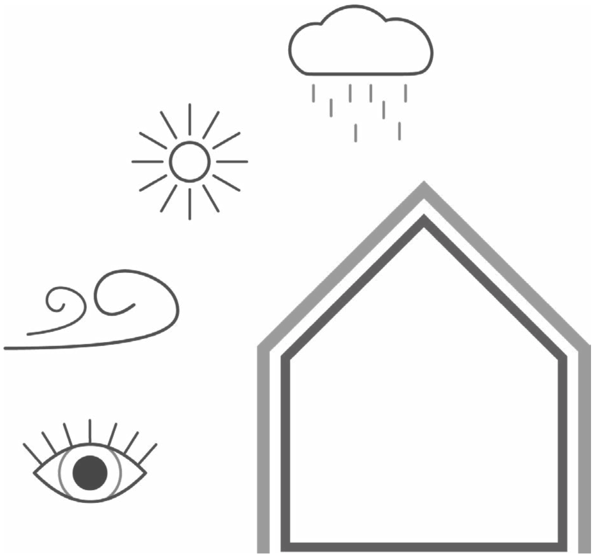
2.8 Target Application

Application Requirements

A facade is exposed to the elements. For a rain-screen facade panel, (sheet or 3D) the following criteria is relevant:

- Water resistance
- Ability to withstand wind-loads and self-weight (partially design dependent)
- Ability to withstand impacts and humidity (nature, human caused, weather related)
- Heat and UV resistance

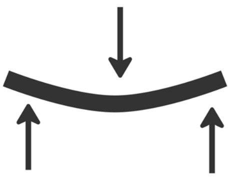
These points have to be fulfilled to a degree where both the functionality and the durability are within the range of the products planned lifetime.



Testing Methods

The following tests determine the functional and mechanical capabilities of the composite samples regarding the above mentioned criteria. It is to be noted that the fulfilment of benchmark parameters is influenced by both material and design. A comparison with other conventional materials properties helps to put the test results into perspective.

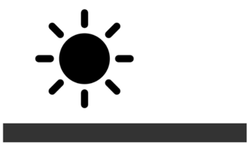
Flexural Strength:
The bending strength can be calculated by referring to the standard relationship between the loads, span length and width and thickness of the sample and the deflection produced during the test.



Water and Frost:
Instead of testing the effect of all weathering influences (UV, water, frost) together, the absorption properties and reaction to repeated freezing and unfreezing of the material can be tested at least.
This gives an indication on how sensitive the composite is to changing temperatures and exposure to water.

Impact Resistance:
Facade panels can be exposed to a variety if impacts like hail, bird-stikes, human impact or tree branches. To evaluate the resistance of polymeric materials the Izod impact test of the Charpy test are used. In both methods a sample is hit by a pendulum with a specific force which breaks the specimen. The absorbed energy is then recorded. A commonly used standard for sample preparation is ISO 179 which is applied for the testing in phase 1 and 2 of this project where the pendulum equalled 1 joule.

Weathering:
To simulate the natural weathering of exposed facade surfaces, weathering machines can imitate cyclical exposure to temperature fluctuation, UV radiation and moisture. Since this procedure takes about 6-8 weeks and such a machine was not available for the time of this project, instead water absorption test and cycles of freezing and defrosting the saturated samples should indicate the materials fitness to withstand the outside environment.



2.8 Manufacturing Methods

Manufacturing

For the processing of polymeric composites several moulding options are commonly applied. To choose the right method for the use with bio-based fillers and bio-plastics, the advantages and disadvantages of each method are looked at in respect to the planned use of materials. Different techniques enable or hinder the use of certain materials, which is being taken into consideration.

Some methods are only applicable in large industrial set-ups or alternatively allow for small scale development with simpler methods. The energy consumption of each method might vary depending on the complexity and heat requirements.
The chosen technique also defines the degrees of architectural freedom, the geometrical limitations of the product and the complexity and price of the equipment.

Injection Compression Moulding:

The process of injection compression moulding is a high precision industrial moulding process taking about 3-5 minutes per piece (Masri et al., 2021). Melted plastic is inserted into a mould that is clamped closed. After the material solidified, the mould is opened and the piece is taken out. This process is not fit for dry woven fibre reinforcement and long fibres in general. Fillers and short fibre bundles can be added to the matrix before injection. Since the process requires an industrial setup for heating and injection, the process is well suited for large quantity productions only (Masri et al., 2021).

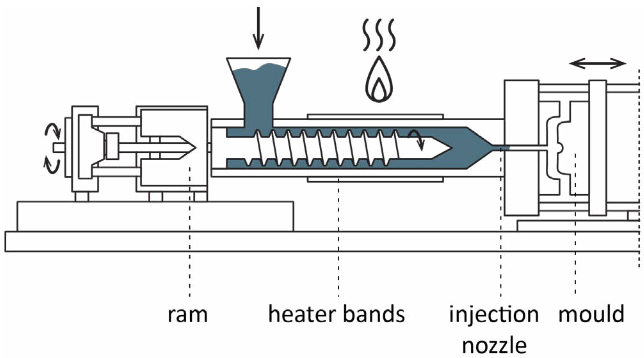


figure 19: Injection molding, schematic based on (Kula et al., 2013)

Resin Transfer Moulding:

In resin transfer moulding (RTM), dry woven fibres as placed in a mould which is then closed. In the next step resin is injected at a high temperature in a perpendicular direction to the fabric, to avoid shifts of the fibre reinforcement. The resin is either injected at high pressure or with a vacuum created inside the mould, which warrants a good impregnation of the fibre material all the way through. The challenges of this manufacturing method are possible dry spots or flow lines of unevenly distributed resin. With proper calibration this method provides a high-quality finish and excellent impact strength. This method can be used in an industrial setup but is also possible for smaller applications (Masri et al., 2021).

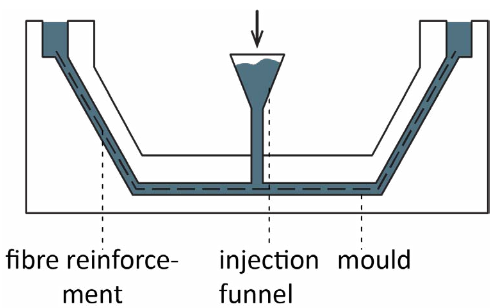


figure 20: Resin transfer molding, schematic based on (Masri et al., 2021)

2.9 Manufacturing Methods - Moulding

Cast-Moulding:

Cast moulding requires a liquid resin which is poured into a mould. This process is very flexible and can be performed on a non-industrial basis. One piece can be produced at a time. Cast moulding can be done with open casts or closed casts comprised of several pieces that can be taken apart. Liquid resin is poured into the mould, the air escapes through venting holes. The casting process relies on gravity. The lower compression leads to less stiffness of the parts. Depending on the resin the piece remains in the mould until cured (Kula et al., 2013).
The process allows for complex shapes but is not optimal for sheets because the likelihood of air inclusions is high. The use of this technique for bio-composites is limited but possible. Since no further compression is done it has to be made sure that all fillers are pre-saturated with the resin to ensure good cohesion.

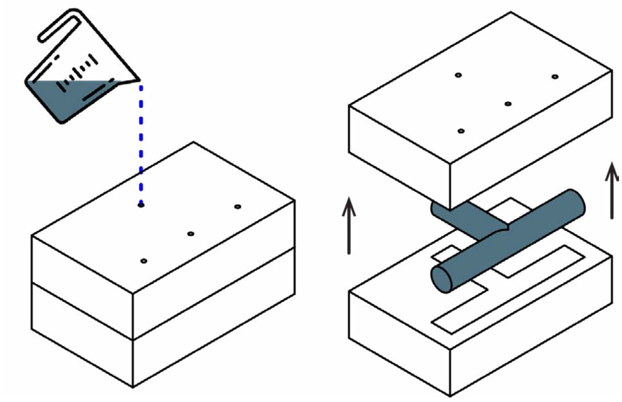


figure 22: Cast molding, schematic

Thermoforming:

In the process of thermoforming a sheet of polymer gets heated in a fixed frame. Then the sheet material gets formed via suction on the underlying mould by the creation of a vacuum below of the material, where it is left to cool.
A trimming of the material to the size of the mould is needed and the thickness of the material is limited in this process.
Since the process has no upper mould, the thicknesses of the resulting sheet might have higher variations, this is why the process is mostly used for packaging and similar low demand applications (Kula et al., 2013). For bio-composites this process might be usable, but the fillers might prevent even heating and the surface finish might be rough due to the stretching of the matrix.
Since the material is required to be in sheet format, this process would need to be combined with another production step to make the sheet.

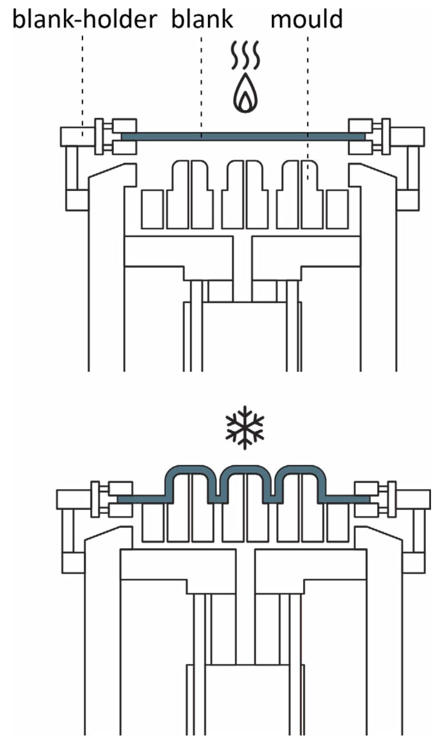


figure 21: Thermoforming, schematic based on (Kula et al., 2013)

2.9 Manufacturing Methods - Moulding

Bulk Compression Moulding:

Compression moulding, also called hot pressing is a process often used in the automotive industry. It entails the pressing of a bulk moulding compound (BMC) with high pressure on a preheated mould. The mixing of the ingredients requires and extra step, where the resin, mixed with fillers is pre-cured at a medium temperature and then cooled to create the dough like viscosity. In the mould the pressure and heat press the material into the shape of the mould.

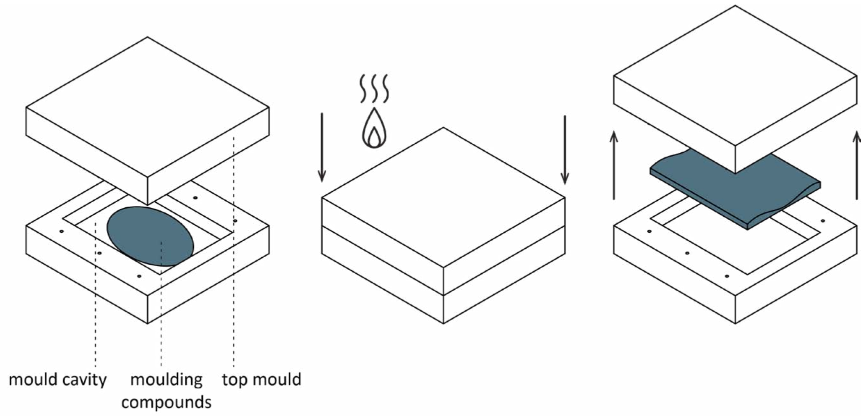


figure 23: Compression molding, schematic

The mould is then held in this position until the material solidifies. Advantages of the technique are a high-quality finish and little porosity. The process allows for a good degree of design freedom in which each of the press contact surfaces can be designed, which allows for varying thicknesses and two-sided sheet objects.

The process is well suited for granulated and short fibre fillers since the high viscosity of the heated polymer allows for even distribution. It is less suited for composites with woven sheet or layered long fibre reinforcement since the material can shift during the pressing process or be damages by the pressure. This technique well suited for high value products at lower numbers rather than high quantity applications (Masri et al., 2021).

Conclusion

Because of the compatibility with the use of bulk filler, which is the focus of this project, and the availability of the equipment, compression moulding is employed as primary production method for the experimental stage of this project. In table 4 the advantages and disadvantages of each method are summarised.
The company NPSP, which produces sheet panels and various façade panels from bio-composites with the compression moulding technique, gave us access to their equipment and could provide expertise on the method.

Method	Filler Type	Advantages	Disadvantages
Cast Moulding	Granulate, powders, short fibres	Low cost, no industrial setup needed	Imperfect cohesion with fillers, higher porosity
Injection Moulding	Granulate, powders, short fibres	Clean surface finishing, repeatability, less material loss	Expensive moulds, lower tensile strength then most thermoset systems
Bulk Compression Moulding	Granulate, powders, short fibres	Good for high quality products, suitable for large objects and complex shapes, low tooling cost	Longer processing time, mould can get damaged in the process
Resin Transfer Moulding	Dry woven fabric	Clean surface finishing, less void content, low tooling cost	Mould cavity restricts the size of components, restriction on choice of reinforcements
Thermoforming	No fillers, powder	Low equipment cost, complex shapes are possible, quick	Large losses of matter, a constant thickness is not guaranteed, compatibility with material composition has to be tested

table 4: Overview of Moulding Techniques, based on data from (Kula et al., 2013) and (Masri et al., 2021)

2.10 Chapter Conclusion

Chapter Conclusion

Bio-composites offer a flexible and promising solution for incorporating sustainable materials into construction projects.

The choice of fillers significantly influences the properties of these materials. Bulk fillers play a crucial role in maintaining the dimensional stability of composites, particularly when utilizing bio-based and waste materials, which can substantially reduce environmental impact.
In addition to fillers, selecting the appropriate matrix material is vital for achieving both functional and sustainable objectives. The use of a (bio-based) thermoset resin meets the demands of the application as facade panelling best. While fibres can enhance reinforcement in various ways, this aspect is not extensively discussed here.

Regarding the processing method, several ways of moulding have been explored. The compression moulding technique, is a good match for a filler/resin composite.
In the context of the circular economy, bio-composites hold the potential for minimal environmental impact by effectively utilizing available resources and re-purposing waste streams. This project will primarily focus on two R-strategies: reduce and recycle.
Waste materials from the food processing sector, such as cacao shells, spent coffee grounds, fruit pits, and nut shells, present promising options for use as fillers in composites. By incorporating these waste streams, the material can ascend in the value chain, contributing to a more sustainable approach to construction.

In this chapter these elements were selected for the experimental phase:

- furan resin as a thermoset matrix
- filler types: cacao bean shells, spent coffee, walnut shells and cherry pits
- compression moulding technique

3.

Material Choices

This chapter outlines the constitute materials of the bio-composite that will be used in the experimental phase of the project based on the results of the research in the previous chapter. An overview of the characteristics, material origin and use implications for the selected filler materials are given. Additionally the chosen matrix material is characterised and the choices are explained.

3.1 Material Choices - Selection Criteria

Context Criteria

The primary selection of filler materials happens by the materials context. The criteria listed below is ranked by relevance but is not an absolute measure, rather it is a guideline to which waste-sources might be preferable.

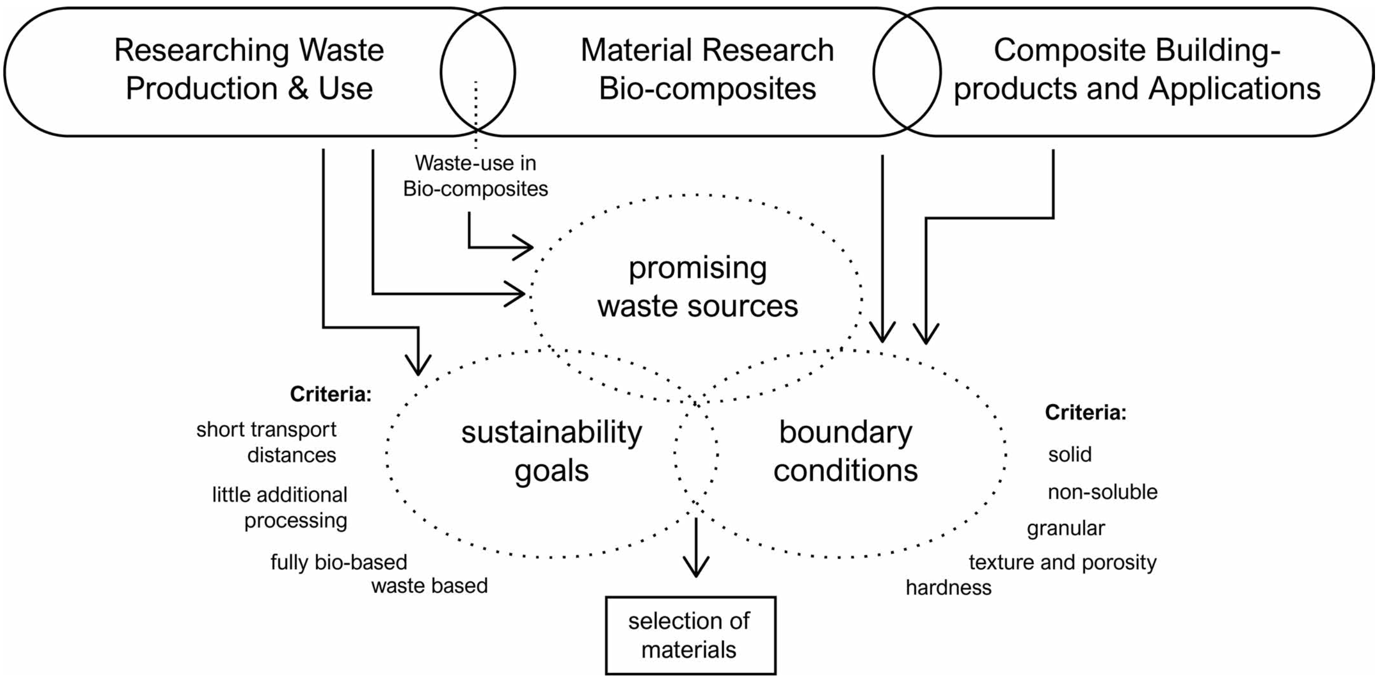
- ***Locality*** (Local availability of processes that produce waste in the Netherlands)
- ***Usefulness*** of the waste-stream (Are there alternative (and better) ways of using the material?)
- ***Ease of Processing*** (How much preprocessing is needed and how easy is it to handle?)
- ***Scalability*** (How much is available, could a reliable material flow be established?)

Material Criteria

The material requirements and selection criteria is relative to the context criteria. Since some of the parameters are not yet known, the material related decisions are made on informed assumptions and previous studies on the use of these materials.

- ***bio-based***
- ***solid***
- ***non-soluble***
- ***possibly hydrophobic***

- ***hardness***
- ***surface texture***
- ***porosity***



3.2 Material Choice - Matrix

Resin selection

The choice of matrix material was made by several criteria, and retained for all steps of the project as a fixed parameter.
The choice fell on a thermoset rather than a thermoplastic, based on the better ease of processing and the thermal demands on the material in a facade application. Thermosets are ideal for the impregnation of natural fibres and fillers and are on average more resilient to higher temperatures and UV radiation once cured.

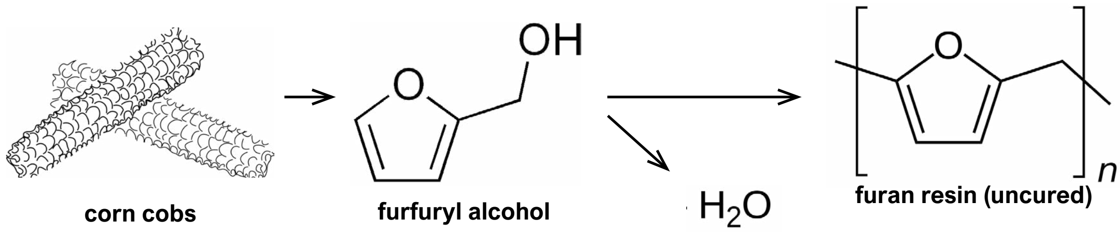
Selection Criteria for the Matrix:
- fully bio-based
- curable thermoset resin
- reasonable heat resilience

Furan Resin

Furan resin is a bio-based resin derived from furfuryl alcohol which is produced from bio-waste such as corncobs, sugar-beet or sugar-cane bagasse (Biron, 2013). The resin is a curable thermoset with high heat resistance and has a dark brown colour. Since the company NPSP was using the same material with their machines it seemed like a fitting material for this project.
Furan resin is available in different consistencies and formulations. The resin used for this project is a VOC-free (Volatile Organic Compounds) variant called “BioRez” by a company from Belgium.

Material Source:
TransFurans Chemicals, Belgium

Chain of Production:



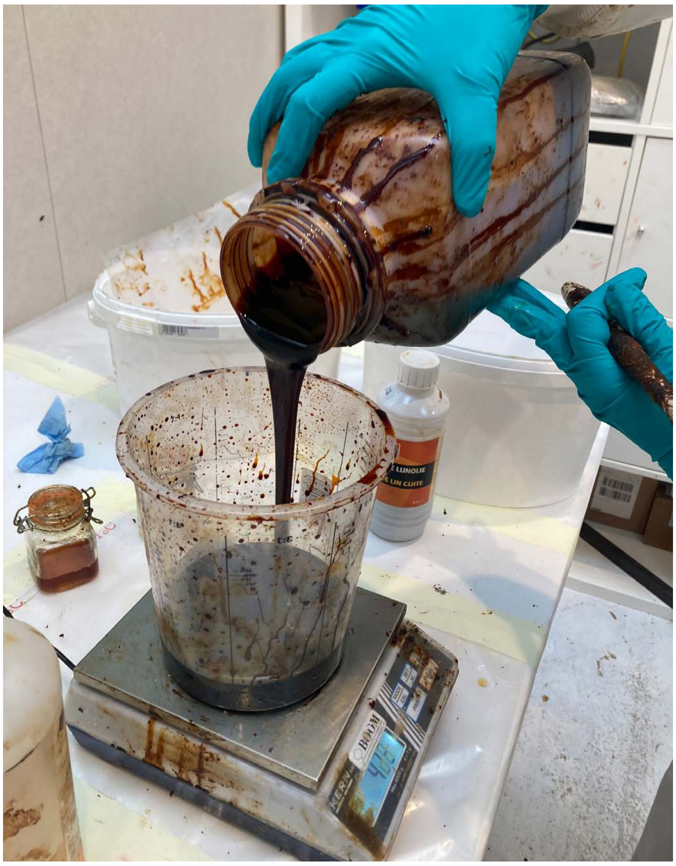


figure 24: Uncured furan resin

figure 26: Typical use of furan as binder for sand casting moulds (vietnam-castiron.com)

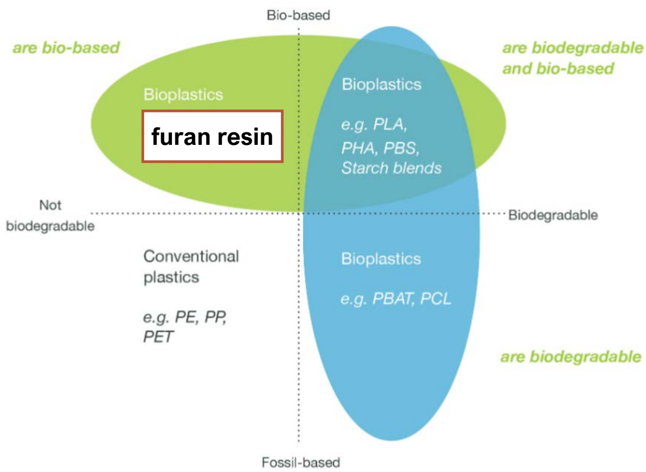


figure 25: furan resin compared to other bio-plastics

3.3 Filler Choices - Cacao Bean Shells

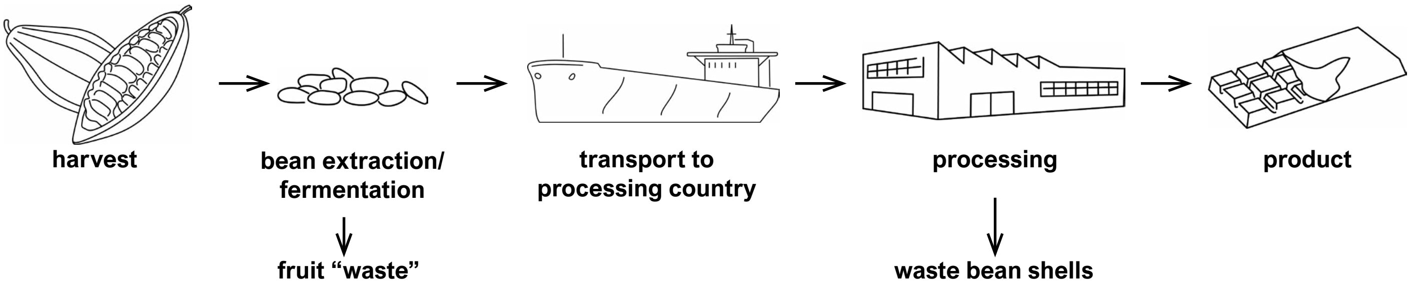
Cacao Bean Shells

The thin shell of the cacao beans is a common by-product of the process of chocolate making. In the winnowing process the inner bean gets separated form the shells with the help of an air stream, that blows away the lighter shell. The shells have a brittle texture and smell strongly of cacao.

Pre-Processing:
No particular pre-processing needed as the material arrived dry and clean. Milling and sieving for the right particle sizes is necessary.

Material Sources:
Crown of Holland, Netherlands (chocolate processing company)
Contacted companies:
Crown of Holland B.V.; Daarnhouwer & Co. B.V.

Chain of Production:



Roasted and Unroasted
After the import of the dried and fermented beans, they are roasted, winnowed and crushed.
Depending on the process and the factory, these steps might be performed in varying order. If the beans are roasted first, the shell is still attached and is removed after. In some processes the beans get crushed and the shells are removed before roasting, which leaves them with a higher moisture and lipid content (Gutiérrez-Macías et al., 2021).

In this project both types of cocoa, roasted and unroasted, are tested as a filler, to establish whether the roasting process has a relevant impact on the properties of the filler. In figure 17 the two production lines of the processing company 'Crown of Holland', who supplied the shells for this project, is illustrated.

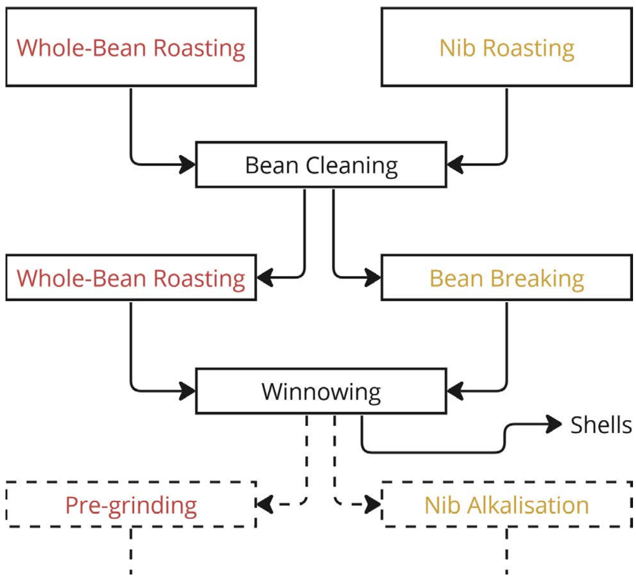


figure 27: Two ways of processing cocoa beans, schematic based on (https://www.crownofholland.com/processing)

figure 28: cacao bean shells, two types

3.3 Filler Choices - Coffee Grounds

Coffee Grounds

Coffee grounds as a waste product can be sourced from various sources. Spent coffee is a waste product with reliable supply from local businesses, cafeterias and hospitals but can also be sourced in larger amounts from food processors that produce instant coffee, drinks and deserts.
For this project two types of coffee where used: Spent coffee from a local café and coffee from a company that extracts coffee oil for cosmetic products.
Both types of coffee looked nearly identical but had a difference in odour. The spent coffee had a marginally more acidic odour while the de-oiled coffee had the fragrant smell of fresh coffee.

Pre-processing:
The spent coffee gathered from the local cafe was air-dried and then dried at about 90°C until fully dry. The particle sizes of both coffee types were of no larger than 500 μm and had to be milled and sieved.

Types: dried spent coffee, de-oiled coffee (mix of spent and unused) sold by Caffe.inc
Material Sources: Espresso Bar in the BK building, Caffe.inc
Contacted companies: Local Coffee businesses; Caffe.inc

Chain of Production:

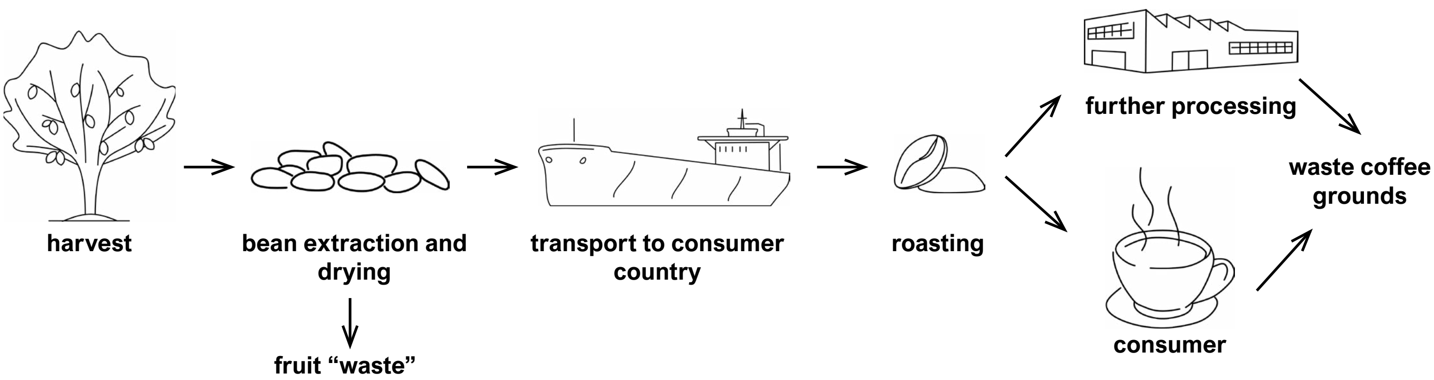


figure 29: ground coffee, two types

"De-oiled" coffee grounds
Caffe.inc is a Dutch company that collects rejected coffee from the industry and spent coffee from hospitals, universities and chains. The company then extracts the coffees oil which they sell as a cosmetic product.
The leftover de-oiled coffee gets sold for the use in scrubs, soil-improver or for bio-materials. The ratio between rejected (fresh) coffee grounds and spent coffee was not disclosed by Caffe.inc.

figure 30: de-oiled coffee "Coffee blocks" (source: caffeinc.nl)

3.3 Filler Choices - Fruit Pits

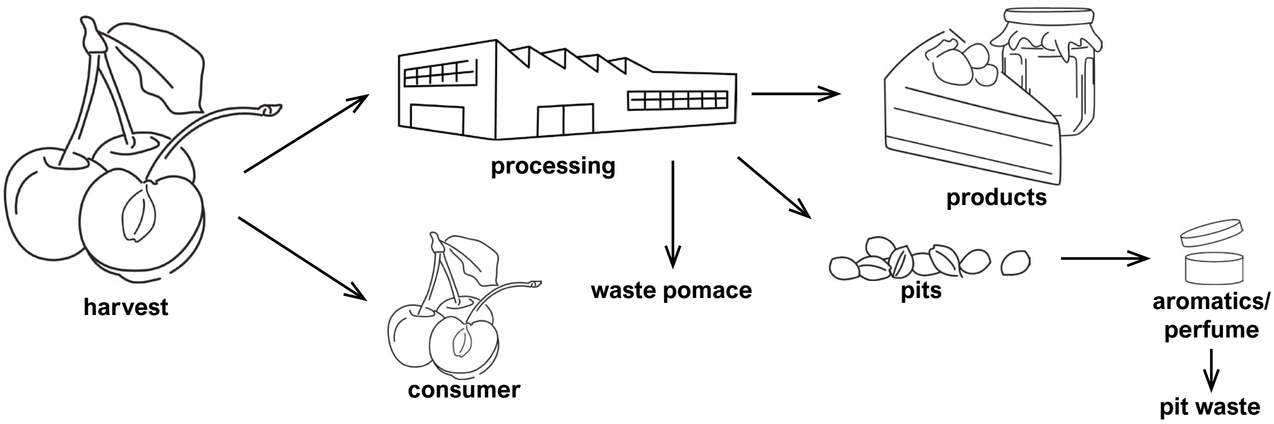
Cherry Pits

Compared to other stone fruit cherries are cultivated in the Netherlands and other neighbouring countries, which is why cherry pits were chosen for this study. Other local stone fruit are plums and prunes.
Cherries pits contain amygdalin which gives them an almond like aroma. The inner pits are used for the production of aromas and cosmetics (Burgstaller & Renner, 2023).
The processed shell and pit get discarded and are often incinerated (Raut et al., 2023).

Selection - Fruit Pits

The pits of stone fruit are a promising material for composites. The packaging and sale of fresh fruit leaves damaged or unripe fruit which are going to waste. In the production of deserts, sweets and conserves fruit pits are produced as a waste material. However, many stone fruit are imported already processed without the pit. Fruit grown and processed in the Netherlands are predominantly apples, prunes, plums and cherries (Nuts & Dried Fruits Statistical Yearbook 2022/23, 2023).

Chain of Production:



Material Source: Private person

Pre-Processing:
The cherry pits arrived dry and reasonably clean with only little fruit flesh left on them. Pre-processing steps from an industrial source might include washing and drying the pits. Milling and sieving is needed.

Contacted companies:
Fruit Management Europe B.V.; VS Apple Industries B.V.; Aarts Conserven B.V., Fruitleather Rotterdam

figure 31: cherry pits

3.3 Filler Choices - Nut shells

Selection - Nut Shells

Generally nut shells seem to be a promising filler source as they are mostly hard and brittle and nuts being a popular ingredients in snacks, deserts and bakery products.
Similar to stone fruit, many nuts that are imported to the Netherlands already without their shell, since the cracking process is less expensive in the countries of cultivation. Nuts cultivated in the Netherlands or in neighbouring countries are therefore the best source for this waste product. The local production of walnuts in the Netherlands is estimated to be about 300t per year, of which most growers process their harvest in-house and bring products to the local market (de Visser et al., 2015).

Walnut Shells

Description: Walnuts have a hard shell and a thin membrane on the inside that separates the two halves. The shells in this project made up about 50% of the nuts weight. This ratio might vary for different walnut varieties.

Material Source: Store-bought unshelled walnuts from Belgium

Preprocessing: Cracking and separating the nuts from its shell, grinding and milling.

Contacted companies: Snack Connection B.V.; Nederlandse Notenvereniging; Nutto & Frutto B.V.

Chain of Production:

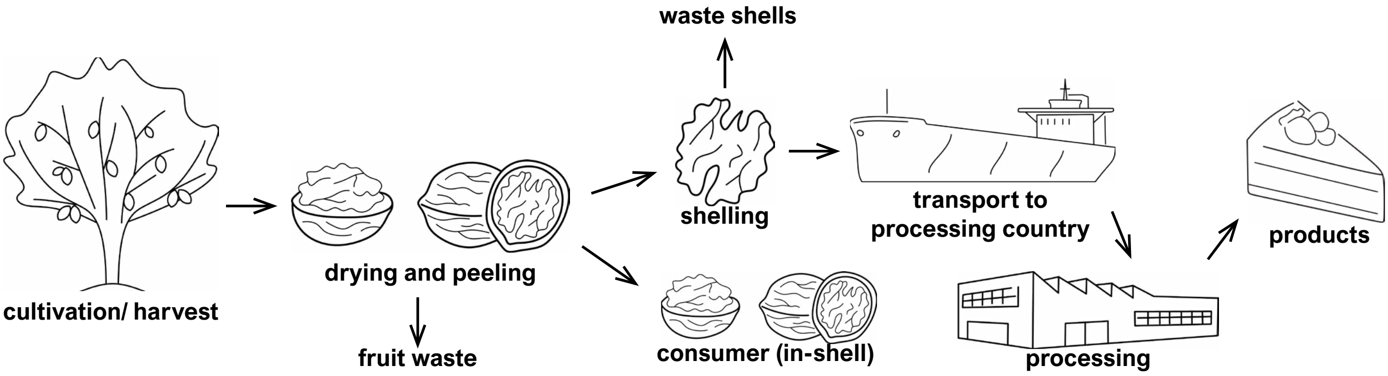
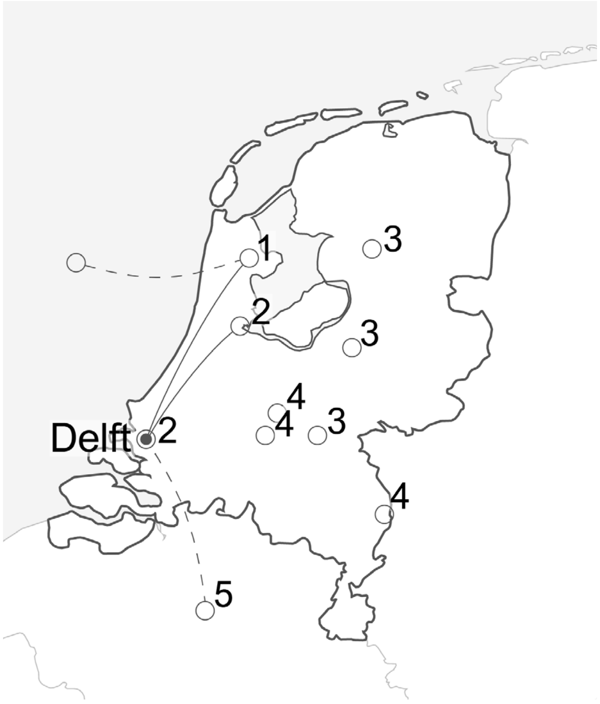


figure 32: walnut shells

3.4 Chapter Conclusion

Locations of Potential local suppliers



1. **Cacao Bean Shells:** Chocolate processing company, Middenmeer

2. **Coffee (spent and de-oiled):** Local buisnesses, Delft; Cosmetic Coffee oil producer, Amsterdam

3. **Walnut shells:** Regional Plantations and nurseries, Examples: Nunspeet, Ochten, Kallenkote

4. **Cherry Pits:** Regional Plantation with own production, Examples: Buurmalsen, Zoelmond

5. **Furan Resin:** Chemical Factory, Geel, Belgium

Conclusion

The choice of materials gravitated towards locally generated waste products. Since the number of possible sources was vast, a selection of one type of fruit pit (cherry) and one type of nut shell (walnut) was made, based on which products are not only imported but also grow locally in the Netherlands or surrounding countries.

Contacting companies about their waste products yielded very different results based on the sector.
Very positive feedback was given from the chocolate and fruit processing industry, with high reply rates and interest in the project.
Problems in acquiring testing material were encountered in the nut industry, as farmer associations and processing companies responded negatively or not at all.

The selection of six different filler types in combination with bio-based furan resin is the base of the experiments in section 4.

4.

Experiments

The experimental design chapter is divided into:
Phase 1A which explores the compatibility and performance of the six different waste-based fillers on a functional and mechanical basis.
Phase 1B looks more intensely into the fillers material properties.
Phase 2 investigates the effects of filler size and composition on the composite properties.
Phase 3 compares the resulting composites with other materials in a façade panel setup, with supporting experiments. Overall the experiments are designed for the intended use-case of a facade panel application and each step narrows down the material choices and composition based on phase specific evaluation criteria.

4.0 Workplan

Objective:

The objective of this study aims to evaluate the usefulness and benefits of varying waste-sources for the use as bulk filling in composite facade panels.
The filler material is considered for multiple criteria. The mechanical and structural properties should be adequate for a rain-screen facade application. The ratio of filler and matrix material as well as grain size are explored to maximise sustainability and cost merits while still fulfilling all functional demands.

The last part of this study aims at demonstrating the additional worth and comparability of the proposed composite in a comparative scenario both by the materials properties and through smart design.

Synthesis:

The previous literature review and investigation of waste-sources as well as manufacturing methods for bio-composites concluded in the following derivations:

- Furan resin as a polymeric matrix
- 6 Filler materials from local waste-sources
- A selection of manufacturing methods for pre-processing and moulding
- From literature review and in discussion with NPSP we gathered an understanding of composition and processing practise of similar material classes, which gives a starting point for the exploration of recipe and methods.

Geometry:

There are may shaping options for bio-composites which can be a unique strength of the material class.
Phase 1 and 2 focus on material properties alone, with phase 3 considering different design and shaping options.
Still, an appropriate geometry for the first phases has to be chosen in regards to the intended application of the material use.
With the aim at a rain-screen facade application and the available moulding techniques, a sheet geometry is the best fit.

Evaluation Criteria:

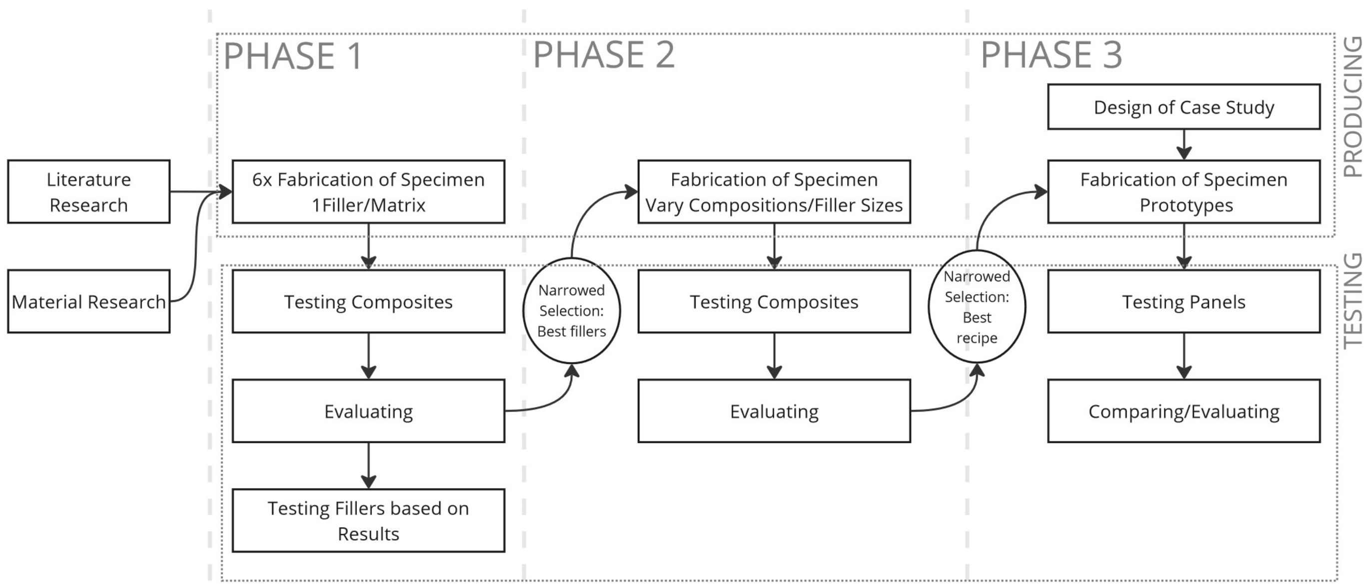
The criteria with which the results of each step and the decision making for the following steps are made is based on what each step aims to reveal.

The choices of waste-flows are based on the local availability of bio-based and non-solvable waste material with secondary criteria of scalability and consistent quality.

The criteria for the results of the first phase focuses on the mechanical and functional properties derived by the compatibility of the filler materials with the resin matrix.
In phase 2 the criteria by which the best composition is chosen is composed by the best balance between the filler content (which influences the waste-based content and therefore improves price and material preserving behaviour) and the mechanical/functional properties.

Experimental Roadmap

The approach for the experimental exploration is divided in three mayor phases which each include a specific objective, the production and testing of specimen.



4.1.1 Design of Experiment - Phase 1A

PHASE 1A

Goal:
The goal of this part is to evaluate the benefits of different filler materials and find the ones with the biggest potential.

Action:
Of each waste type a composite on furan/filler basis is created. The sample plates are milled into test samples according to the applied testing norms and tested for bending strength, impact resistance, water absorption and frost resistance.

Parameters:
The only variable of the sample sheets is the material of filler.

The filler materials to be tested are:

a. Cacao bean shells, raw
b. Cacao bean shells, roasted
c. Spent coffee grounds
d. Deoiled coffee grounds (Caffe.inc)
e. Walnut shells
f. Cherry pits

The recipe, particle size and moulding process remain the same for each composite.

Recipe:

Component	Description	Weight %
Resin	Furan resin	50
Filler	Powdered filler, **<125 µm**	45
Catalyst	HM1448 ((2-hydroxyethyl) ammonium nitrate)	3
Releasing Agent	Linseed oil	2

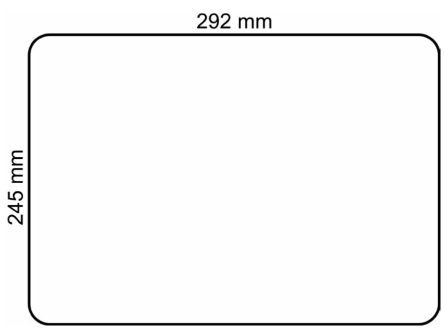
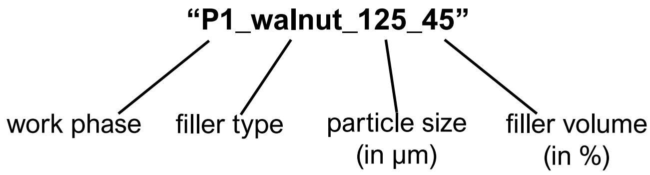


figure 33: Format of sample sheets

Samples:
The composites are fabricated in sheet format with the dimensions of 245 x 292 mm with 500g of dough, which results in a plate of about 5mm thickness.
Each plate of this phase as well as the following phases is named with this scheme:



In Phase 1A the following samples were produced and tested:

- P1_cacao_raw_125_45
- P1_cacao_roasted_125_45
- P1_spent_coffee_125_45
- P1_deoiled_coffee_125_45
- P1_walnut_125_45
- P1_cherry_pits_125_45

Equipment used:
All steps of the specimen production were performed at the company NPSP under partial supervision of Dimitra Tsoli, Zoya Zarafshani and Aditia Babu.

Ingredients:

Filler material: aquired from different sources including factories, local buisnesses and privately.

Furan resin: The brand of resin, provided by NPSP, is called BioRez and is a VOC-free, fully bio-based resin from Trans Furan Chemicals (TFC).

Curing Agent: The catalyst HM1448 (by TFC), used to accelerate the curing process, was provided by NPSP.

Releasing Agent: Linseed oil, provided by NPSP is used to ensure easy removability of the Piece from the mould.

4.1.1 Design of Experiment - Phase 1A

Equipment for milling and sieving:

Ball Mill - Fritsch, Pulverisette

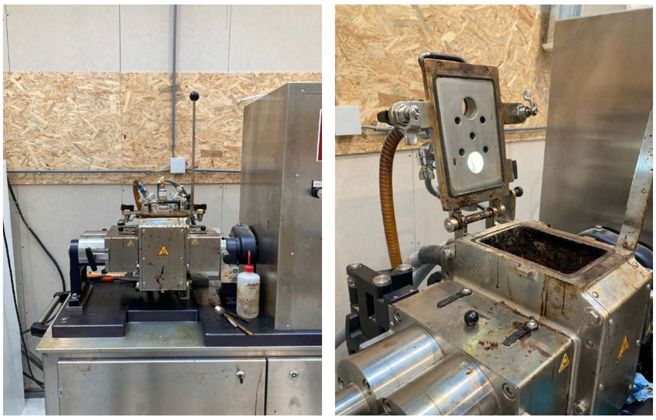
Herb Grinder - Moulinex, AR1108 Pulse Grinder and Hand-grinder, granite

Sieving Tower - Fritsch, Analysette 3 Spartan

Other - Scale, bucket, brushes, cups

Equipment for mixing:

Kneader - Linden, Type K Double-Z-Kneader



Other - Scale, measuring cups, gloves and face mask

Equipment for pressing:

Hot-press - Bucher, Hydraulic Press

4.1.2 Preparation of Samples - Phase 1A

Procedure

The same procedure was executed for each individual filler material.

Step 1 - Milling of material
Milling of the filler material into fine powder, using the ball-mill and herb-grinder.
The ball-mill works best for brittle materials (cacao beans , coffee) and had limited functionality with larger pieces (walnut shells), which is why the herb-grinder was used complementary.

Step2 - Sieving the particles
The powdered filler is sieved to determine particle sizes. The powder with grains of 125 µm and smaller are collected. Step 1 and 2 are repeated until enough powder of the right size is accumulated.

Step3 - Drying of the filler
To avoid any kind of leftover moisture, the filler is spread on a tray and oven dried at 110°C for approximately 2 hours.

Step4 - Measuring the ingredients
All ingredients are measured by weight.

Step5 - Adding liquids to the kneader
All liquid ingredients are added to the kneader which is heated to 95°C (Resin, Catalyst, Linseed Oil). The mixture is heated up under stirring for 10min while a vacuum extracts evaporating moisture. The un-cured resin and the catalyst naturally contain a small amount of water.

Step6 - Adding the filler to kneader
The filler is added to the mixture and everything is kneaded for another 5min until a homogeneous dough is created. The dough is taken out of the kneader.

Step7 - Moulding
The preheated mould of the hot-press is brushed with oil. The dough, now medium warm to room temperature, is added to the mould which is then closed. At 150°C for 15min the specimen is cured at about 60 Bar pressure.

Step8 - Cooling
After the release from the mould the specimen cools down under a heavy plate, to ensure a flat surface.

Observations

Milling and Sieving:

The material needed to be very dry to be milled and sieved. Harder material was easier to sieve but harder to mill. The ease of the pre-processing steps varied between the materials.

Filler Type	Milling	Sieving
Cocoa shells, raw	Easy	Easy
Cocoa shells, roasted	Easy	Easy
Coffee, spent	Easy	Difficult (wet)
Coffee, de-oiled	Easy	Difficult (wet)
Walnut shells	Medium difficult	Easy
Cherry Pits	Medium difficult	Difficult (wet)

The sieving worked best for the heavier materials. The two types of coffee grounds and also the cherry pits could not be sieved easily due to agglomeration on the sieves (figure 34) . For the coffee the finer powder tent to build a layer on the bottom of the sieve or build larger clumps. The cherry pits, have a hard shell but a softer core which produced a mushier powder which seemed to stick to the sieves.

figure 34: Agglomeration on the sieves (de-oiled coffee)

Step 2 alternative - Wet sieving
To solve the problem of agglomeration, the coffee and cherry pits were wet sieved, which was done by adding water to the powder in the sieve and washing out the finer particles into a bucket from which they could be filtered out later. This slowed down the process as the particles had to be dried again before further processing. On an industrial scale it might be easier to get to the desired grain size with the aid of other milling methods.

4.1.2 Preparation of Samples - Phase 1A

Observations

Mixing:

For all filler types the dough had a dense, slightly crumbly texture (a bit like clay) with minor differences (figure 35). The only bigger difference in texture of un-pressed dough was between the dried coffee and the de-oiled coffee as seen in figure 36. Compared to the other doughs the de-oiled coffee was more compact and elastic.

figure 35: Pre-cured dough, Filler: Roasted cacao shells

figure 36: Two doughs: Spent and de-oiled coffee filler (top to bottom)

Observations

Pressing:

Both composite with the cocoa shell fillers and the de-oiled coffee filler composite turned to have uneven surfaces and tiny cracks on the surface of the sheet. These "bubbles" developed only after the extraction from the mould, in the cooling down phase. Possible reasons are discussed in section Phase 1B.

The composites of walnut, and spent coffee had an even, shiny surface with close to no bubbles. The cherry pits also had an even surface with smaller gaps and a slight marbling effect on the surface.

500 grams of dough resulted in one plate of about 5,2mm thickness. The thickness of the same plate varied on average about +- 0,1mm in different spots.

4.1.3 Testing - Phase 1A

After finishing the production of sample plates, they were tested for their mechanical and functional properties.
With the intended final application in mind the following material properties give an indicator about the usability:

- Bending strength
- Impact resistance
- Water absorption
- Frost resistance
- (Surface texture and Appearance)

Preparation of Specimen

From the sample sheets, three sizes of samples were cut with a CNC mill (figure 39).
With priority to the samples for the bending test, according to ISO 14125A (International Organisation for Standardisation, 1998) and the impact test ISO 179 (International Organisation for Standardisation, 2023) the following specimen were cut:
 9 specimen for **flexural** testing
12 specimen for **impact** testing
 5 specimen for **absorption and frost** resistance

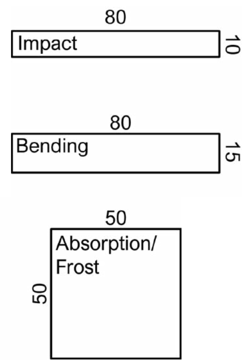


figure 39: Sample dimensions (in mm)

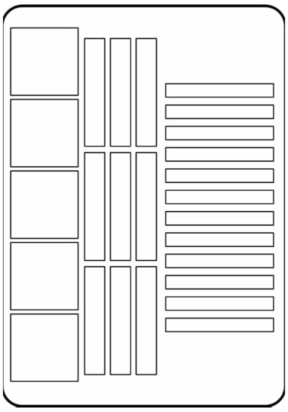


figure 40: Layout for CNC-Milling

Three Point Bending

Procedure:
After measuring the dimensions and weight of a sample with a calliper and scale (0,01g precise), it is bend until fractured in a three-point bending setup on a universal testing machine (UTM). 5 to 8 Samples were tested per material variant.

Standard: ISO 14125A
Sample Size: 5mm x 15mm x 80mm
Hardware: Instron 5969 testing system, scale, calliper

figure 37: UTM with 3-point bending setup

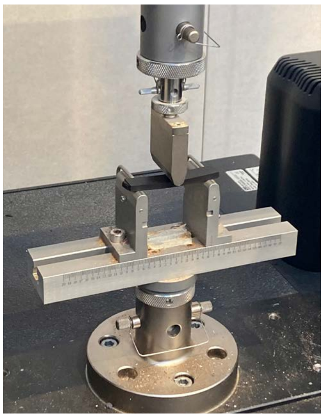
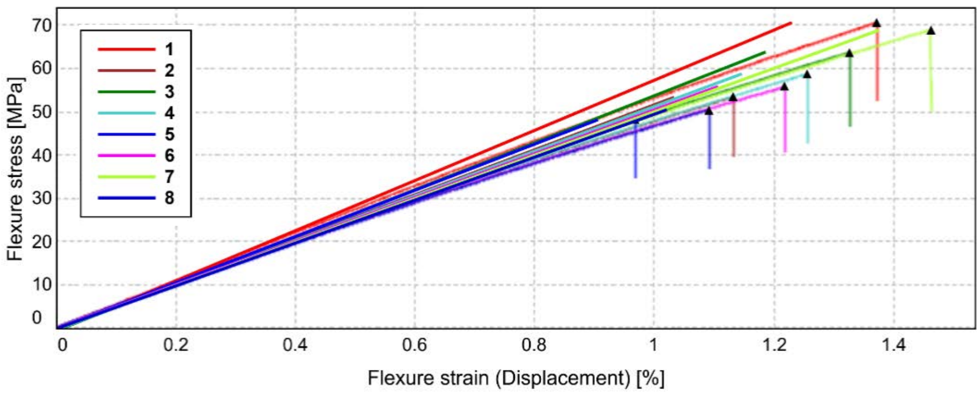


figure 38: Sample being tested (Spent Coffee)

Measurements:
The UTM outputs a detailed report for a group of samples, including the deflection, loads, calculated bending strength and modulus.
It is to be mentioned that the 3-point bending setup is more uncertain in its results compared to 4-point bending since the maximum flexural moment is applied only at the centre compared to a wider length in 4-point bending. So the test will reveal only the capacity of that specific section rather than a picture of the larger samples quality.



graph 1: Plotted results of bending test (walnut /furan composite)

Observations:
Of the sample plates that showed surface bumps, some samples could not be used for testing since they already showed longitudinal cracks within the material cross-section. All samples displayed brittle failure with no plastic deformation (graph 1).

4.1.3 Testing - Phase 1A

Charpy Impact Test

Procedure:
The charpy impact test determines the impact resistance by measuring the energy absorbed by a pendulum breaking a sample. Before the testing the pendulum of the test setup is released several times and the energy loss without a sample is noted to determine the relative error. After measuring the thickness and width of a sample, it is placed on the testing stand and then impacted by the 1 joule pendulum.
The absorbed energy can be read from the scale attached to the pendulum. At least 10 specimen were tested for each material.

Protocol: ISO 179
Sample Size: 5mm x 10mm x 80mm
Hardware: HY4251 Charpy impact tester

figure 41: Charpy Impact test pendulum

figure 42: Sample on testing stand

Measurements:
The swinging angle of each measurement was later converted into the charpy impact as follows:

$$\text{Charpy Impact [kJ/m}^2\text{]} = \frac{\text{Absorbed Energy}}{\text{Sample Cross-section}}$$

$$\text{Absorbed Energy} = 1\text{J} - \left(1\text{J} \times \frac{\text{Measured Angle}}{\text{Maximum Angle - Average Hammer Absorption}} \right)$$

Observations:
All samples fractured completely upon impact.
Usually the fracture pattern showed a compression curl on the side of the impact, similar to the bending samples (further described in section 4.1.7).

Water absorption

Procedure:
The samples are dried at 90°C for 2h to ensure they are fully dry. After noting their dry weight, three samples of each material variant are submerged in small containers with water at room temperature. The weight gain of each sample is measured in intervals of 24h until no change can be observed. Three samples of each composite variant were submerged.

Protocol: (modified ISO 62)
Sample Size: 5mm x 50mm x 50mm
Hardware: Measuring cups, water, scale, room thermometer

figure 43: Water absorption

Measurements:
The water absorption in percent is determined by the difference to the start weight. Since three samples were taken of each composite type, the results are an average.

$$\textbf{Water absorption [\%]} = ((W_1 - W_0)/W_0) \times 100$$

W_1: Wet weight; W_0: Dry weight

Observations:
The composites that showed bumps and cracks (Filler types cacao and de-oiled coffee) tinted the water light brown after a while, which coincided with a slight loss of mass after full saturation was reached. This implies that part of these fillers are soluble in water.
Only three of the six sample types reached full saturation within 28 days which were the raw and the roasted cacao bean shell and the de-oiled coffee. After 28 days the experiment was ended.

4.1.4 Testing - Phase 1A

Frost Resistance

Procedure:
Taking the saturated samples of the water absorption test, the samples are dried of with a cloth and weighted.
The samples are placed in individual plastic bags and placed in the a freezer.
After 8h the samples are removed from the freezer and thawed at room temperature for 4h, after which they are again placed in the freezer.
This cycle is repeated 10 times.

Sample Size: 5mm x 50mm x 50mm
Hardware: Plastic bags, paper towels, thermometer, freezer

Temperature: The temperature of the freezer was measured at about -17°C. The thawing was done at room temperature of about 19-20°C.

Measurements:
For this test the samples are observed for surface damages, cracks, change in texture or colour and materials loss due to the freezing. Also the weight before and after the freezing cycles are measured to quantify material loss.

Observations:
After the freeze-thaw cycles no significant material loss could be observed.
However the composite that already showed bumpy and cracked surfaces to begin with developed a very rough surface and the surface fissures opened up (see figure 44).
Also the colour of the samples with cacao shells and cherry pit filler became lighter, turning from almost black to brown.

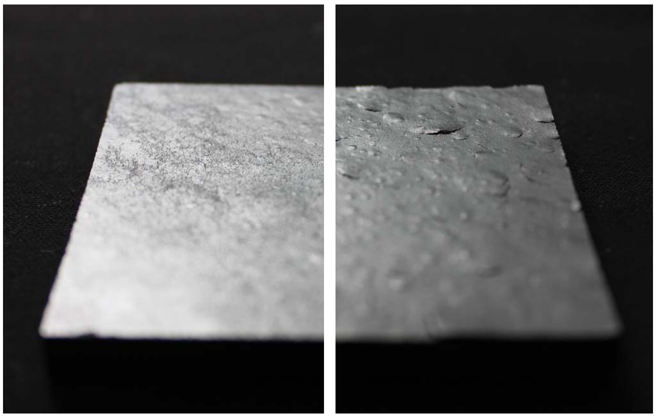
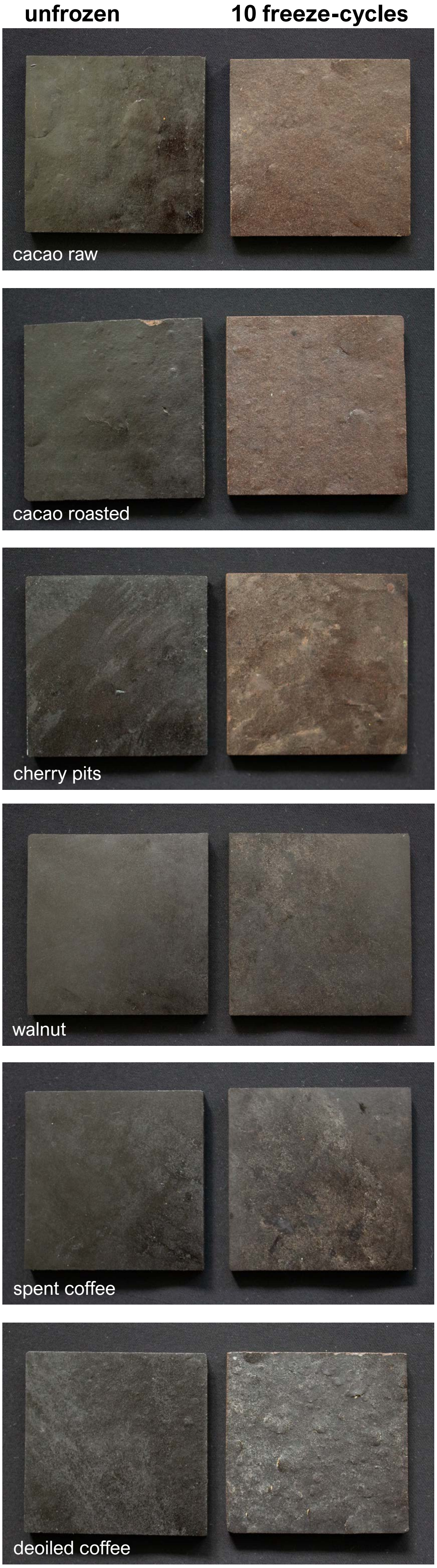


figure 44: de-oiled coffee composite before (left) and after 10 freeze cycles (right)

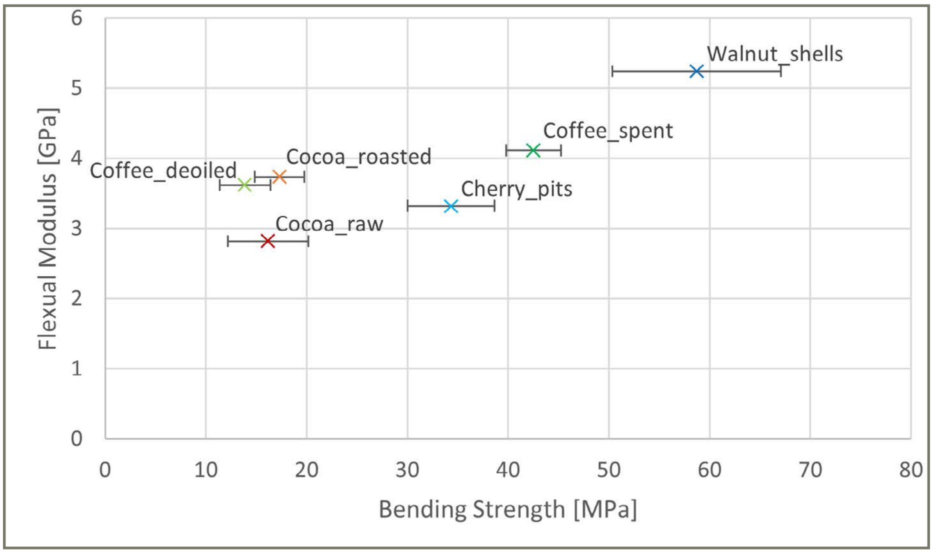


4.1.4 Results - Phase 1A

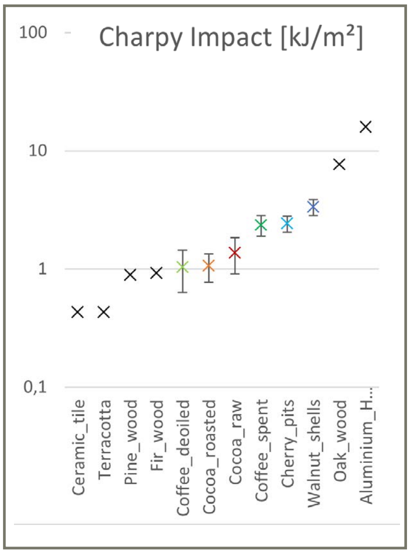
Results - Impact and Bending

The bending test showed brittle failure for all material variants. The highest bending strength and impact resistance could be observe for the walnut/furan composite, followed by cherry pits and spent coffee (graph 2,graph 3).
The stiffness of most samples was corresponding to their strength. The roasted cacao composite showed a higher stiffness than the raw cacao composite at about similar strength.

Visually the two cacao filled composites and the de-oiled coffee showed bumps and cracks.
Their lower performance in impact resistance and bending can be ascribed to that.
The whiskers on the diagrams below signify the standard deviation of the test results. Surprisingly the walnut composite showed a high variance of results in bending, compared to the other materials (8 specimen tested for each).



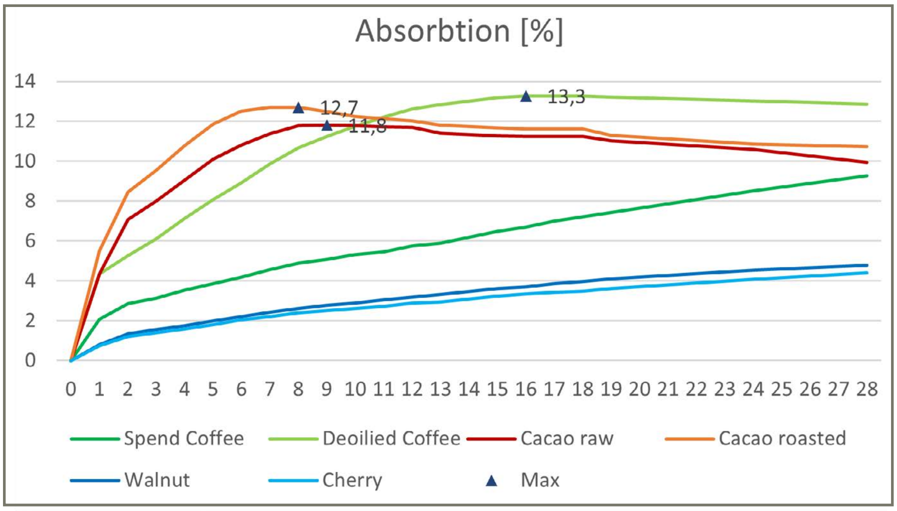
graph 2: Results of 3-point bending test



graph 3: Results of impact test

Results - Absorption and Frost Resistance

The absorption of water corresponded with the visual occurrence of bumps and tiny cracks on the surface of the composites (de-oiled coffee, cacao), as was to be expected.
For the cacao shell based composites, a drop in mass could be observed after full saturation, which seems to be caused by the washing out of soluble components of these fillers, which also reflected in the tinting of water. The lowest absorption showed the walnut and cherry pit composites with only about 5% after 28 days.

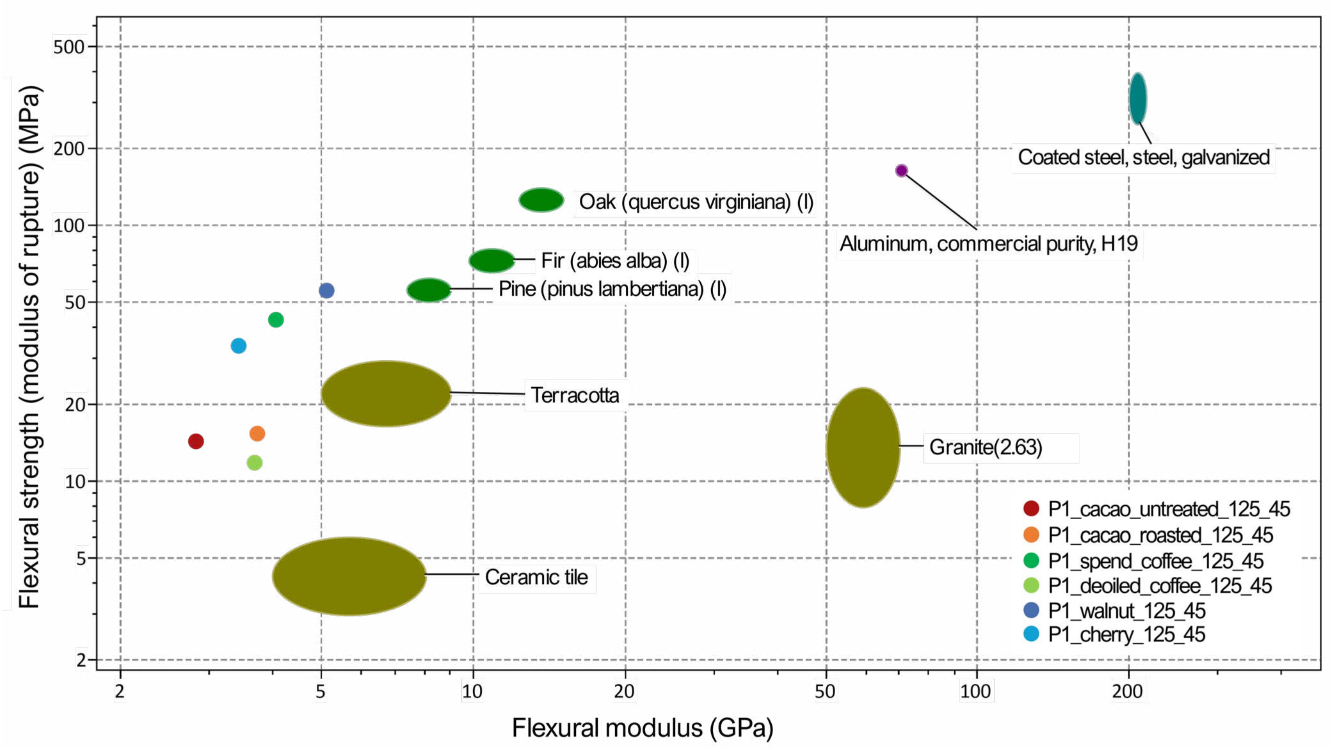


graph 4: Results of absorption test

The fully saturated samples showed not much swelling or deformation and also there was no visible difference between the saw-cut, unsealed edges of the samples compared to the centre.
This is useful information regarding the application design, as it implies that composite panels are not at risk of higher water absorption when the material has been machined or drilled into.

All of the samples showed a high frost resilience, even though the change of colour of the cacao shell and cherry pit composites could indicate a degradation on the material surface.
No strength test was done to compare the pre and post-freezing material properties, which would have been useful.

4.1.4 Results - Phase 1A



graph 5: Comparing Bending strength and Stiffness, based on data from (Granta Edupack, 2023 R3)

Comparison with different materials

In direct comparison, the furan filler composites are comparable in regards to bending strength to softwoods or terracotta, as can be seen in graph 5. The stiffnesses being in the range of ceramic tiles and terracotta.
Regarding the impact resistance the cherry, walnut and spent coffee composites showed resistance higher than that of soft wood, which is quite good considering they have no fibrous reinforcement (graph 3).
This shows that this type of composites could be a viable alternative facade cladding.
The density of the composites ranging from 1310 kg/m³ (spent coffee composite) to 1410 kg/m³ (walnut composite), is a bit denser than gypsum which makes all tested composites lighter than both aluminium and steel (Ashby & Jones, 1996).

Process Pictures

4.1.4 Results and Conclusion - Phase 1A

Discussion

The walnut shell composite displayed a high bending strength and impact resistance, had a very low water absorption rate and resilience against frost. It overall performed the best, followed by the spent coffee composite and the cherry pits.
It is interesting that the de-oiled coffee and the spent coffee ground composites performed largely different.
The latter having almost three times the bending strength and better impact resistance.
A reason for this could be the use of un-spent coffee for the de-oiled coffee product, which implies that a soluble ingredient caused the bumps and cracking in the composite, which is otherwise extracted in the process of brewing coffee.
This together with the weight-loss of the cacao composites in the absorption testing suggests that remaining soluble parts in fillers have a negative effect on the composites performance.
The cherry pits with their harder shell and softer core performed reasonably well as a filler. Still the steps of milling and sieving were problematic.
The trouble of material sticking to the sieves, that also the coffee grounds displayed was overcome in part by an adjustment of the sieving technique (dry to wet sieving). Still the cherry pits stood out as complicated, since their core ground to a mushy texture that stuck to all equipment.

Sample plate	Density [kg/m³]	Bending strength [Mpa]	Elastic Modulus [Gpa]	Impact resistance [kJ/m²]	Water absorption (24h/max) [wt%]	Dispersion
P1_cacao_raw_125_45	1320	16.20 (±3.99)	2.82	1.37 (±0.46)	4.3/11.8	uneven surface and cracks
P1_cacao_roasted_125_45	1350	17.31 (±2.45)	3.74	1.06 (±0.29)	5.5/12.7	uneven surface, small cracks
P1_spent_coffee_125_45	1310	42.52 (±2,73)	4.12	2.35 (±0.47)	2.1/-	uniform dispersion, smooth surface
P1_deoiled_coffee_125_45	1330	13.89 (±2.50)	3.62	1.04 (±0.40)	4.4/13.3	bumpy surface and cracks
P1_walnut_125_45	1410	58.71 (±8.37)	5.25	3.34 (±0.52)	0.8/-	uniform dispersion, smooth surface
P1_cherry_pits_125_45	1350	34.34 (±4.32)	3.32	2.42 (±0.37)	0.8/-	slightly uneven dispersion, surface “marbling”

table 5: Overview, testing phase 1A

Process Reflection

The tests were done to test the properties needed a facade application.
With the impact test the resistance to sudden strong impacts was tested. Additionally an evaluation of the surface hardness in a scratch test might have been useful to do, to reflect the resilience to outdoor objects, maintenance and the overall surface durability.
The full saturation with water followed up by the freeze-thaw cycles were an extreme scenario which does not necessarily reflect reality but was designed to test the limits of the composite.
No strength test was done to compare the pre- and post-freezing material properties, which would have been useful.

Conclusion

After the evaluation of the different filler types, the best performing composite fillers to be further investigated in the second phase of testing are: walnut shells and the spent coffee grounds.
They performed best mechanically and functionally, while still being easy to process. Cherry pits, even though performing reasonably well were eliminated because of the difficult processing.

The material performance seems to be strongly decreased by the cracks and bubbles that some of the composites showed.
Reasons for this will be explored in phase 1B.

4.1.5 Design of Experiments - Phase 1B

PHASE 1B

Goal:

The aim of phase 1B is to gather more information about the filler types and to answer the following questions:

- What are the reasons for better/worse mechanical performance?
- What caused bubbles and cracks in some composites but not in others?
- Which processing methods could be improved?

The experiments in this section are informed by the results of the previous testing.

Hypothesis:

The mechanical and functional performance aligned with the observation of bubbles on the material surface and internal cracking.
(More bubbles - less strength, more absorption, less frost resistance)
Possible reasons for bump/crack development could be:

- The release of moisture through heat and pressure (process and material related)
- A chemical reaction of the filler in the curing process (material related)
- A difference in thermal expansion of filler and resin (material related)
- Inadequate mixing (material and process)
- Problem with dispersion leading to air pockets (process and material related)

Actions:

The following steps were taken to obtain more information about the properties and differences of the different filler types:

1. Microscopic analysis of bending fractures
2. Microscopic analysis of filler powders
3. Measurement of filler density
4. Contact angle testing of the Filler

Chosen Tests:

Density:
Since the main molecular components of all our filler materials are similar (cellulose, hemicellulose, lignin) and therefore we assume a comparable atom mass, the comparing the density of the filler types gives an indication about their porosity.
The density is also useful for comparing the volume a filler takes up in the composite with the mass, since the recipe is assembled by mass not by volume.

Fracture surface analysis:
Looking closer at the fracture surfaces gives the opportunity to have a look inside the material.
Possible findings:

1. The existence or absence of air inclusions or bigger particles or impurities
2. Evenness of the distribution of filler is within the material
3. Formulation of the fracture might give indication of probable cause and failure mechanism

Visual analysis of the particles:
The particle size and shape of aggregates has a great influence on the properties of the resulting composite (see section 2.6).
The aim of this analysis is to:

- Find out if the powders are homogeneous or show differences in shape, texture or size
- Check for visible agglomeration, crystallisation and impurities

Contact angle testing:
A contact angle test is usually executed to determine if a material (surface) shows hydrophobic or hydrophilic properties.
In the test, a droplet of liquid is dispensed on a materials surface. The angle in which the drop connects to the horizontal is the contact angle. This test is used in the development of liquids, for example inks, but also for the development of surface coatings, rain resistant textiles and powders (Ossila, 2024)
For the fillers the contact angle behaviour can give us an indicator how well the resin matrix and filler mix, if the filler absorbs liquids quickly or if the mixing process should be extended to ensure a full impregnation of all filler particles.

4.1.6 Measuring Density - Phase 1B

Density

Procedure:
The powdered filler material is weighted on a scale (precise to 0,01g). A graduated measuring cylinder (20ml) is filled with water and the volume is noted down. Then the powder is added in the cylinder and the new volume is read.
The procedure is executed three times for each filler.

Measurements:
The density of the powder can be determined by the weight divided by the difference in volume.

$$\textbf{Density [kg/m}^3\textbf{]} = W/(V_1 - V_0)$$

V_1: Volume water + filler; V_0: Volume water

Since both cacao fillers and the de-oiled coffee showed to have water soluble components (see section 4.1.3) the accuracy of the result might be deficient. Still an indication on how the fillers differ is given.

Findings:

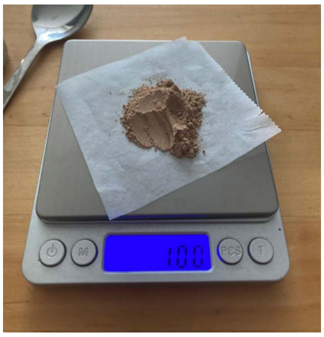
Filler	Average Measured Density [kg/m³]
Cacao, raw	1070,1
Cacao, roasted	1083,0
Spent coffee grounds	1088,5
Deoiled coffee grounds	1117,3
Walnut shells	1469,6
Cherry pits	1145,1
Furan resin (TFC Biorez)	1210

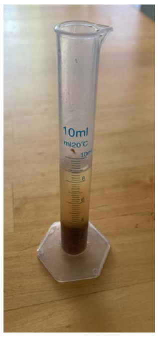
With the walnut shells being the most dense of the selection, the materials still fall within a close range of each other.
Compared to other material groups that are common as fillers, the chosen waste material are much less dense than mineral alternatives and are comparable with the density of hard wood.

Material	Density [kg/m³]
Calcium carbonate	2650- 2710
Kaolin	2500- 2620
Oak (hardwood)	890- 1080
Pine (softwood)	360- 440
Aluminium	2680- 2740
Steel	7800-7900

table 6: Material densities (Ashby & Jones, 1996)

Process Pictures:





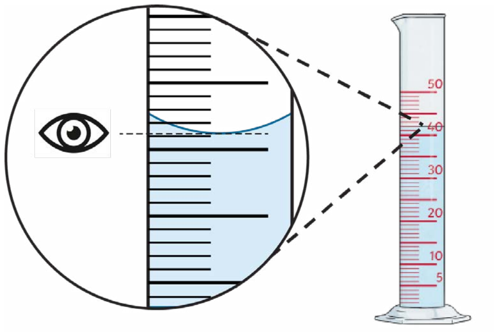


figure 45: Volume reading at the lower miniscus

Discussion:
The walnuts exhibited the highest density, and the composite with walnut also demonstrated the highest strength, suggesting a potential correlation. However, other factors beyond density play a role in the suitability of a filler material in the application of the bio-composite.

The results provide insight into the volume-to-mass relationship, which is important for understanding composite formulation. As the recipe relies on weight measurements, knowing how fillers occupy volume within the composite is essential for both process-ability and mechanical behaviour, informing the composition ratios for phase 2 testing.

The comparison of densities also shows the potential of bio-composites to function as light-weight building products, which is favourable due to lower emissions in transport. Metal and ceramic based materials range in densities of about 2500-8000 kg/m³ (Ashby & Jones, 1996).

Test limitations:
The method of measuring density has limitations, particularly in accuracy due to manual readings. Additionally, the accuracy of filler density may be compromised, as previously noted, due to the presence of soluble components in certain fillers.

4.1.7 Fracture Surface Analysis - Phase 1B

Fracture surfaces

Procedure:
Several of the samples tested in Phase 1A are observed with a microscope.

Equipment: Keyence VHX-7000 digital microscope

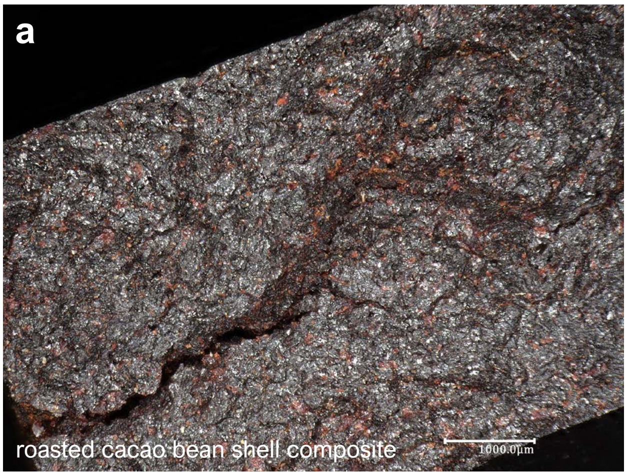
Measurements:
No specific measurements are taken but the surface is examined for patterns of fracture propagation, visual impurities, bubbles, cracks and outstanding particle agglomeration.

Observations:

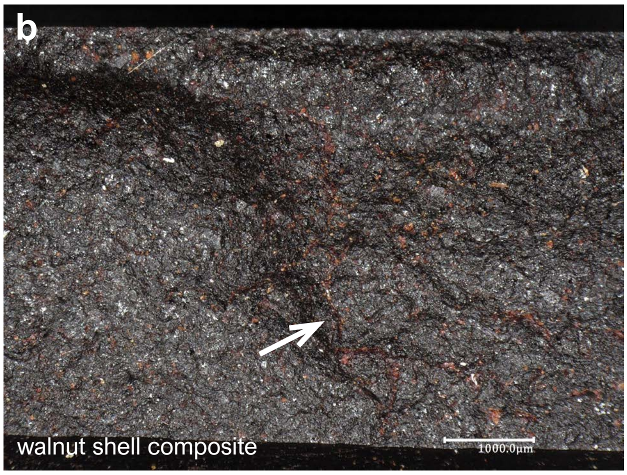
Cracks and bumps
The first observation to be made is that the composites that showed bumps on the surface of the sheet material (the composites from both cacao types and de-oiled coffee) showed many small to medium sizes cracks in the layers of the material (see picture a). It is most likely that the cracks pre-existed and lead to the low bending strength in these sample, as some fractures were visible even before the bending test.
Besides these fractures not many bubbles in the form of round air inclusions could be observed in any of the samples.

Uneven filler distribution
There were two kind of uneven filler distribution observed, which both might be a result of processing.
The first one (b) could be observed in the walnut and cherry pit composite (both of which performed reasonably well in bending), is the formation of path like structures of filler dense composite. This could be attributed to the moulding process or too short a mixing period. It is unclear if this influences the mechanical behaviour.

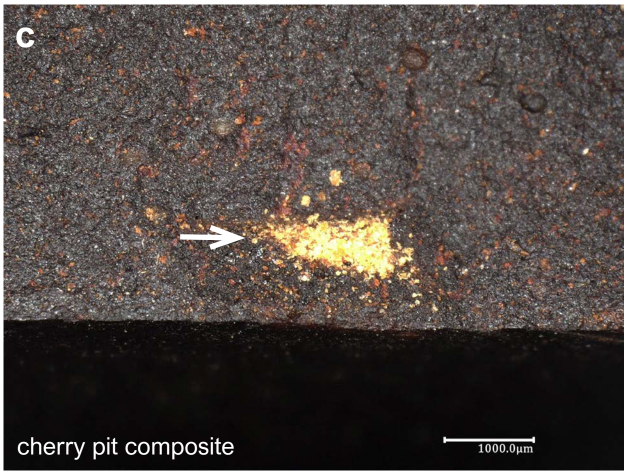
The second kind of distribution problem is the agglomeration of filler material in big clumps (c,d). This could be observed for both coffee composites and the cherry pits.
The reason for this is most likely wet-sieving that was used for these three filler. The materials natural tendency to agglomerate, which made the wet sieving process necessary, left the powder in clumps after the drying process.
A solution for this would be another round of milling to break up clumps or other sieving methods.



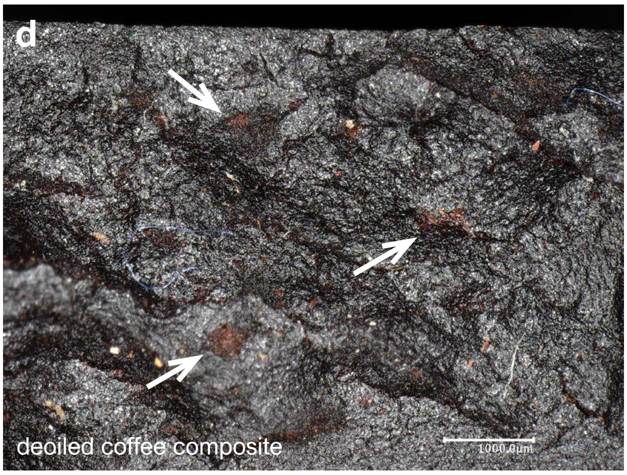
roasted cacao bean shell composite



walnut shell composite

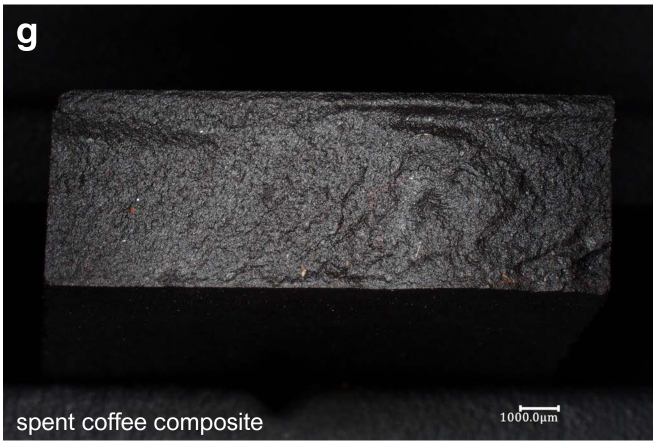


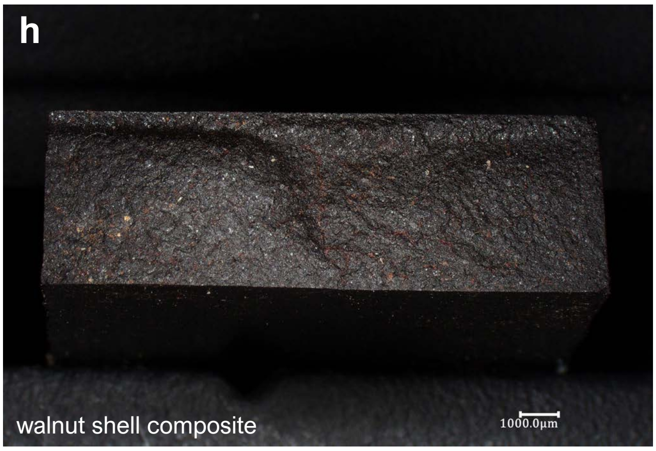
cherry pit composite



deoiled coffee composite

4.1.7 Fracture Surface Analysis - Phase 1B





The fracture surfaces of the composites with a low bending strength (e,f) are more uneven and rougher than the ones with high strength (g,h). This could be due to the pre-exisisting cracks in the structure of the samples. Another reason could be a irregular bonding result within the material.

Failure mode

The fracture patterns are comparable to ceramic breaks (figure 46 and figure 47). Even though the origin of the fracture is not easy to spot in most samples, a compression curl and propagation patterns similar to high strength ceramic breaks (Baudín & Bueno, 2007) can be spotted in the samples of walnut, spent coffee and cherry pits fillers. The failure mode is therefore most likely in tension on the bottom surface of the samples, propagating upwards.

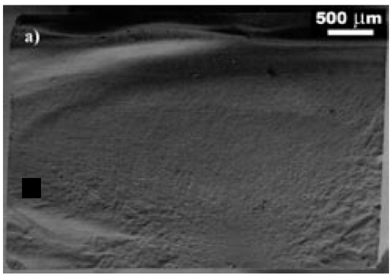


figure 46: Typical fracture pattern of structural ceramics (Baudín & Bueno, 2007)

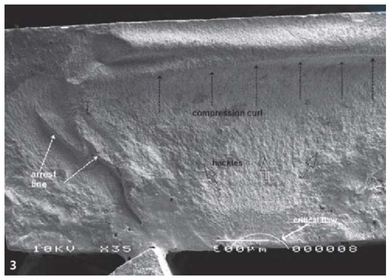


figure 47: Ceramic fracture pattern explained (Rizzante et al., 2020)

Conclusion and Discussion:

Most of the observed fracture surfaces displayed only small sporadic defects which indicates that the general process of sample preparation was successful. Some of the larger defects indicate that further improvement of the preperation method is possible.

The pictures show several possible weaknesses of the different composites and the likely mode of failure, which is in tension.

The composites that had uneven surfaces show a lot of cracking and therefore expectable low mechanical strength. Since the reason does not seem to be air inclusions but rather fracture after the release of pressure from the press, the thermal expansion or a chemical reaction of filler and resin releasing gas could be a reason.

The dispersion issues with some of the samples can potentially be overcome by adjusting the processing steps, increasing mixing time and/or the elimination of wet-sieving to avoid agglomeration of filler.

4.1.8 Filler Particle Analysis - Phase 1B

Filler Particles

Procedure:
With a digital microscope, particles of each filler type from Phase 1A are observed (<125 µm). Also particles from the two next bigger the sieving steps 250/125 µm and 500/250 µm are looked at. These sizes are used in phase 2.

Equipment: Keyence VHX-7000 digital microscope

Measurements:
Again no specific measurements are taken. The focus of the observation lies in the shape and texture of the particles, the size composition and other notable characteristics.

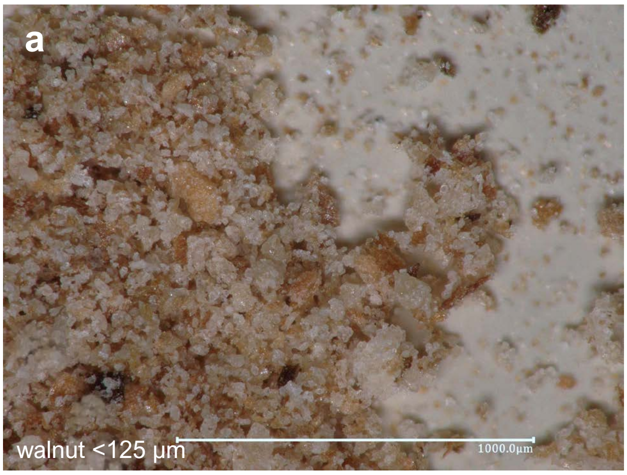
Observations:

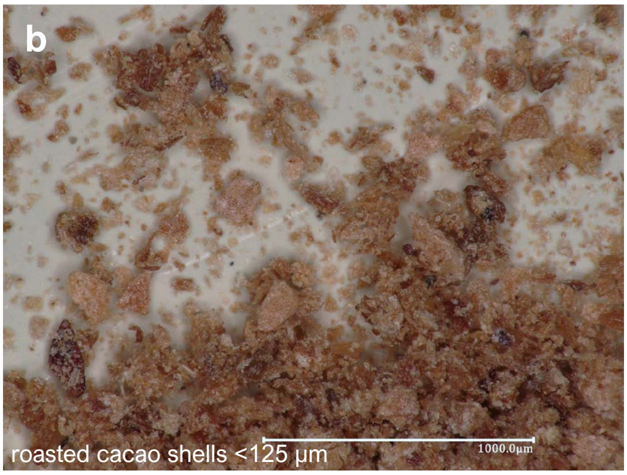
Particle shapes
The powders show a variety of different particle shapes: The two types of cacao shells display a sharp and flaky particles (b), while the walnut shell powder and the ground cherry pits are more rounded (a,d), almost like sand.
The two coffee types where indistinguishable from each other on close inspection and displayed mostly uniform, slightly rounded shapes with agglomerations of finer particles and crystalline structures sticking to the bigger grains (c).

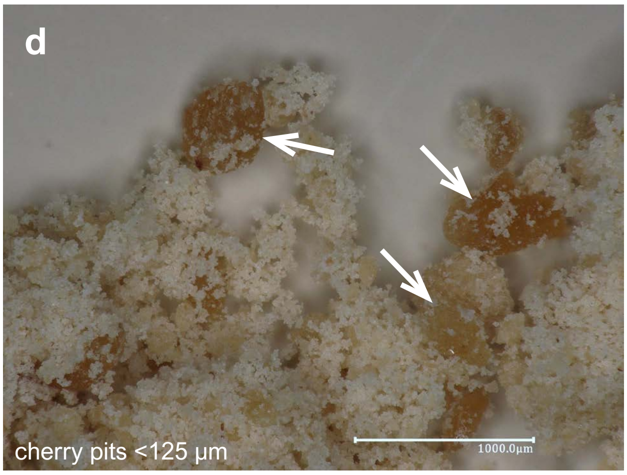
Crystal structures
Small pointy crystals can be found in the spent coffee powder and the de-oiled coffee, which might indicate soluble parts.

Sieving and milling issues
As already observed on the fracture surfaces of the cherry pit samples, a large amount of particle agglomeration for the cherry pit powder can be observed, which makes it look like huge grains are in the mix (d).
The hypothesis is that after the process of wet-sieving, when the sieved powder had to be dried again, the particles are "baked" together. This method would need to be changed or eliminated in the future.

Particle size mixture
Since the particles of the bracket <125 include all particles smaller than 125 µm, the mixture can be different. For the cherry pits, fine but uniform grains can be observed (except for the agglomerations) (d), while both the walnut powder and cacao shells seem to have a balanced mixture of smaller and larger particles within the range (a,b).





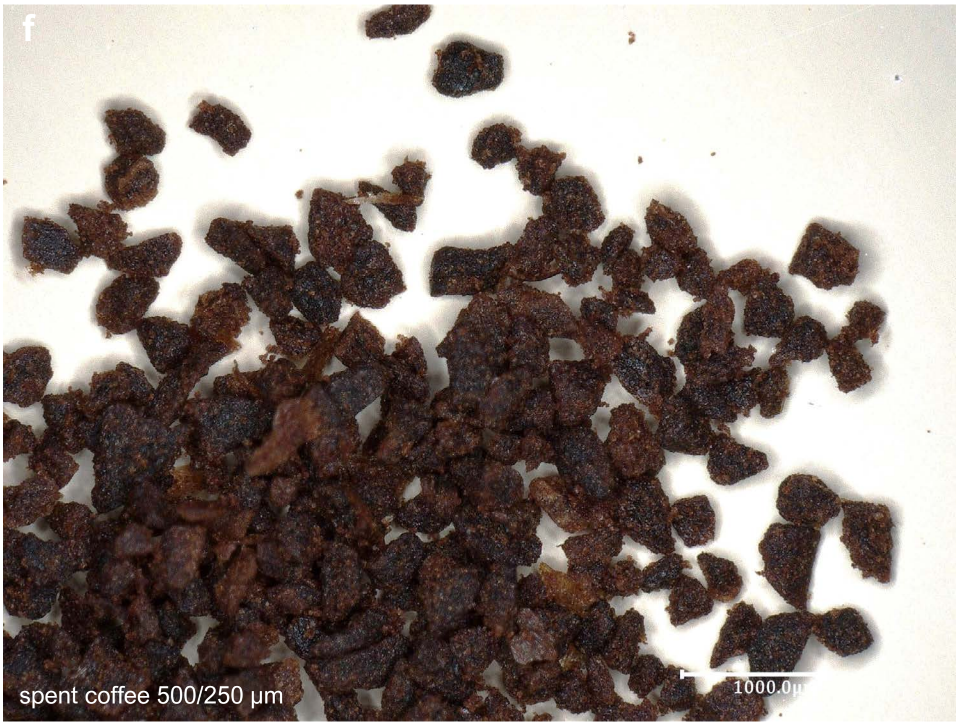


4.1.8 Filler Particle Analysis - Phase 1B

Looking at the slightly bigger size bracket of the sieving step between 500 and 250 µm, the variance in shape and texture of the walnut powder can be seen better.
In between well rounded particles there are sharp edged pieces of darker colour, which most likely comes from the thin membrane that walnuts have to separate the nut halves.
If we use the analogy of concrete mixing, sharp edges are something to be avoided, as they can lead to stress concentrations.

A reason why the walnut shell composite was still the one with the highest strength, could be that the longitudinal pieces fulfil the role of rudimentary fibre reinforcement.

Next to the walnut powder, the spent coffee filler of the size bracket (500/250) appears to have more equal particle sizes and shapes and a rough texture, with some very fine particles sticking to the larger surfaces.
Also in this scale some crystals are visible.



Conclusion and Discussion:

We observe an array of particle shapes and textures amongst the different fillers. Cacao shells show flaky and brittle behaviour, whereas harder materials tend to form rounder grains.
Both coffee ground types display a tendency to adhere to one another, forming crystalline structures in some spots.
The possibly soluble crystalline residues might be a cause for the bumps and cracks but this would need further investigation.

Also interesting would be to see if after repeated "washing" of the coffee grounds, the crystals would disappear.

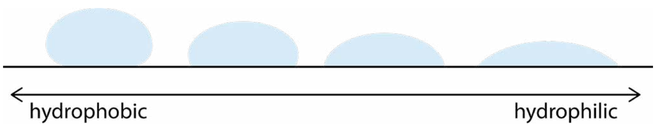
The gathered insides about grain shapes and textures help us understand how a spacial arrangement within a composite might look like and which mechanical mechanisms might be responsible for poor or good behaviour, which is useful for the next experimental phase.

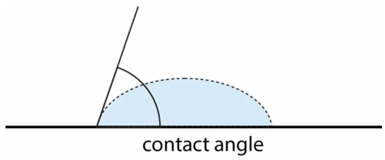
4.1.9 Contact Angle and Wettability - Phase 1B

Contact angle of Filler Powders

Hydrophilic or hydrophobic behaviour might be the reason some fillers caused bubbles and inhomogeneous results. In that case added mixing time, or less pre-curing could help the dispersion and prevention of these bumps.
Since the waste-based fillers in this project are integrated into the composite as powders, the powdered form of the source materials, compressed into a flat disc, was used, which is one way to determine the wettability of the powders (Mäntykangas, 2020).

figure 50: Goniometer, brand Ossila





Procedure:
The Sessil Drop method, which is usually done with a goniometer (figure 50), was chosen because it is easy to recreate by simple means, since professional equipment was not available at the time for this project. The setup is described in figure 48.

A filler material, milled to fine powder of <125µm (same size as used in the samples of phase 1A), is compressed into a flat disc, with the help of a self-made mould and plunger.
A drop is dispensed onto the disc and a close-up photo of the drop is taken from a horizontal level view. To achieve a consistent size of droplet a pipette or syringe can be used. In this setup the drop was created by submerging a metal skewer in a jar of water and letting the water drop from its tip which resulted in equal drop sizes each time.
For each filler type, 3-6 droplets were photographed to ensure the accuracy of the results.

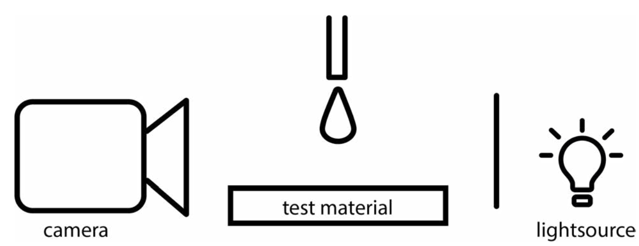


figure 48: Goniometer, schematic

figure 49: Setup for contact angle test

Measurements:
Digitally the curvature of the drop and its baseline are determined and the angle at the contact point of both sides is calculated.
For this procedure a Goniometer can be used, which has a camera with a light in the background and software to fit a polynomial curve onto the taken picture and calculate the resulting contact angle.
The improvised setup here is a simplified version of a goniometer but was sufficient for the purpose of the experiment.
The polynomial fitting of the droplets curvature and the calculation of angle, which is usually performed by the goniometer, was done with Rhino3D and Grasshopper for a consistent process of analysis.

4.1.9 Contact Angle and Wettability - Phase 1B

Findings:
It can be observed that all materials seem to be hydrophobic (angle >90°) with the lowest angle from the walnut shell powder and both cacao and both coffee types reacting more hydrophobic.

Filler	Contact angle
Spent coffee	137.6° (±9.7°)
Cacao, raw	126.9° (±9.0°)
De-oiled coffee	122.5° (±7.5°)
Cacao, roasted	109.7° (±8.2°)
Cherry pits	101.3° (±5.3°)
Walnut shell	100.7° (±2.9°)

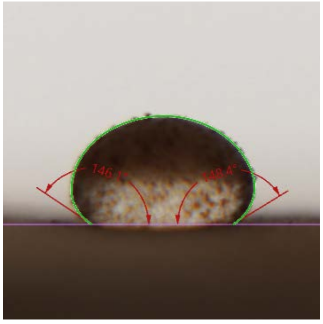


figure 51: Result image of droplet on spent coffee

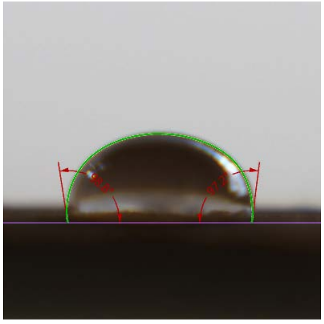


figure 52: Result image of droplet on walnut shell

Conclusion/Reflection:
The improvised test setup gives a high chance of inaccurate results. Besides that, it would be useful to repeat the test with furan resin as dripping medium, since the reaction of the filler powders to the polymeric resin might vary from the reaction to water. Since the used furan is a water-borne resin, the results are still relatable.

The test gives an indication that a higher degree of hydrophilia might be beneficial in the search for suitable filler materials, since both the walnut shells and cherry pits, which composites showed relatively high mechanical properties in testing, reacted the least hydrophobic.
The assumption is that with less hydrophobic behaviour, the resin is absorbed quicker into the surface pores of the filler, which results in a good mechanical bond after curing.

4.1.10 Conclusion - Phase 1B

Phase 1B of this study aimed to explore the diverse parameters influencing the usefulness of fillers in bio-composites and to identify suitable waste materials for this purpose.

Density testing revealed the potential for lightweight design, although higher densities may offer advantages in terms of strength.

The examination of fracture patterns in bending samples under the microscope suggested that composites, failed predominantly in tension.
The well performing composites (Walnut, spent coffee and cherry pits) displayed a mostly uniform material dispersion with only minor anomalies like some large grains and filler agglomeration that could be eliminated by altering the preparation process.
Cracks observed in composites containing cacao shells and de-oiled coffee points to potential chemical reactions or thermal expansion issues.

A analysis of filler powders showed different characteristics among materials, with cacao exhibiting flaky sharp particles and coffee varieties displaying more rounded grains.

Walnut fillers showed a large range of shapes and textures. Smaller crystalline structures observed in coffee grounds may indicate soluble remnants released during the coffee brewing process, potentially contributing to bubble formation in the moulding process.

Contact angle analysis yielded inconclusive results, likely due to limitations of the testing setup or the lack of direct relevance to composite performance. Nevertheless, a tentative correlation between hydrophobia and decreasing mechanical performance could be made.

In conclusion, Phase 1B provided various insights into the complexities of filler selection and the challenges associated with achieving optimal composite performance. Further investigation and refinement are necessary to address the identified issues. More parameters might come into play in the process of optimizing the composite formulation and integration into an application.

4.2.1 Design of Experiments - Phase 2

PHASE 2

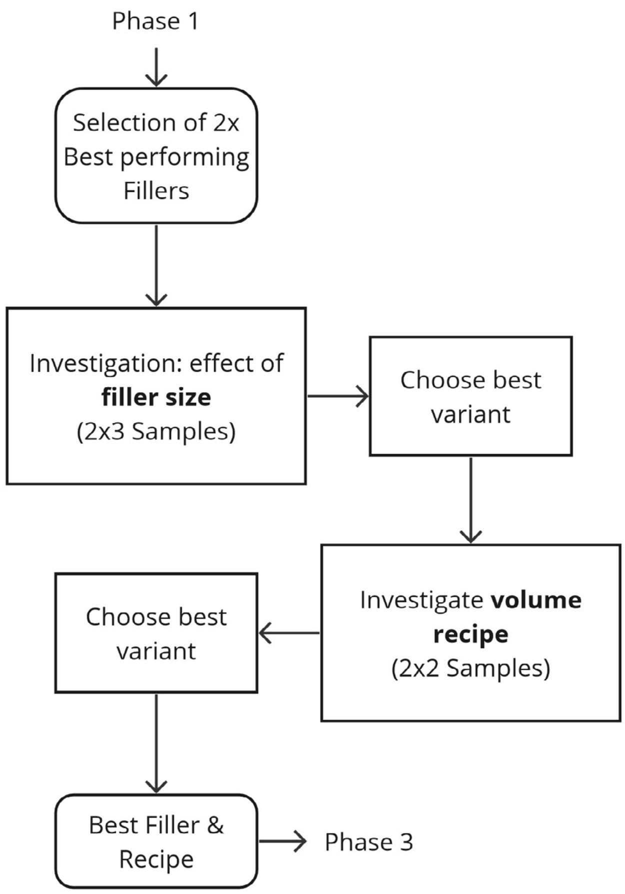
Goal:
From the previous step we have chosen two filler types to proceed with. The goal of this phase is to explore how the size of particles used and the ratio between filler and matrix influence the result.

Action:
Of the two chosen waste types, a series of variations on furan/filler basis is created. First different particle sizes are tested in three steps, (in addition to the already tested variation from phase 1). After determining the best result of mechanical properties and processing quality, two additional variations are produced that vary in the ratio between filler and resin in 10% each way.
All samples are tested mechanically and the merits regarding waste content and process-ability are weighted.

Parameters:
From the previous step we have reduced the selection of fillers to the two most promising, which are:

walnut shells

spent coffee grounds



The variables are explored in a two step approach:

Grain sizes:
a. Grains between 500 µm and 250 µm
b. Grains between 250 µm and 125 µm
c. Grains <125 µm (tested already in phase 1A)
d. A blend of different grain sizes (see 4.2.2)

Compositions:
a. 35wt% filler powder
b. 45wt% filler powder (tested already in phase 1A)
c. 55wt% filler powder

Equipment used:
The equipment and ingredients for this phase are identical with the previously produced samples.
Again the specimen production was done at NPSP partially suprvised by Zoya Zarafshani, Aditia Babu and Dimitra Tsoli.

Evaluation Criteria:
The criteria for the selection process in the first phase was exclusively focused on the mechanical and functional properties of the composite.
After exploring in which neighbourhood the results ended up, the second phase will again look at the difference in mechanical behaviour but will also consider the implications that the filler load and size have on the process-ability, and sustainability.

The goal is:
The optimal **balance** between maximum of **waste content** and mechanical and functional **performance.**

4.2.2 Grain Size

The Effect of Filler Size in Research

The filler size influences the bonding with the polymer, how evenly the additives can disperse and how loads can be transmitted.

In a study investigating the effect size and load of walnut shell filler in epoxy, a rising water absorption rate was observed with rising grain size (Shejkar et al., 2021).
Another project explored the change in Young's modulus and glass transition temperatures of PLA at varying sizes of talc nano-fillers and with newspaper as a fibre reinforcement (Senthil Muthu Kumar et al., 2020).
The tests showed an decreasing Young's modulus and a rising glass transition temperature with growing particle size. The samples made without filler and the pure PLA showed a Young's modulus below the composite with the biggest particle size. The reasoning for that was that the larger fillers limited the chain movement of the matrix.

The consent of most studies seem to be a drop in mechanical quality with increasing filler size
(Erkliğ et al., 2016; Senthil Muthu Kumar et al., 2020; Shejkar et al., 2021). A drop in tensile and bending strength makes sense, considering that, like in concrete, larger particles can cause stress concentrations. For larger particle sizes in a composite, the good adhesion between filler and matrix gains importance.

It is hard to compare the results of these studies because of fundamental differences in the experimental setup. (Shejkar et al., 2021) using the hand lay-up method noted larger void spaces (air inclusions) with larger grain sizes, which might not be the case for a different production method, for example with BMC. A hybrid filler recipe is hard to compare with to a mono-filler composite as well as each filler is to a degree unique in its behaviour.

Mixing particle sizes:

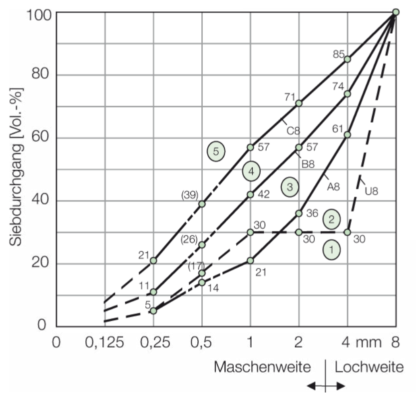
Mixing various filler sizes in composites is a topic that has been investigated on a nano-level for dental composite (Simonov-Emelyanov & Kharlamova, 2020) but is missing in the literature about building materials.
Therefore, in this project, the practise of concrete mixing is imitated. The aggregates of different sizes are mixed in a way that gives the best spacial distribution of bigger and smaller pebbles.
The result is a recipe with a minimum of aggregate surface, which reduces the need for expensive cement, while maintaining the same material quality and workability (Weber & Riechers, 2003).

In translation to bio-composites that could mean the optimisation of the use of waste material with a minimum need for resin, which improves the material in terms of sustainability and reduces the price, while still meeting mechanical requirements.

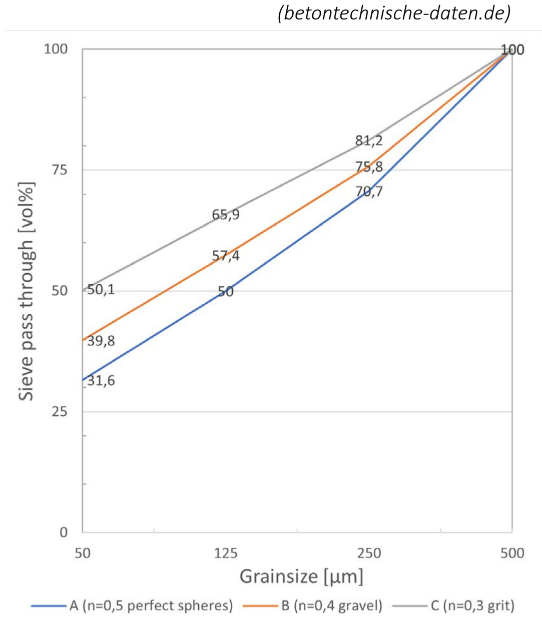
The way the mixing ratio of aggregate sizes is determined in concrete mixing is calculated by the Fuller curve, developed by William B. Fuller and Sanford E. Thompson in 1907 (Weber & Riechers, 2003).
The Fuller grading curved is oriented on the largest grain in the blend and can be described with this formula. The by-factor n accounts for the shape of the grain, where 0.5 would be the a perfect sphere.

$$A = 100 \times (d/D)^n$$

A: sieve pass through [%]
d: grain size
D: biggest grain
n: factor for grain shape
(n=0.5 perfect sphere;
n=0.4 pebbles; n=0.3 grit)



graph 6: Fuller-curve with 8mm largest grain (betontechnische-daten.de)



graph 7: Adapted fuller-curve with 500 µm largest grain

4.2.2 Grain Size - Preparation of Samples

Recipes Grain Size

Component	Description	Weight %
Resin	Furan resin	50
Filler	Powdered filler in the size brackets: **500/250 µm** or **250/125 µm** or **mixed**	45
Catalyst	HM1448 ((2-hydroxyethyl) ammonium nitrate)	3
Releasing Agent	Linseed oil	2

Particles Brackets

The sizes in which filler is considered is determined by the available sieves.
In the sample naming, the size numbers 125, 250 and 500 refer to <125; 125 to 250; and 250 to 500 µm respectively.
The mixed particle sizes are determined by the definition of the fuller-curve constructed earlier. The factor *n* is chosen for both tested materials separately as we established in Phase 1B that they show different shape and texture properties.
Therefore for the blend of spent coffee composite the B-line is chosen (*n*=0.4), since the particles have shapes comparable with gravel. For the mixed size walnut composite, the middle between C and D line with the factor *n*=0.35 is chosen, to accommodate for the mix of sharp and rounded particles.

Procedure

The procedure for the sample production is similar to the steps taken in phase 1A (section 4.1.2). The only additional step is the measuring and adding the filler of mixed particle sized powder for the corresponding samples instead of just adding one filler type.

Samples:

Similar as in phase 1, composites are fabricated in sheet format with the dimensions close to an A4 format.

For the investigation of the particle size, the following samples are produced and tested:

Grain Size related:
- P2_walnut_500_45
- P2_walnut_250_45
- P2_walnut_blend_45
- P2_spent_coffee_500_45
- P2_spent_coffee_250_45
- P2_spent_coffee_blend_45

Also relevant for comparing the results are these samples from the previous phase:

- P1_walnut_125_45
- P1_spent_coffee_125_45

Composition of *"blend"* of grain sizes:

Particle size bracket [µm]	Walnut (n=0,35)	Spent Coffee (n=0,4)
500/250	21.5%	24.0%
250/125	17.0%	18.5%
<125	61.5 %	57.5%

figure 53: filler size brackets (example walnut)

4.2.2 Grain Size - Preparation of Samples

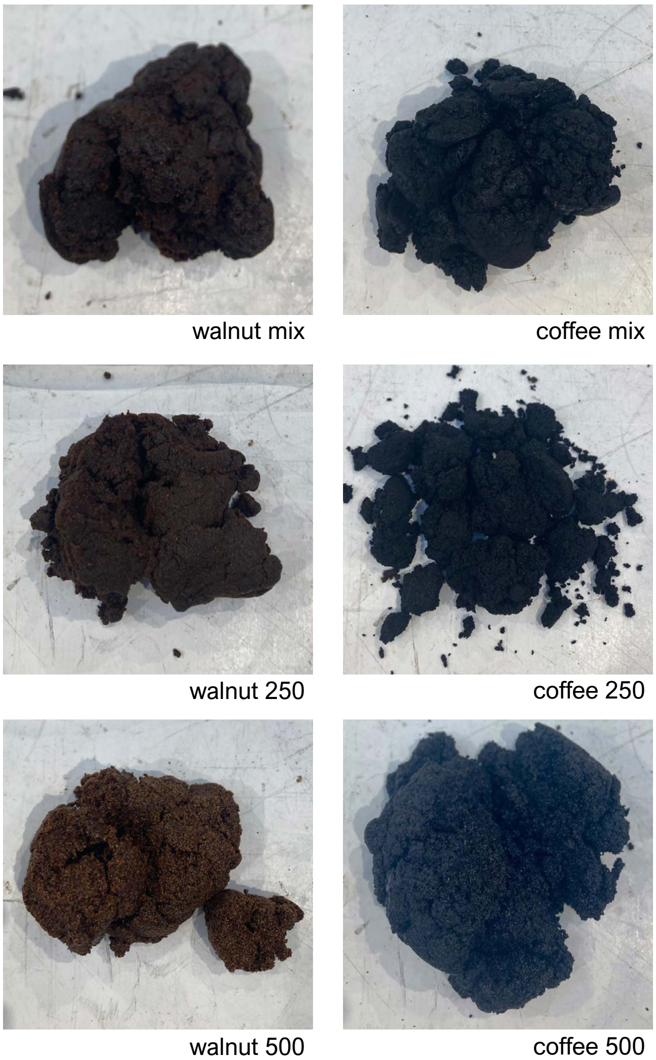


figure 54: BMC consistency before pressing, six doughs

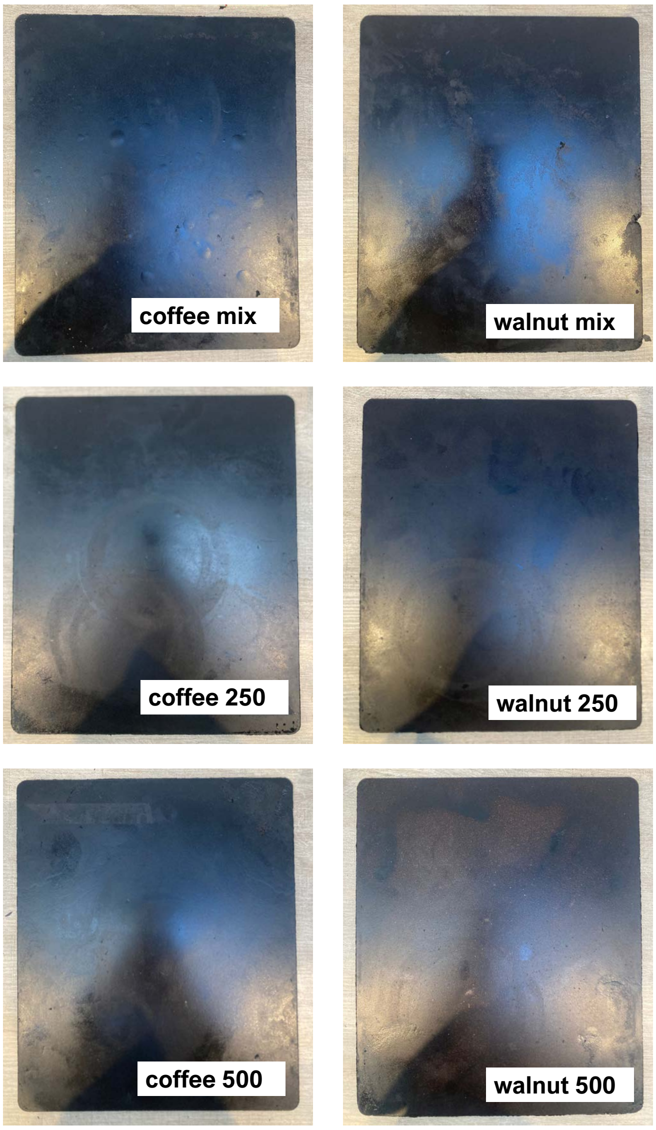


figure 55: sample plates - gain size

Process Observations:

In the process of making the dough, the mixtures showed different textures (figure 54). As expected the larger grains resulted in a more grainy compound. For both filler types, the dough in the 250/125 size bracket displayed the driest, crumbly texture, while the mixes sized filler doughs where smooth and slightly viscose in texture.

In the process of pressing the plates, the doughs of bracket 500/250 caused a larger amount of spillage than usual. The normal process involves a few drips of resin along the side of the mould, with the 500-mixtures it was about twice as much.

Observations:

The mixed filler size plate of the coffee filler shows some sporadic bumps. Other than that all plates are bubble and crack free.
In the mixed filler walnut sample, a small spot of the mould is not filled out completely, other than that the dispersion looks even.
The colour of all plates is uniform black, like in phase 1, except for the walnut_500 sample, where the particles are visible and the plate appearers in different shades of dark brown.

4.2.3 Grain Size - Testing and Results

Testing

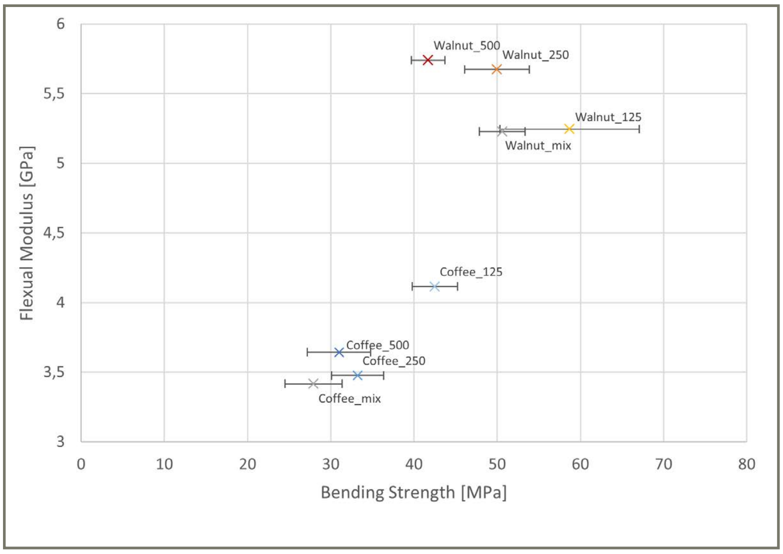
From the plates, samples are cut with a CNC-mill and tested for 3-point bending and impact resistance. The same protocol and steps as in phase 1A are followed (section 4.1.3)

Results

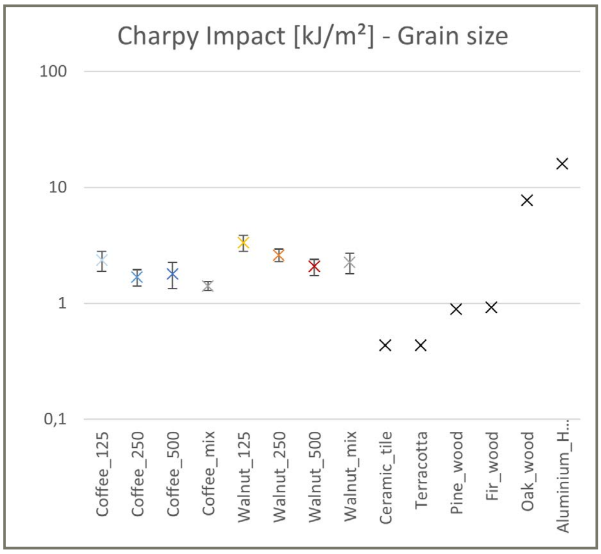
Surprisingly the results for the walnut shell composites turned out very different that the spent coffee composites.
As expected from the literature review, the walnuts bending and impact strength dropped with rising filler size, while the stiffness increased.
This was not the case for the coffee based composites, where the strength behaved as expected while the stiffness was the highest for the composite with the smallest particles.

The two mixed samples also compared differently. The mixed walnut sample had a higher bending strength than the medium and large filler sizes, with the same stiffness as the <125 µm composite. This can be considered a successful attempt in optimising the recipe, as the mix also showed a lower result deviation than the <125 µm variant.
The mixed grain coffee composite failed, as it did not perform better than any of the other samples in either impact, bending strength or stiffness.

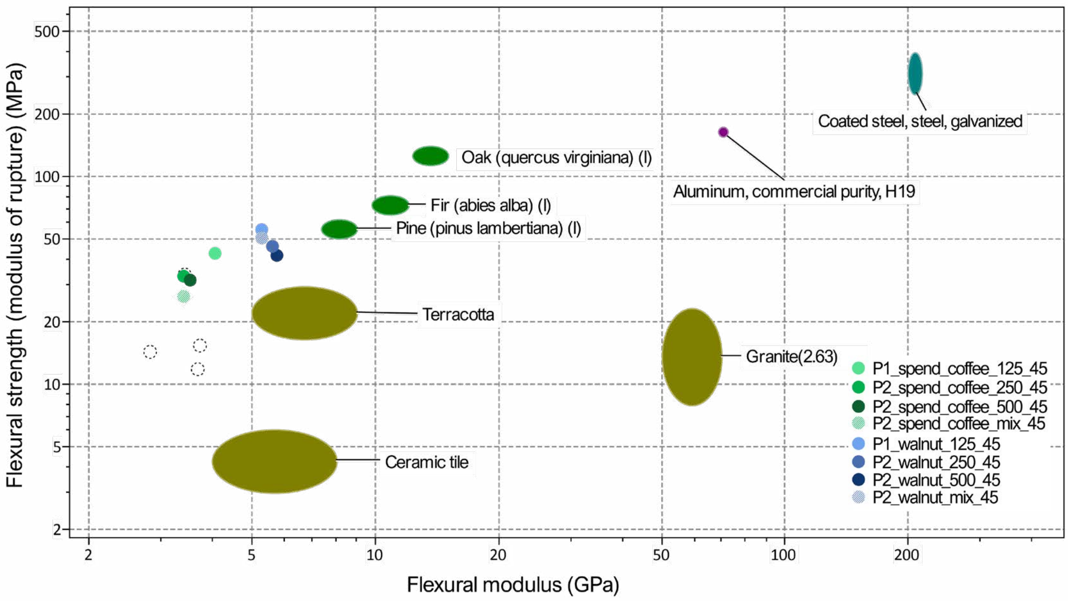
Selection for next step:
Moving forward with the investigation of the filler/ matrix ratio, the **mixed particle composition** of the walnut filler and the **smallest grain size** of the spent coffee filler will be used.



graph 8: Results of 3-point bending test



graph 9: Results of impact test



graph 10: Comparing Bending strength and Stiffness, based on data from (Granta Edupack, 2023 R3)

4.2.4 Composition

The Effect of Filler Load in Research:

In a study comparing different filler loads in walnut shell/polyester composites (Ahlawat et al., 2018) found an increasing flexural modulus and but a drop in tensile strength with rising filler load. They tested the loads of 10, 20 and 30 wt% filler in comparison to the neat polyester with a open mould casting technique.

Another study showed a steady drop in tensile strength with rising filler load of rice husk which was measured up to 20wt% and a polyester matrix (Hardinnawirda & Aisha, 2014). The highest Young's modulus was measured at 15wt% but then started to drop.
Possible reason for the receding tensile strength were estimated to be poor adhesion between the hydrophilic filler and the hydrophobic matrix. The improper distribution of fillers might also have been a cause.

In a compilation of studies with PPC matrix and bio-fillers, a review showed a rise in tensile strength (Senthil Muthu Kumar et al., 2020, cross-referenced) and flexural modulus with rising filler content. The filler load of 5 to 25wt% was studied. The tested materials included amongst others spent coffee grounds, banana peel powder and crushed eggshells.

It has to be mentioned though that is this review bio-composite foils were tested, not rigid panels.

Process-ability:
Besides implications on mechanical performance the main concern with the filler load is the process-ability. In the compression moulding of thermosets, the filler content of the bulk moulding compound has to be sufficient to prevent the compound from spilling at the application of pressure.
The optimal balance between filler and resin is dependent on the density and porosity of the filler, as well as the viscosity and compatibility of the matrix. This might vary for every filler/resin combination.

Potential for filler increase:
Looking at the consistency of the previous mixtures, we start out at 45 weight % with a semi-dry and crumbly texture for the spent coffee composite (<125μm, figure 36) and a firm but viscous texture for the mixed grain walnut dough (figure 54). Therefore, the walnut mixture seems to have more potential for an increase in filler volume.
This aligns with the goal we tried to achieve by the strategic mixture of different particle sizes according to the Fullers Ratio, minimising the demand for resin by reducing the filler surface area compared to its volume.

4.2.4 Composition - Production of Samples

Recipes Composition Ratio

Component	Description	35% filler	55% filler
Resin	Furan resin	60.3	41.3
Filler	walnut, blend or spent coffee, <125 μm	35.0	55.0
Catalyst	HM1448	3.0	2.0
Releasing Agent	Linseed oil	1.7	1.7

Procedure
The procedure of producing the samples is the same as in the first part of phase 2.
In the recipe, the amount of resin is adjusted to the new filler percentage. The catalyst in turn is adjusted to make up 5% of the resin, as it has been in previous recipes.

Samples:
For the exploration of the composition the following samples are produced and tested:

Composition related:
- P2_walnut_mix_35
- P2_walnut_mix_55
- P2_spent_coffee_125_35
- P2_spent_coffee_125_55

Also relevant for comparing the results are these samples from the previous phase:

- P2_walnut_mix_45
- P1_spent_coffee_125_45

4.2.4 Composition - Preparation of Samples

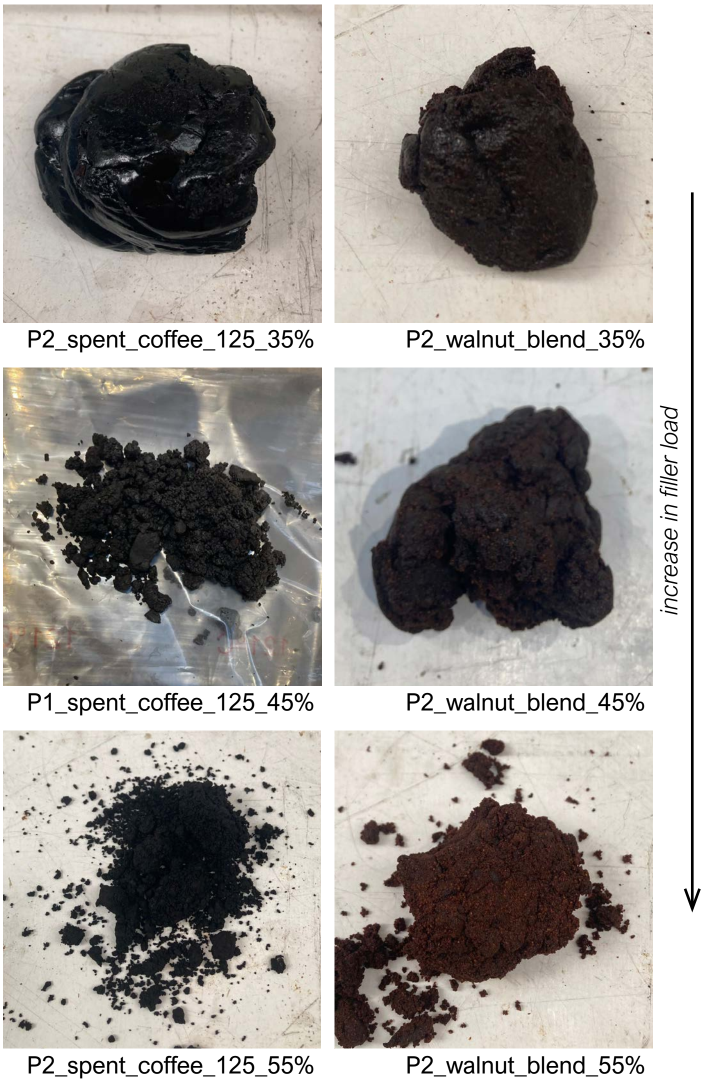


figure 56: Consistency before pressing, all relevant doughs

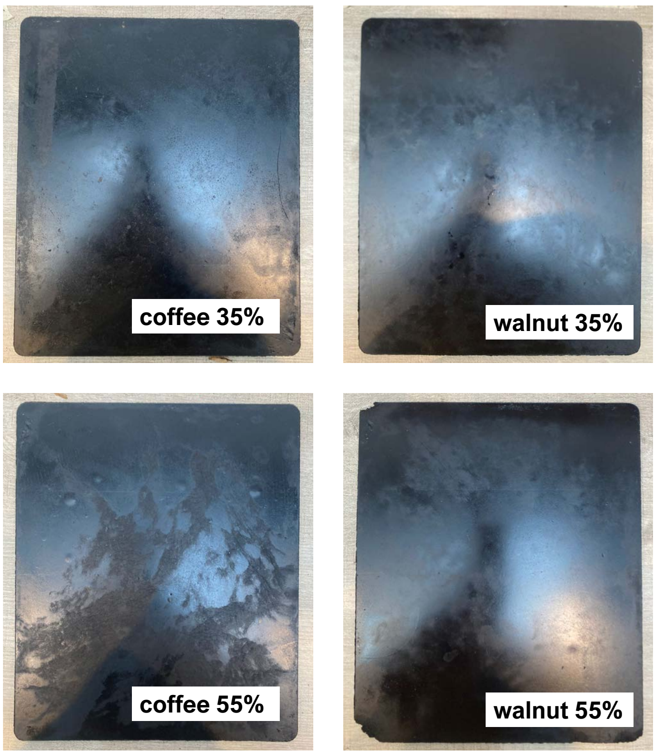


figure 57: pressed plates - composition

Process Observations:

In this round of mixing and pressing the different recipes showed strong differences in consistency.
It is visible (figure 56) that the BMC with spent coffee filler show a more drastic difference in appearance with increasing filler load. The 35% dough is glossy and viscose, the 55% dough is very dry.
Compared the walnut variants on the left seem more consistent in texture, with all of them holding their shape when compressed into a ball.
In the pressing process all mixtures were unremarkable with no spilling.

Observations:

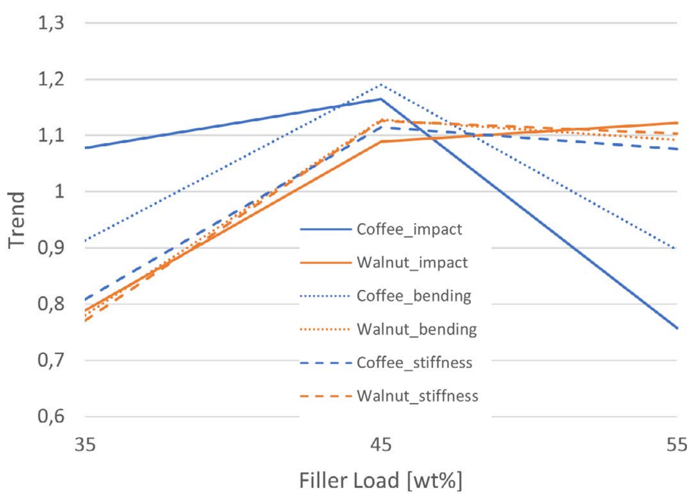
Of the four plates that were pressed in this step, two have notable characteristics.
The 55% coffee composite has a pattern of rough spots on the surface, which is likely from a lack of resin.
The 55% walnut plate has a smooth surface but the material did not fill out all the corners of the plate.

The high percentage of filler seems slow down the flow of material in the mould. Possible solutions could be a better distribution of the BCM before closing the mould or pressing at lower temperatures or pressure, which would give the dough more time to disperse before curing.

Testing

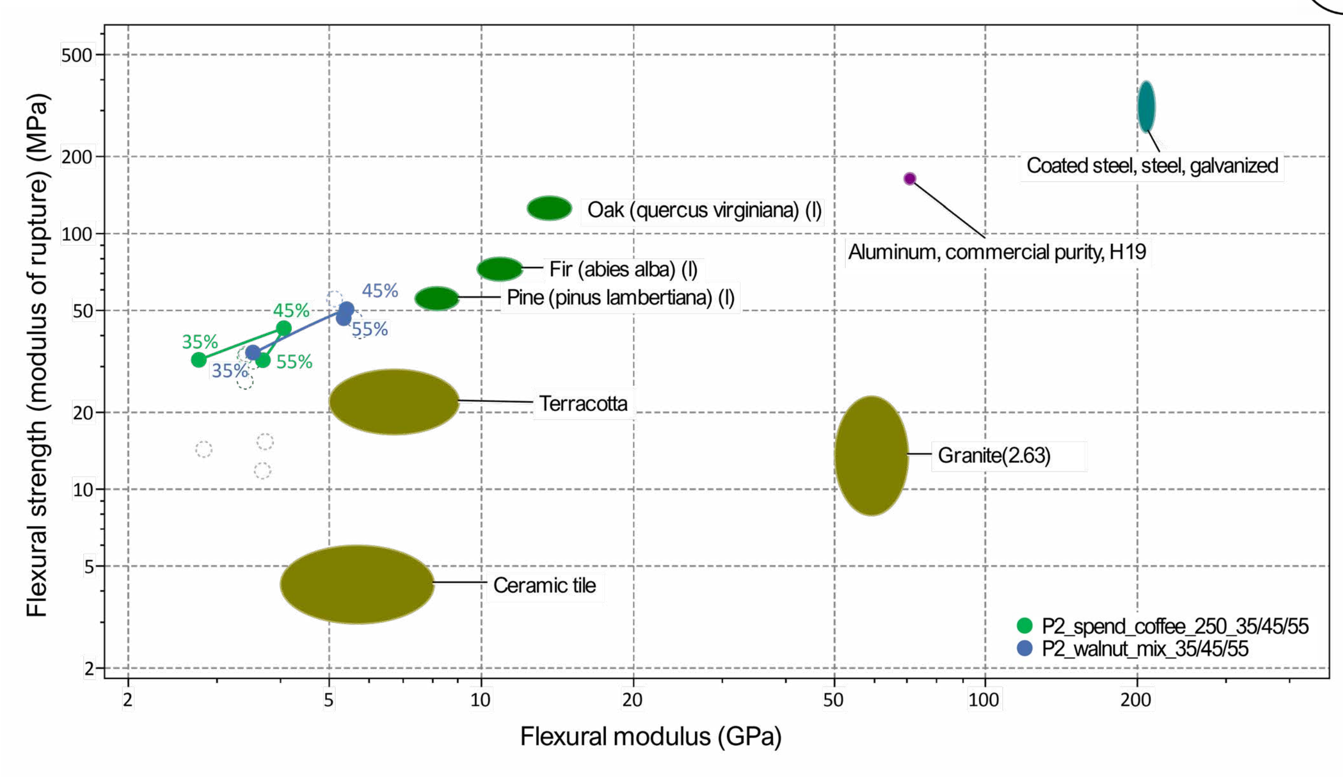
The identically to the previous steps, the plates are cut into samples and tested for 3-point bending and impact resistance (described in section 4.1.2).

Results:



graph 11: Trend of mechanical behavior with changing filler load

4.2.5 Composition - Results and Discussion



graph 12: Comparing Bending strength and Stiffness, based on data from (Granta Edupack, 2023 R3)

Conclusion and Discussion:

In the outcome of this step we can see that there is an upward trend for impact resistance, bending strength and stiffness for the walnut composites going from 35 to 45% filler load. With the increase to 55%, there is a slight improvement of impact resistance and a minimal decrease in bending strength and stiffness.
For the coffee composites the stiffness shows similar behaviour. The bending and impact strength on the other hand peak at 45% with a steep decrease in both directions.

In global comparison with other material groups and previously tested variants, the walnut composites with mixed grain sizes and a filler load of 45-55% is performing the best. The increase from 45 to 55% filler causes only a small trade-off in bending strength and stiffness which makes it the most successful recipe.

4.2.6 Conclusion - Phase 2

In this phase we first explored the impact of filler size and then ratio between filler and matrix for two filler types: spent coffee and walnut shells.
In both steps several variations were produced and mechanically tested.
In the exploration of filler size, an experimental attempt was made to blend grains of different sizes by the ratio used in concrete-mixing to achieve the optimal spacial distribution of grains.
This attempt worked well for the walnut filler but failed with the coffee ground filler. The reason for this could be the tendency of the coffee to agglomerate.
In the second step three different ratios of filler to resin were compared, again involving samples and testing.

The results are promising for the walnut composite of 55% filler, that not only performed reasonably well mechanically but also has a high percentage of filler, which makes it the favourable choice in terms of sustainability and price.
The coffee composites did not respond positively to any of the variations. The best functionality/ sustainability ration of the coffee variants probably has the 45% composite with the smallest particle size bracket.

For phase 3 we will be moving forward with the overall most promising recipe, which is the walnut composite with a blend of grain sizes and 55% filler content.

4.3.1 Design of Experiments - Phase 3

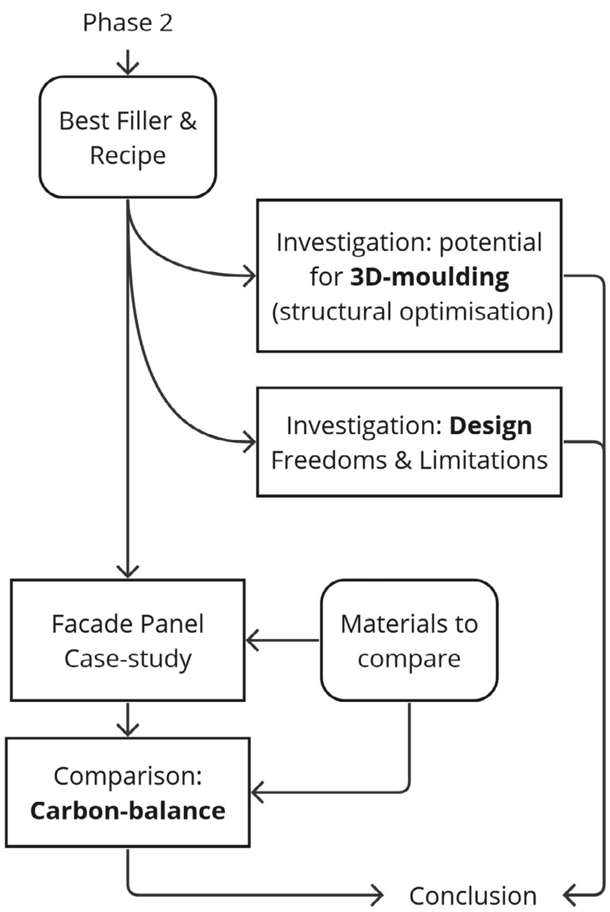
PHASE 3

Goal:
The goal of this phase to explore experimentally what the material developed in the previous two phases unique benefits are compared to other typical materials used in rain-screen facade panels and furthermore demonstrate that it has design-freedoms that allow for innovative design and structurally optimised shapes.

Action:
a. The composite variant walnut_blend_55 is moulded in a 3-dimensional mould and samples of it are tested in 3-point bending to evaluate the materials potential for structural optimisation through design.

b. A comparative assessment of the composite variant walnut_blend_55 is performed. The assessment involves a simple case-study of a rain-screen facade panel, in comparison to similar applications from different materials.

c. Lastly follows a discussion of the architectural design options that this bio-composite enables, limitation and potentials for scalability.



4.3.2 Structural Verification

a. Structural Optimisation

Since we concluded that the composite material is most likely stronger in compression, smart design might make it possible to achieve higher product performance, by employing the 3D moulding possibilities the material is capable of.

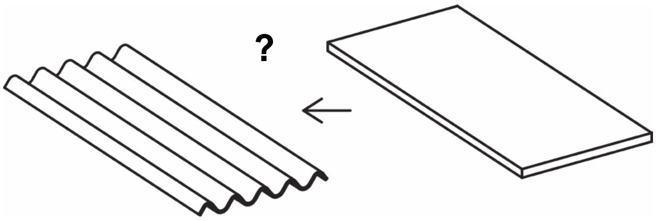
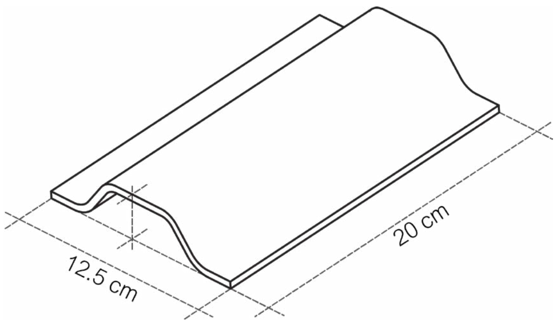


figure 58: 3D-moulded Plate



graph 13: Sample dimensions

By testing a simple 3D shape in 3-point bending, we want to see if it is possible to reduce the need for material by intelligent design, or if the 3-dimensional moulding is lowering the capacity of the material.

Action:

The composite variant walnut_blend_55 is used to mould a corrugated sheet. For simplicity this an existing mould from NPSP was used (figure 58).
From this sheet six identical samples with the dimensions 12.5 x 20cm are cut (graph 13) which are tested in 3-point bending.
Including the results from phase 2, a comparison is made between the theoretical plate thickness is that needed to achieve the 3D moulded elements strength. This way we can see if it is possible to reduce the need for material by intelligent design, or if the 3-dimensional moulding is lowering the capacity of the material.

Parameters:

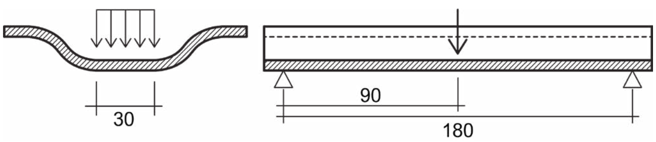
Composite used: walnut_blend_55
The same production steps are taken as in phase 1 and 2, with the only difference of the mould. The corrugated sheet mould takes 1.96 kg of compound.

Recipe:

Component	Description	Weight %
Resin	Furan resin	40
Filler	Powdered filler, blend of grain sizes (see graph 7)	55
Catalyst	HM1448 ((2-hydroxyethyl) ammonium nitrate)	3
Releasing Agent	Linseed oil	2

Testing:

The bending test of the samples was done in a 3-point setup in the Lab at 3ME.
Since the samples did not fit the width of the supports and loading pin, the setup was modified a bit, so the sample was oriented with the central rib downwards and the loading pin pressing down on the middle part only (graph 14). This test setup makes the imterpretation of the results tricky, since the forces are transferred no only in one direction .



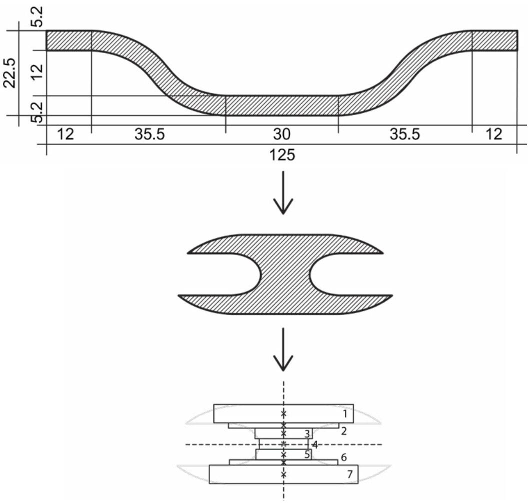
graph 14: test setup, cross-section (left) and longitudinal section (right) of a sample

Observations:

All samples displayed a clean break in the middle of the sample, most likely failing from the underside of the piece in bending.
The samples also showed only little variation of results between the samples.

4.3.2 Structural Verification

figure 59: the test setup



graph 15: cross-section simplification

Discussion:

As can be seen in table 7, the bending strength of 31 Mpa is not as high as the results we got in phase 2, where the flexural strength was at 49 Mpa on average.

The most likely reason for this, is the test setup, where the 3D element is only loaded in the centre, causing stress development in more than one direction, This would mean that a loading over the full width of the element would result in a larger maximum bending moment.

Other reasons for the differing flexural strength could have been differences between the two produced batches. Since the manufacturing process and material source were identical, this being the cause of such a large difference is unlikely.

Measurements:

The maximum bending moment capacity of the samples was calculated as on average 0.102 kNm.

If we compare this with the maximum capacity of and rectangular cross-section with similar material thickness, using the results from phase 2, we get an increase of bending moment capacity of about 240%.

3D Cross-section:
M_{max} = **0.102 kNm**

Equivalent Rectangular Cross-section:
A = 136mm x 5,2mm
σ = 48.98 MPa (result from phase 2)
$M_{max} = (\sigma * I)/y$
M_{max} = **0.0304 kNm**

~3x higher

This is what we expected with a larger structural height, but it demonstrates that moulding in 3D for better structural efficiency is possible.

To account for the structural height aswell, the cross-section was simplified in two steps (graph 15) to calculate the moment of inertia, with which we can calculate the maximum bending stress.

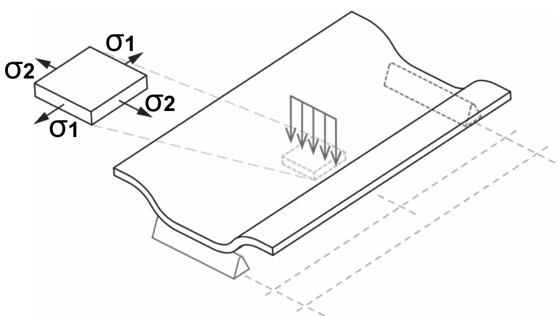
$$I = \sum I_i + A_i \times y_i^2 \qquad \sigma = \frac{My}{I}$$

Results:

Specimen Nr.	Deformation at break [mm]	Force at Break [N]	Mmax [kNm]	σ Bending strength [Mpa]
1	2,81	2367,78	0,107	32,39
2	2,26	2092,23	0,094	28,62
3	2,34	2318,99	0,104	31,72
4	2,53	2288,65	0,103	31,31
5	2,36	2275,45	0,102	31,13
6	2,46	2290,85	0,103	31,34
mean	**2,46**	**2272,32**	**0,102**	**31,08**
SD	**0,18**	**85,97**	**0,004**	**1,18**

Area	731,6	mm²	σ = M*y/I
Support Span L	180	mm	M = (1/4) * F * L
Thickness d	5,02	mm	
Iz	36515,97	mm4	
y	11,1000	mm	<- distance centroid to underside

table 7: cross-section simplification



graph 16: stress development due to test set up

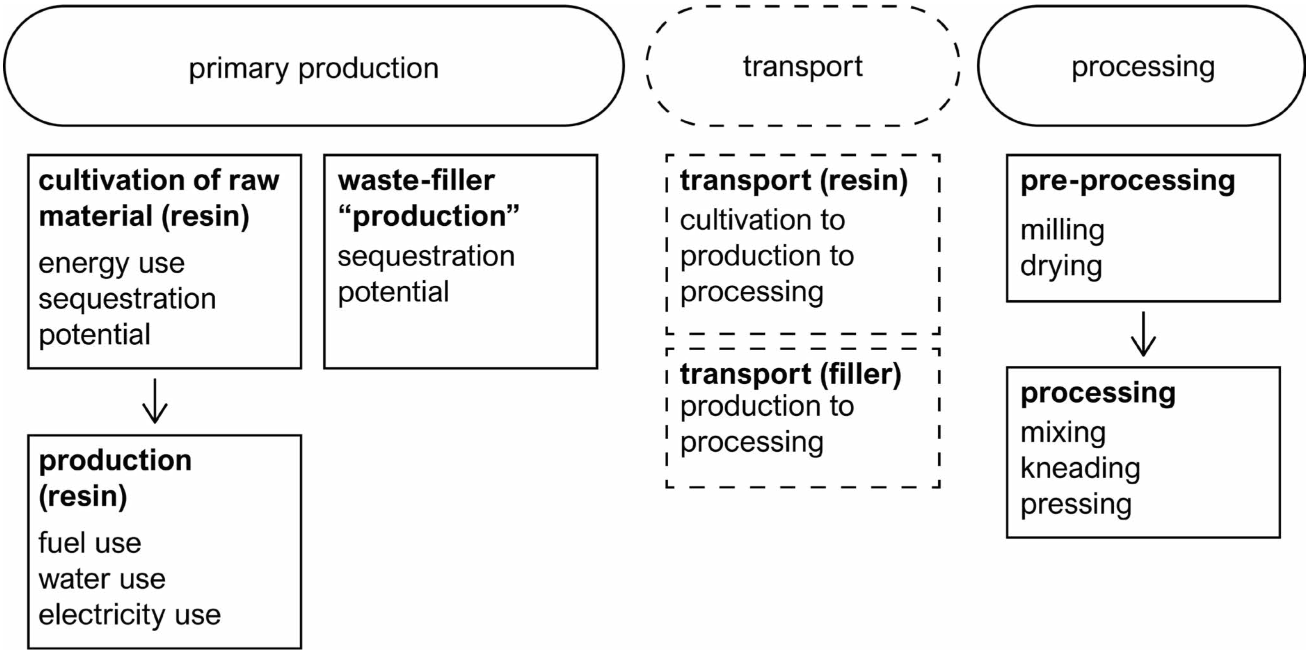
4.3.3 Sustainability Comparison

b. Sustainability Comparison

To compare the engineered bio-composite as a rain-screen facade panel with other common systems, a simple case-study is set up which compares a flat facade panel of our designed material with a selection of alternatives.
For the assessment of the sustainability, the material will be considered cradle-to-gate (C2G), meaning it considers the global warming potential if form of the equivalent emission of green-house gases at the example of CO2, of all steps from the sourcing of raw material to the finished product. (LCA Stages A1-3 are being considered) Is does not consider the complete life-cycle.

<u>Bio-composite:</u>
- 55% Walnut shells
- 40% Furan resin
- 5% Additives (Linseed oil and Catalyst)

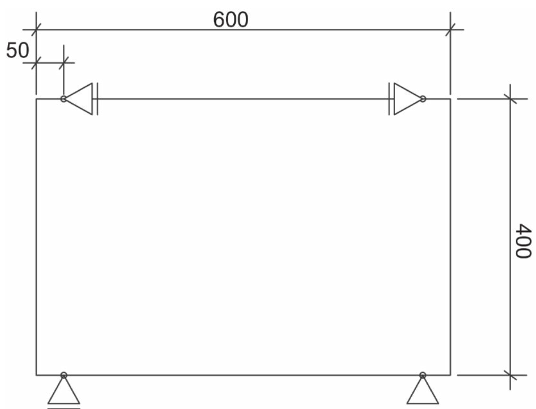
<u>The material is compared to:</u>
Aluminium, galvanised steel, ceramic tiling and granite. (Bruhn et al., 2024 ; Budinski & Budinski, 2002).

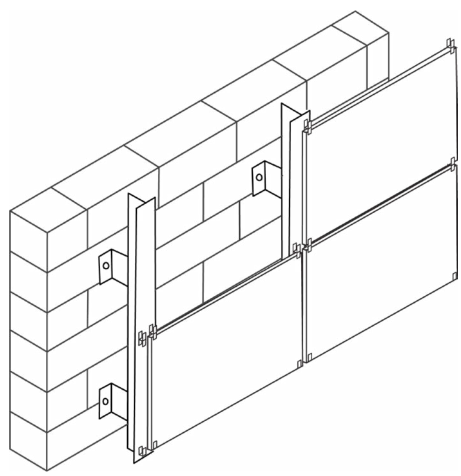


Case study

To have a comparable product, the case-study consists of a 60x40 cm flat sheet rain-screen facade panel.

Load Case:
- Wind pressure; w = 1,30 kN/m2
- Self-weight





Since several vastly different materials are compared, the installation is based on simple fasteners that hold the panels.
To make installation systems of the different cladding types comparable we assume a point supports, located at the rim of the tiles, 5 cm removed from the vertical edges.

4.3.3 Sustainability Comparison - Primary Production

Walnut shell:

Since the shells of the walnuts are a by-product of another value chain, we consider the material from the point of its generation, not from cultivation.

Sequestration Potential:
Based on the average chemical composition of walnut shells as characterised by (Queirós et al., 2020) we can assume a carbon content of about 48 weight percent, which is bound in the lignin, cellulose and hemicellulose.

Component	weight percentage [%]	carbon content [%]
cellulose	30.4	44.4
hemicellulose	24.9	45.5
ligning	35	~60-65
other (ash, proteins, etc)	9.7	-
Total		**~48%**

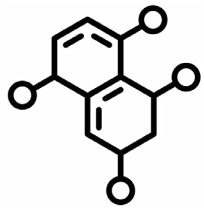
table 8: Chemical composition of walnut shells and carbon content, based on (Domingos et al., 2022)

<u>converting to CO2 weight:</u>
44.01 g/mol (molecular weight CO2)/
12.01 g/mol (molecular weight Carbon) = 3.67

<u>per kilogram shells:</u>
0.48kg carbon ×3.67 ≙ 1.76kg CO2

For each kilogram of walnut shells we can therefore assume a carbon balance of about **-1.76kg**.

Furan Resin:



Emissions in production:
4.7kg (assumed all fossil source)

Sequestration potential of organic matter:
0.7kg carbon per kg resin

<u>per kilogram resin:</u>
0.7kg carbon ×3.67 ≙ 1.76kg CO2

Based on data from (Tumolva et al., 2011)

<u>total balance:</u>
4.7kg - 2.57kg = **2.13 kg** CO2-eq

Additives:

Catalyst:
Ammoniumnitrate 1.18 kg CO2-eq/kg
(Brentrup et al., 2016)

Release Agent:
Linseed oil 2.69 kg CO2-eq/kg
(CarbonCloud, 2024)

Synthesis:

Ingredient	Content [%]	Material Price [€]	CO2-eq [kg/kg]
Walnut Shells	55	(1.5)	-1.76
Furan Resin	41	3.2	2.13
Linseed Oil	2	6.14	2.69
Catalyst (HM1448)	2	10	1.18
Total	100	2.46	**-0.02**

table 9: Data based on (carboncloud.com, 2024; Brentrup et al., 2016)

Material Price:

The material price given in table 9 is supposed to be an indicator of the materials feasibility.
Since prices are made by supply and demand, it is hard to estimate the price of a currently low-value by-product which, as soon as it has a new elevated purpose, will increase in value for all involved parties. This topic is further discussed in section 4.3.4.

4.3.3 Sustainability Comparison - Processing

The manufacturing of resin based composites includes several steps, where energy is consumed. For simplification the process is divided in the milling process of the filler material, the drying of the filler, the mixing of resin and filler in the heated kneader and the hot-pressing.

Larger productions tend to be more energy efficient since there is less downtime in between processing steps and the equipment can be used to its full capacity. Therefore the estimations made here, are most likely on the higher side, since a non-serial small to medium production is considered.

Milling:

Pin mill energy consumption:

3 kWh/t (at 202s-1 rotor speed and grain sizes of about 100 μm) ~10 kg/h production rate
= 0.3 kW/kg powder

Based on data from (Ämmälä, 2023)

Carbon energy equivalent:
0.355 kg CO2-eq/kWh carbon emission for electrical energy in the Netherlands (Ember, 2023)

≙ 0.107 kg CO2-eq/kg filler
or **0.059 kg** CO2-eq/kg composite

Drying:

Oven energy consumption:

Duty Cycle = 20% (0.2) (estimate)
Energy Consumption = 3 kW × 1 hour × 0.2 = 0.6) kWh~0.6kWh at 110°C and 1h

Based on data from (EPA & Energy-Star, 2024)

1h ≙ 0.213 kg CO2-eq
2h ≙ **0.426 kg** CO2-eq

Kneading:

Kneader consumption:
8l ≙ 3-10 kW (Linden, 2024)
duty-cycle of 20%

Consumption for 8l capacity kneader model:
1.3 kWh
Material density: 1.37 kg/l

1.3 kWh/ 10.96kg * 0.5h (30 minutes processing time) = 0.059 kWh/kg

= 0.021 kg CO2-eq/kg composite

Moulding:

With compression moulding but also injection moulding it has been observed that the energy consumption is dependent on the operating temperature and pressure but also on the duration of use, where the average consumption goes down with longer use cycles (Krishnan et al., 2010).
An average production cycle could therefore be:

1 plate (60x40x1,1cm), 15min
~0.28 kWh/kg (Krishnan et al., 2010)

= 0.099 kg CO2-eq/kg composite

Synthesis:

0.059 kg (milling) + 0.426 kg (drying) + 0.021 kg (kneading) + 0.099 kg (moulding)
= **0.605 kg** CO2-eq/kg composite

To compare the walnut bio-composite with the selected reference materials in a sheet format, we assume a processing method for each (roll forming for steel and aluminium and shaping/ grinding for the ceramic tiles and granite stone slap respectively).

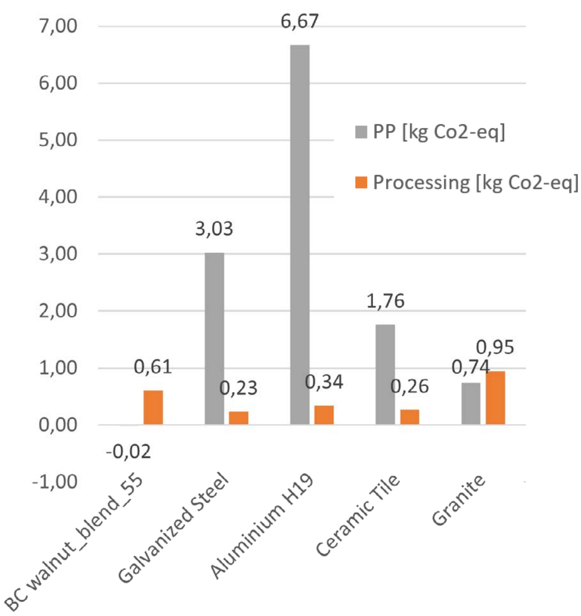
Material	Primary Production [kg CO2e]	Processing [kg CO2e] (process)
Walnut Bio-Composite	-0.02	0.605 (compression moulding)
Aluminium	6.67	0.343 (roll forming)
Steel	3.03	0.234 (roll forming)
Ceramic Tile	1.76	0.264 (grinding)
Granite	0.735	0.949 (grinding)

table 10: Carbon Equivalent of Primary Production and Processing, reference materials based on (Budinski & Budinski, 2002)

4.3.3 Sustainability Comparison - Results

Comparison per kg material:

The comparison of material per kilogram shows that the walnut composite is very efficient in primary production and performs better that all of the compared materials (graph 17).
In processing the heat intensive drying and moulding of the composites results in higher emissions than the processing of steel, aluminium and the ceramic tiles.



graph 17: CO2-eq of Primary Production and Processing per kg

Result:

Facade Panel	Thickness [mm]	Weight [kg]	Material Price [€]	GWP [kg CO2-eq]
Bio-Composite	11	3.54	8.7	0.6
Aluminium	5	3.29	11.3	23.1
Steel	3	5.69	7.8	18.6
Ceramic Tile	9	5.18	2.8	10.5
Granite	5	3.84	22.3	6.5

For the calculation of the panel thickness for each material, a karamba3D based grasshopper script was used (see section 6.1.3). The composite panel is with 1.1cm the thickest. The thickness is necessary to fulfil the SLS criteria for the maximum deflection.
Both the ceramic tile and granite panel are stiffer than the composite, which is why the bending stress is the governing factor for both. The stiffness of the composite panel could be increased with the

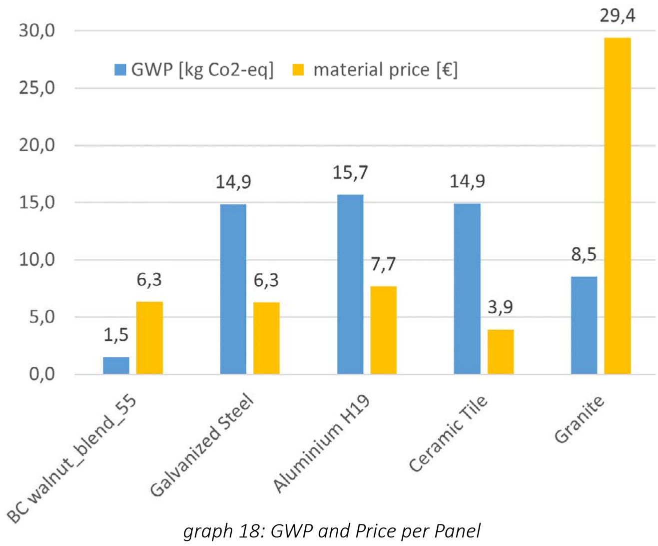
Applying the data to the case-study:

To see how our material holds up in the comparison in the real facade application, first the needed thickness for the individual panels have to be calculated.
For this a material safety factor of 1,5 and a maximum deflection of the panel according to Eurocode 1 (European Comission, 2019) were considered.

Material safety factor: $\gamma_m = 1,5$
Max Deflection at SLS: $\Delta_{max} = b/200 = 0.3$ cm

Material Data:

Material	Youngs Modulus [GPa]	Bending strength [MPa]	C2G-eq Emissions/ kg	Bending moment (max) [kNm]
Walnut Bio-Composite	5.1	49	-0.02	0,014
Aluminium	72.0	184	6.67	0,014
Steel	215.0	600	3.03	0,014
Ceramic Tile	8.0	6	1.76	0,014
Granite	70.0	23	0.735	0,014



graph 18: GWP and Price per Panel

addition of a rim or ribs on the back of the plate, which would have allowed for a thinner plate.

In graph 18 the carbon balance the carbon impact for each panel type can be seen. The composite presents with the lowest impact.
As an indicator of feasibility, the material price is shown in yellow. Price wise the composite is comparable with steel and aluminium.

4.3.3 Sustainability Comparison

Transport:

The transport of raw material to the location of the primary production and to the main production location is ideally as short as possible.
Many raw materials travel long distances for several steps of processing in different locations.

Transport of Raw Materials
For the transport of raw material we have to consider the furan and the filler.
If we assume a local plantation as the producer of the filler walnut shells, we are talking about distances of about 50-150 km of transport (see examples suppliers in section 6.1.3).
The furan resin is produced in Belgium so the distances and emissions caused by the transport can be considered moderate.

Of the alternative materials, longer transport distances can be expected for both steel and aluminium, of which more than 50% of Dutch supply is imported from outside Europe (Datawheel, 2022). Granite is also not local to the Netherlands and is usually imported from other EU countries like Germany or Norway (Datawheel, 2022).

Additional Considerations:

The comparison does not account for the later life-cycle stages. Nevertheless, evaluating the panel's expected durability and EOL scenarios is essential.

Durability:
The overall durability of the bio-composite depends on its constituent materials. Although long-term studies on the durability of furan resin are limited, existing research indicates that this thermoset resin possesses significant resilience against fire, moisture, and UV radiation (Fink, 2005).
The organic walnut shells, on the other hand, is susceptible to bio-degradation. However, the low levels of water absorption discussed in section 4.1 imply that the complete encapsulation of fillers within the matrix effectively shields them from the elements.
A life span of around 20 years could be realistic, with a high likelihood of change in the appearance over time, like experienced in the frost test.

End-of-Life:
Several EOL scenarios for the façade panelling are imaginable. Mechanical recycling, which involves reintroducing the shredded material as filler for new panels, appears to be the most feasible approach. Alternatively, the shredded material could undergo bio-degradation, where the filler would decompose, leaving the matrix in a sand-like form. This residue could potentially serve as aggregate in other processes or as filler for new composites.
Extending the life-cycle of the composites through repair methods could also significantly enhance the product's overall viability. Further investment is required to explore these possibilities fully.

Reflection and Conclusion

For the comparison only cradle-to-gate was discussed because this is in this thesis project mostly the material sourcing and processing were investigated.
Globally also the life-cycle, options for repair, reuse and re-manufacture should be explored, which are partially material related, partially design depended.

The energy consumption of different processing step is only approximated but might be drastically different depending on production size and machine specification.

The assumptions were made on the conservative side. The energy needed for the furan production is assumed all fossil based, since the origin might vary. For the manufacturing steps in the Netherlands, a national average of fossil vs. renewable energy is used.
The bio-composite with 55% walnut-shell filler is slightly carbon negative in primary production and after processing accounts for a fraction of what metal claddings but also stone and ceramics emit. Even though the thickness of the composite panel needs to be a bit larger, the composite compensates by its lightness.

4.3.4 Design Opportunities

c. Design Opportunities

Besides structural integrity, the 3D shaping options that this material allows for is a large opportunity for the architectural expression.
Opposed to continuous fibre composites, a sheet material that can be manipulated into certain shapes, the design freedom of compression moulding with BMC has almost no limitations, since the dough can be moulded into any shape and is not restricted by continuous fibres.

Design shaped by Material and Process

In the case of our filler/resin bio-composite the use in a facade application demands low porosity/ absorption, high UV-resistance and reasonable strength.
The chosen recipe and processing method enable the material to fulfil these demands.
If now, the same material should be used in a different context, for example a load bearing building block, the recipe and method would be the wrong ones. For one, is it likely that the moulding in a volumetric shape would not work sufficiently since the material would not be heated evenly in the moulding process. The cooling process would lead to uneven shrinkage and deformation ("Designing for Mouldability", 2024).
Still, with an adjustment of the recipe, replacing more resin with filler and choosing another curing method, the same material combination might enable the making of volumetric structural blocks.
In this manner, the field of application could be extended in several directions.

figure 60: demonstration of a 3D-moulded decorative tile

Material colour

Since the furan resin has a dark brown colour and the walnut is also brown, the resulting composite is almost black. The colour, even though quite dark, has a pleasing appearance and changes its hue in varying light conditions.
The inherent colour and natural patterns derived from moulding filler and matrix, present a playground for architects and designers to find entirely new ways of expression. Beyond aesthetics, the visibility of bio-based facade products can serve as a visible token in a society increasingly valuing sustainable behaviour.

figure 61: different tiles with recipes from phase 2, in daylight

4.3.4 Design Opportunities

Design Freedom vs Reproducibility

As demonstrated, the medium and manufacturing methods leave us with a wide range of shaping and implementation options. One advantage of the compression moulding technique is that complex shapes can be created and reproduced without bigger effort, with the only investment being the initial creation of a mould.

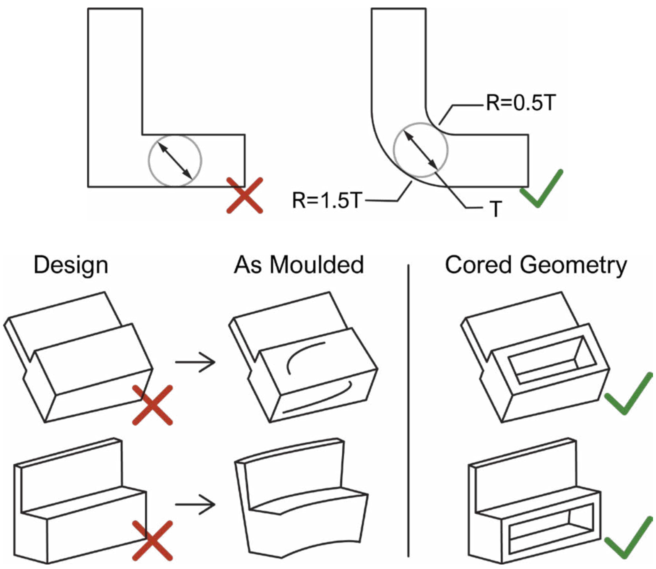
The downside of the manufacturing method is, that each new design needs a new mould. Cladding designs, that demand a large number of unique pieces are therefore not feasible.
Small assortment of panels or tiles, that can be combined in various orientations, can exponentially increase the complexity of possible configurations without the creation of a lot of individual moulds. Even though the number of moulds are a limitation for designing with compression moulded composites, this limitation might pose a inspiring challenge for contemporary design practices.

Scalability of the production process

The suggested material and application is one way of many to contribute to a circular economy in which waste is considerer a resource and all available sources are valorised to the best of their potential, avoiding additional waste and long transport distances.
Therefore the focus of this “product” should not be the scaling to an extensive production, but should aim to fill out its local niche.
As the availability of the chosen waste-source is the defining factor, a medium sized production with repeatable designs and production on demand could be a promising economic concept.

Design Rules for Compound Moulding

When using the compression moulding technique, several design rules must be followed. Large variations in thickness should be avoided to prevent warping and deformation during cooling (“Designing for Mouldability,” 2024). However, (Senthil Muthu Kumar et al., 2020) concluded in a review of several studies about bio-based fillers, that the thermal stability rose with an increase in filler load.
Another essential rule is to avoid sharp edges and corners, as they can create stressed areas in the moulded piece (“Designing for Mouldability,” 2024).



graph 19: Designing for Mouldability

Post-Processing: Machinability

The machinability of the walnut_blend_55 composite is overall good. Since the furan resin is, as a thermoset, quite heat resistant, the material does not tend to melt when being processed.
The material can easily be drilled and sawn. Also CNC-milling and cutting with a router are no problem.
Since the material is quite brittle, though strong, drilling and routing should be done slow, with a support from the bottom of the piece, otherwise the edges of the drill-hole might break out.

figure 62: example of possible drilling and sawing

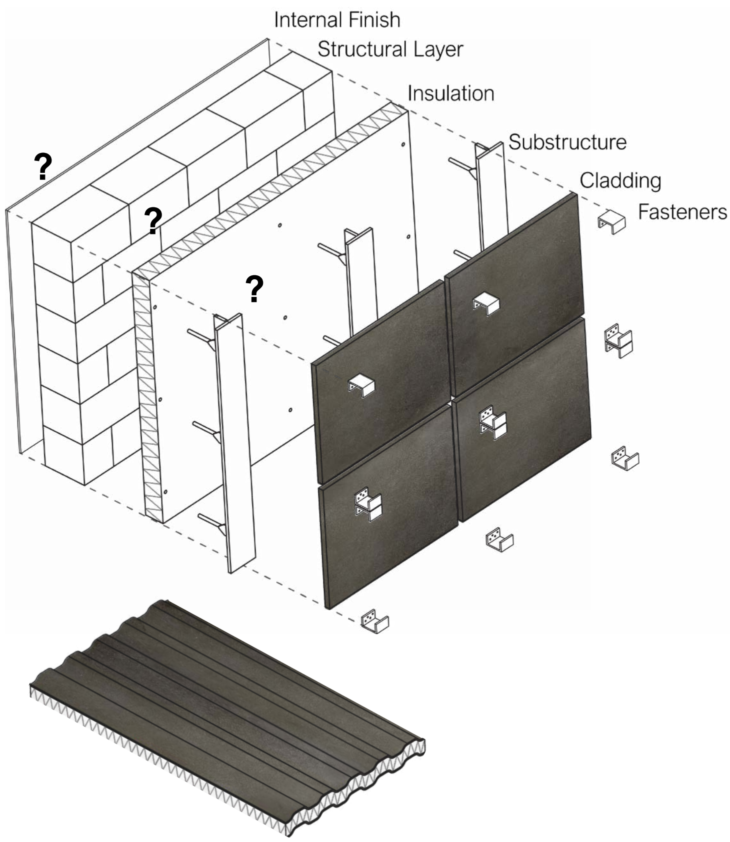
4.3.4 Design Opportunities

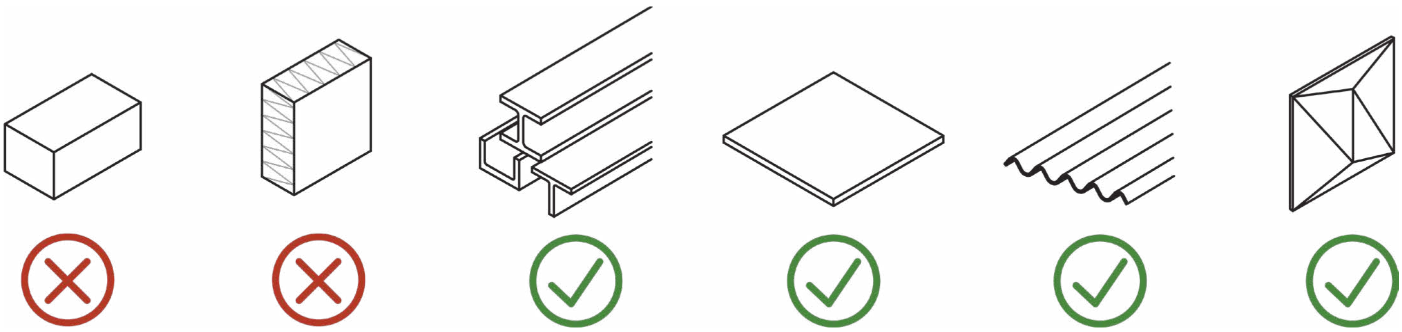
Alternative Usecases

After demonstrating that the composite material is suitable for facade applications, the question arises about other potential use cases. The engineered material offers high resilience to weather, a brittle nature, mouldability in thicknesses of about 1-10mm, and natural colour variations as it weathers.
Based on the properties explored in this chapter, several alternative applications beyond facade cladding are conceivable, while some are excluded.

Limitations: Volumetric moulding is likely not feasible due to shrinkage and warping, and low porosity makes it unsuitable for insulation purposes.

Possible applications include: roof tiling, also use as a facing for insulated roof panels. Floor tiling may be feasible but requires further evaluation of abrasion resistance. Additionally, it could be used for secondary structures and interior finishing, where complex designs are possible, similar to the facade applications.





4.3.5 Conclusion Phase 3

In this phase the usability of our engineered bio-composite in regards to sustainability, design and structure was investigated.
In a test of a 3D-moulded element, it was demonstrated that the moulding method is adequate to produce more complex shapes for structural purposes.
In a comparison with other materials that are commonly used in facade cladding, a simple case-study was set up to evaluate the bio-composites carbon balance in a cradle to gate. The result showed a carbon negative balance in primary production and emissions in processing, that were in a reasonable range compared to the other materials.

For the design of facade panelling with this bio-composite, there are many option but also some limitations.
Design rules apply for moulding BMC, which make panels and sheet materials the favourable choice.
Complex 3D-shapes are possible to be produced without rising cost. At the same time is the design of many individuals pieces not feasible, since each new design needs new mould.
The processing of the material is easy, which gives more options for installation and post-processing.
The material has potential for the use in other application types aswell and might benefit from the addition of fibre reinforcement into the mix, to broaden the materials abilities further.

4.4 Chapter Conclusion

Chapter Conclusion

This chapter describes three phases of experiments. In Phase One, various waste sources were evaluated for their effectiveness as fillers. After comparing their usability and investigating the reasons for different material behaviours, spent coffee and walnut shells were selected as the best fillers for Phase Two.

In Phase Two, the optimal combination of grain size and composition was determined experimentally. Spent coffee and walnut shells yielded very different results: walnut shells performed as expected, while coffee filler produced inconclusive outcomes in several tests. The walnut filler blend with 55% of mixed grain sizes provided the best balance between filler content and mechanical properties.

In the final phase, this formulation was tested for aspects relevant to facade panel design. This including reviewing design guidelines, evaluating shaping and machining options, and performing structural tests on a 3D element. The material's carbon footprint was also assessed in the first three stages of a life-cycle analysis.

The results are promising, showing that the composite has a lower carbon impact compared to conventional facade materials. Although the potential for other applications is promising, further investigation is required. The experimental phases explored just one way to integrate waste streams with many options left unexplored, highlighting the considerable potential of this material class.

5.
Research Conclusion and Reflection

This chapter discusses the results of all experiments, focusing on the functionality and sustainability of the composites. It reflects on the methods used, the overall project, and the potential applications of the developed materials. The conclusion highlights the benefits and challenges of using waste-based fillers in bio-composites, offering insights for future research and development.

5.1 Discussing the Results

Answering the Research Questions

Was the initial research question of how waste-based fillers can be integrated into bio-based composite façade panels, answered?
Yes, partially. During the research of waste-flows in the food industry, and ways to integrate bio-based fillers in composite panelling, it became apparent that there are not only many filler material options to consider, but also endless ways to approach the task of integration.
So in the end one valid path of integrating waste into composite panelling was illuminated and some side roads were explored.

Identifying Waste-flows

Identifying local waste flows turned out to be of varying difficulty, depending on the waste producing sector.
For some materials it was easy to get solid information and samples of produced waste (coffee and cacao processing companies, fruit processing), in others it was hard to find information.
The waste-flows that were selected in this project were only a small assortment of possible local sources.
For this, the cherry pits and walnut shells were both picked as representatives of a bigger group. Still, each other fruit pit or nut shell have quite unique properties in a composite.

Phase 1

Of the six selected fillers, three showed promise for use in composite applications: walnut shells, cherry pits and spent coffee.
The reason for cracks and unevenness of the surface of the other three composites and the thereby drastically lower mechanical and functional properties, could not be identified in full. Still, some causes, like the inclusion of air bubbles in the pressing process, could be eliminated.
In the end the walnut and spent coffee fillers were selected to proceed with.

Phase 2

In the second phase the integration of the filler types was systematically tested. The two filler types that were tested in this phase behaved very different with the variation of filler size and composition ratio. The walnut shell filler behaved as expected with an reduction of strength with larger particles, while the coffee ground composited showed no clear correlation.

Phase 3

In Phase 3 the best recipe, which was the walnut_blend_55% composite was evaluated for the use in the facade panel application. The carbon balance of 0.6 kg/kg is very competitive and the material has adequate mechanical properties for the use in many design options.

Overall the outcome of the thesis is very positive and all main goals were reached.

Potentials

The investigation of waste-based fillers in fully bio-based composite has a large potential to lead to and extensive set of materials that serve a low-carbon circular environment.

Material Potential:

The material that was created would by itself already be viable for facade panelling.
This project did not at all consider fibre reinforcement. A hybrid filler composite with both granular filler and fibre reinforcement would most likely show a much higher tensile strength then an only filler composite.
This might reduce the material need in applications significantly.

Application Potential:

In the future, bio-composites like those explored in this project could be used in a variety of building applications beyond facade panelling. These include secondary or even main structures, as well as interior or roof applications. The building industry stands to benefit from this material class, which offers low environmental impact, unique aesthetics, new design opportunities, and lightweight construction opposed to concrete or steel.

Economic symbiotic Potential:

With the integration of existing waste-streams from the food industry, vital symbiosis between bio-composite producing companies like NPSP and "waste" supplier from many fields of the large food sector of the Netherlands trading and processing industry could develop.
This win-win-win scenario benefits not only both sides economically but also has by proxy a positive impact on the building industry and reduces the burden of waste treatment.

5.2 Reflection on Project Methods

Limitation of this Research

Testing:
The testing methods that were used in this project were mostly influenced by the availability of equipment and time.
The use of three point bending instead of four-point bending because the setup was available.
Instead of a real weathering testing, absorption and frost resistance testing was done since no weathering machine was available.
The contact angle testing was executed with a home-made setup that probable lacked precision.

Material selection:
In the first stages of the project many waste sources were investigated for their benefits. Still, no holistic analysis and mapping of all possible and qualified sources could be done due to in-transparency of some industrial sectors and time limitations for investigation.
From the pool of qualified sources, only a few were chosen, because the capacity of the project was limited. The ultimate decision about which materials would be tested, was made based on availability and local sources.

Depth of research:
In the progression of this project, the approach varies between a target oriented approach with decisive decision making regarding one final goal, in this case the successful development of a bio-composite and design of a rain-screen facade panel with it, and exploratory deep dives.
In the balance between the two, some topics have only been treated briefly and not in depth.
The investigation of the bumps and cracks that appeared on some sample plates after pressing is one of the topics that are really interesting but which this project failed to answer in the end, even though several approaches were made to get to the answer.

Possible future work

Further research could focus on some of the topics that have been touched in this thesis project but have not been fully explored.

- A holistic mapping of waste-streams for the bio-based industry could be vital for future material development.
- The introduction of natural fibre as reinforcement into the waste filler/ resin composite.
- The making of a criteria toolbox that lines out indicators for compatibility of some bio-based fillers with certain types of bio-plastics. For this, the first step would be the finding of the reasons for mismatches, like the bumps and cracks that disqualified some of the filler type in this project.
- The closer inspection on how different manufacturing methods influence the process of composite making and their sustainability
- The use of this or similar bio-composites in other applications.

Limitations of Waste in Bio-composites

One significant challenge for bio-composites is balancing biodegradability and durability. While bio-composites are designed to be eco-friendly, their lifespan and structural integrity can be more short-lived and has align with a holistic maintenance and eol scheme.
Another limitation is the dependency on local sources. Sourcing waste materials locally is crucial to maintaining the sustainability and cost-effectiveness of bio-composites. However, this can also limit scalability of productions and availability might change .

Furthermore, there may be inconsistencies in material performance. This is a common issue with all bio-based materials.

5.3 Project Reflection

Socio-cultural Reflection

In practice, the results of my exploration offer direct applicability, especially in the development of related or similar building products. Collaborating with NPSP, a company that currently investigates furan-based bio-composites, enriched the potential for implementing these findings practically.
With the focus on waste based sources for fillers and the freedom for experimental approaches in recipe making, I believe my results add to the knowledge base about bio-composites and integration of waste materials in the building industry, beyond what a commercially motivated research would have achieved.

The impact of my project on sustainability is given by promoting industrial symbiosis and advocating for waste reduction. The development of low-carbon building materials furthers environmental conservation and enables a more sustainable urban development.

Addressing the United Nations Sustainable Development Goals, my project aligns closely with several key objectives.
Firstly, it contributes to **Sustainable Cities** (goal 11) by promoting the development of environmentally friendly building materials.
Secondly, it advances **Responsible Consumption and Production** (goal 12) by utilizing waste materials and giving the opportunity for sustainable industrial symbiosis.
Lastly, by focusing on low carbon building materials, my project actively works towards mitigating environmental impacts and combating climate change, aligning with goal 13, **Climate Action**.

Process Reflection

In this graduation studio, my topic is placed in the field of material science, structural design, and circular product design, as it aims to engineer bio-based materials for sustainable building products.

Reflecting on the research approach, the overall process was evenly structured, with a clear sequence of actions and subsequent decision-making.
However, it would have been beneficial to establish the evaluation criteria for each step at an earlier stage. I found myself struggling with the tension between maintaining a target-focused approach and diving into in-depth research on specific details.

Ethically, the project remains conscientious of its societal and environmental concerns.
The project exclusively targeted waste products lacking superior alternative uses, such as animal food or human nutrition. Furthermore, by optimizing waste-based content and diminishing reliance on virgin-grade bio-materials, the environmental impact is reduced.

In terms of architecture and the built environment, the project offers promising outlook for sustainable design and construction practices. By advocating for the adoption of bio-based materials, it lays the groundwork for greener and more eco-friendly architectural solutions. This not only aligns with overarching goals of environmental sustainability but also offers new architectural opportunities.

The results yielded from the process turned tout to be interesting and served as a catalyst for further exploration. However, they also presented several alternative focal points for investigation at each juncture, complicating efforts to remain aligned with the initially established objectives.

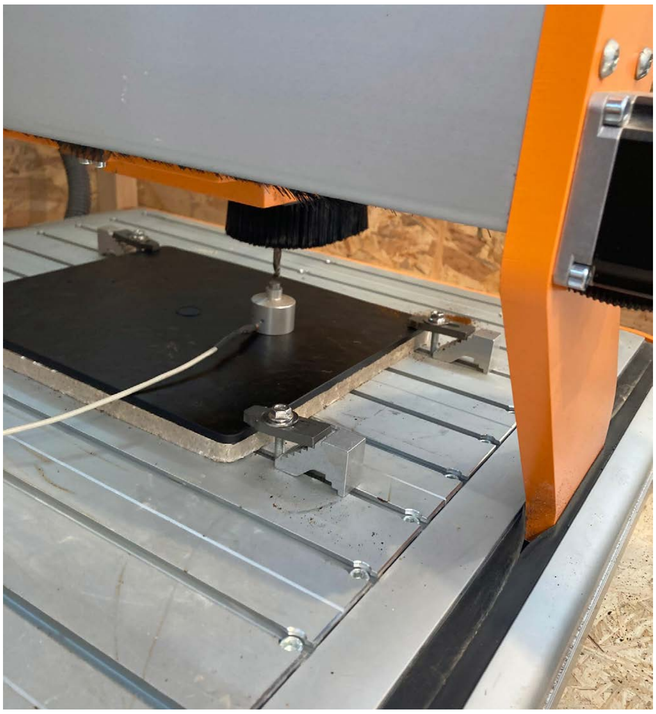
Despite this challenge, the project adopted a step-by-step methodology, where each research phase informed and influenced subsequent steps. In this regard, even though the final outcome wasn't predetermined from the start, the overall set goals were ultimately achieved.

6. Appendix

6.1 Tables and Graphs - Material Research

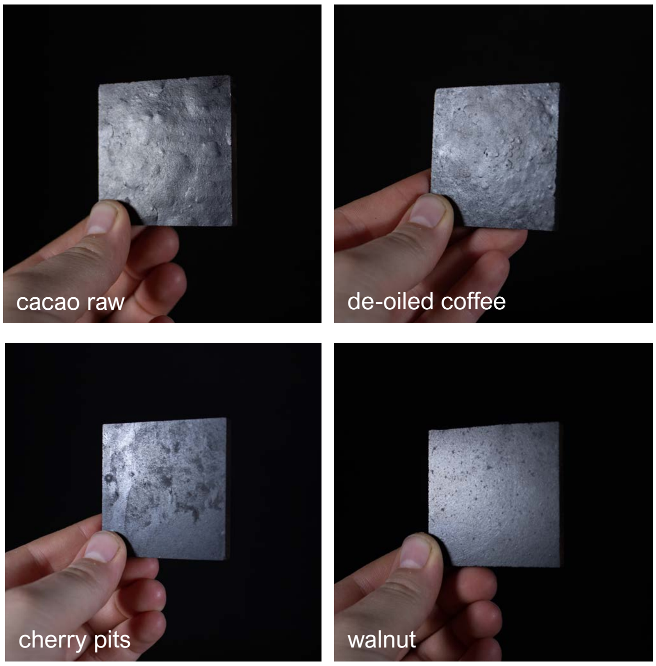
Additional Photos

Phase 1 - CNC-milling of a sample plate



Phase 2 - Walnut filler of different size brackets

Phase 1 - Samples after absorption testing



Phase 2 - Particle Size

Phase 1 - Sample plates

6.1.1 Tables and Graphs - Phase 1

Test results Phase 1A - Tensile and Impact

Cocoa, raw	
Date:	240209
Method:	Hotpressing (BMC)
Note:	two plates pressed

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	600	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	30	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Agent	linseed oil	20		1,7
Filler	cocoa, raw	540	powdered, <125µm	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	14,4	0,47	3,18	70,05	*
2	16,5	0,65	2,68	80,54	*
3	11,6	0,51	2,49	64,64	*
4	20,7	0,81	2,63	99,01	*
5					
6	12,9	0,45	2,95	66,71	*
7	21,1	0,75	2,99	103,41	*
8					
Mean	**16,20**	**0,61**	**2,82**	**80,73**	
S.D.	3,99	0,15	0,26	16,84	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,0638	1,1464
2	0,0707	1,1709
3	0,0707	1,2943
4	0,1054	1,9072
5	0,0985	1,7662
6	0,0707	1,2547
7	0,0638	1,1690
8	0,0222	0,3895
9	0,1054	1,7674
10	0,0985	1,8315
Mean	**0,08**	**1,37**
S.D.	0,03	0,46

Cocoa, roasted	
Date:	240209
Method:	Hotpressing (BMC)
Note:	two plates pressed

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	600	Biorez(TransFurans Chemicals)	50,4
Catalyst	HM1448	30	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	20		1,7
Filler	cocoa, roasted	540	powdered,	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	16,7	0,45	3,87	66,36	*
2	21,5	0,57	3,89	94,27	*
3	15,1	0,42	3,72	58,53	*
4	18,7	0,55	3,48	77,46	*
5	18,2	0,47	3,94	72,21	*
6	14,1	0,41	3,51	59,7	*
7	16,9	0,47	3,76	72,23	*
8					
Mean	**17,31**	**0,48**	**3,74**	**71,54**	
S.D.	2,45	0,06	0,18	12,17	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,0707	1,3628
2	0,0499	0,9226
3	0,0777	1,4819
4	0,0430	0,7709
5	0,0499	0,9352
6	0,0707	1,3093
7	0,0638	1,2019
8	0,0638	1,1946
9	0,0361	0,6336
10	0,0430	0,7928
Mean	**0,06**	**1,06**
S.D.	0,01	0,29

6.1.1 Tables and Graphs - Phase 1

Test results Phase 1A - Tensile and Impact

Coffee grounds, spend	
Date:	240223
Method:	Hotpressing (BMC) one plate
Note:	pressed

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	330	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	16,5	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	11		1,7
Filler	coffee, spend	297	powdered, <125µm	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	40,1	1,1	3,98	180,28	*
2					
3	39,9	1,1	3,95	180,68	*
4	45,5	1,2	4,1	191,69	*
5	45,3	1,3	4,07	210,47	*
6					
7	40,2	1,0	4,37	171,98	*
8	44,1	1,1	4,22	181,95	*
Mean	**42,52**	**1,13**	**4,12**	**186,18**	
S.D.	2,73	0,10	0,16	13,45	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,0985	1,7774
2	0,1678	3,1212
3	0,1609	2,9533
4	0,1193	2,1081
5	0,1054	1,8769
6	0,1193	2,2270
7	0,1193	2,1135
8	0,1193	2,1164
9	0,1609	2,8647
10	0,1331	2,3818
Mean	**0,13**	**2,35**
S.D.	0,02	0,47

Coffee grounds, deoiled	
Date:	240223
Method:	Hotpressing (BMC) one plate
Note:	pressed mix of used and unused coffee

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	330	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	16,5	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Agen	linseed oil	11		1,7
Filler	coffee, deoiled	297	powdered, <125µm, spend/fresh mix, deoiled, Caffe.inc	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	11,1	0,32	3,55	47,55	*
2	12,4	0,4	3,18	56,65	*
3	16	0,44	3,7	68,51	*
4	14,9	0,4	3,73	59,45	*
5	10,3	0,31	3,52	44,85	*
6	16,3	0,46	3,67	65,7	*
7	13,2	0,4	3,73	57,46	*
8	16,9	0,45	3,87	72,5	*
Mean	**13,89**	**0,39**	**3,62**	**59,08**	
S.D.	2,50	0,06	0,21	9,69	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,0777	1,4163
2	0,0361	0,6578
3	0,0915	1,7341
4	0,0291	0,5438
5	0,0291	0,5199
6	0,0430	0,7694
7	0,0707	1,2598
8	0,0638	1,1674
9	0,0638	1,1493
10	0,0638	1,1478
Mean	**0,06**	**1,04**
S.D.	0,02	0,40

6.1.1 Tables and Graphs - Phase 1

Test results Phase 1A - Tensile and Impact

Walnut shells	
Date:	240223
Method:	Hotpressing (BMC)
Note:	two plates pressed

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	600	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	30	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	20		1,7
Filler	walnut shells	540	powdered, <125µm	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	70,6	1,4	5,8	290,59	*
2	53,3	1,1	5,2	240,39	*
3	63,8	1,3	5,43	266,08	*
4	58,8	1,3	5,16	246,79	*
5	48,1	0,97	5,34	213,31	*
6	55,8	1,2	5,05	238,72	*
7	68,9	1,5	5,02	294,52	*
8	50,4	1,1	4,96	213,39	*
Mean	**58,71**	**1,23**	**5,25**	**250,47**	
S.D.	8,37	0,17	0,28	31,17	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,1609	3,1057
2	0,1678	3,2396
3	0,1609	3,1122
4	0,1678	3,3056
5	0,1540	3,0222
6	0,1609	3,1011
7	0,1540	2,9512
8	0,1540	2,9547
9	0,2372	4,4754
10	0,2164	4,1134
Mean	**0,17**	**3,34**
S.D.	0,03	0,52

Cherry pits	
Date:	240311
Method:	Hotpressing (BMC)
Note:	one plate pressed

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	330	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	16,5	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	11		1,7
Filler	cherry pits	297	powdered, <125µm	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	29,9	1	3,22	132,24	*
2	41,2	1,4	3,49	170,25	*
3	36,1	1,3	3,28	170,94	*
4	32,6	1,1	3,18	147,37	*
5	35,5	1,3	3,19	164,26	*
6	29,7	1	3,38	132,44	*
7	39	1,3	3,56	170,76	*
8	30,7	1,1	3,27	135,98	*
Mean	**34,34**	**1,19**	**3,32**	**153,03**	
S.D.	4,32	0,16	0,14	17,88	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,0985	1,8427
2	0,1262	2,3934
3	0,1401	2,6256
4	0,1331	2,4887
5	0,1262	2,4334
6	0,1331	2,5322
7	0,1193	2,2618
8	0,0985	1,8407
9	0,1609	2,9954
10	0,1470	2,8069
Mean	**0,13**	**2,42**
S.D.	0,02	0,37

6.1 Tables and Graphs - Phase 1

Test results Phase 1A - Waster Absorption

	sample	dry [g]	24h [g]	24h-Av [%]	28d [g]	28d-Av [%]
Spend Coffee	SC_1	16,86	17,04	2,06	18,24	9,26
	SC_2	16,25	16,44		17,67	
	SC_3	16,49	17,14		18,28	
Deoilied Coffee	DC_1	16,55	17,05	4,35	18,67	12,85
	DC_2	16,36	16,87		18,48	
	DC_3	16,03	16,51		18,08	
Cacao raw	CU_1	18,22	18,98	4,35	19,88	9,95
	CU_2	17,94	18,71		19,70	
	CU_3	17,93	18,75		19,89	
Cacao roasted	CR_1	15,97	16,93	5,50	17,75	10,72
	CR_2	16,27	17,16		18,03	
	CR_3	15,90	16,70		17,52	
Walnut	W_1	17,69	17,86	0,79	18,55	4,79
	W_2	17,45	17,59		18,30	
	W_3	17,87	17,98		18,70	
Cherry	CP_1	16,97	17,09	0,75	17,70	4,39
	CP_2	17,59	17,73		18,37	
	CP_3	17,36	17,49		18,13	

Test results Phase 1B - Density

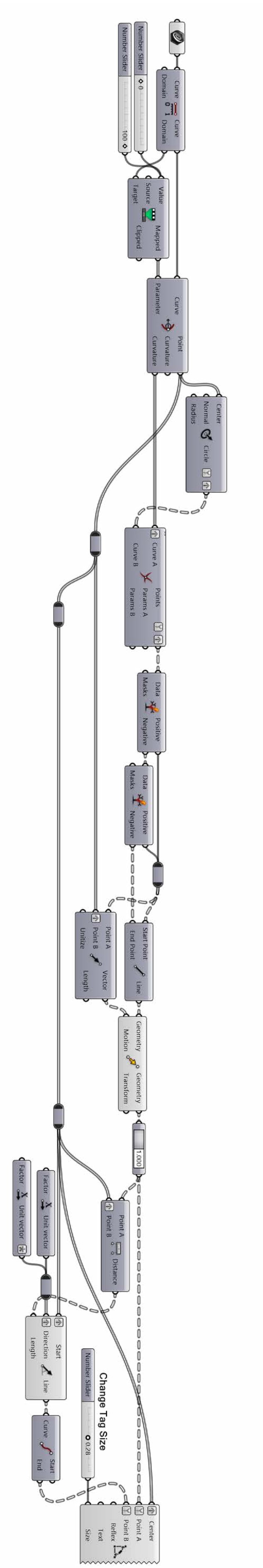
	Weight [g]	Vol before [ml]	Vol after [ml]	Density [g/ml]	Ave Density
cacao raw	1,01	12,5	13,8	0,777	1070,1
	0,34	12,5	12,8	1,133	
	0,13	6	6,1	1,300	
cacao roasted	0,98	8	8,9	1,089	1083,1
	0,75	6	6,7	1,071	
	5,01	15	19,6	1,089	
coffee spend	2,97	15	17,4	1,238	1088,5
	0,75	6	6,75	1,000	
	1,98	15	16,6	1,238	
	5,29	50	56	0,882	
	3,04	25	27,8	1,086	
coffee deoiled	5,03	12,5	16,6	1,227	1117,3
	0,4	6	6,4	1,000	
	2,25	12,5	14,5	1,125	
walnut shells	2,02	12,5	14,3	1,122	1199,6
	1,03	6	6,8	1,288	
	5,01	15	19,6	1,089	
	1,96	15	16,5	1,307	
	4,77	30	34	1,193	
cherry pits	5,02	12,5	16,9	1,141	1145,1
	5,04	12,5	16,9	1,144	
	0,23	6,2	6,4	1,150	

6.1.1 Tables and Graphs - Phase 1

Test results Phase 1B - Contact Angle

Filler	Coffee Spend	Coffee Deoiled	Walnut	Cherry	Cacao_raw	Cacao_roasted
	146,1	115,1	98,8	98,6	129,8	112,5
	148,4	120,3	97,8	99,2	132,4	127,0
	135,0	109,7	102,5	103,5	112,3	98,3
Measured Angles [°]	152,7	126,3	101,1	112,0	116,9	103,4
	133,5	126,4	98,8	99,6	130,0	110,7
	131,5	135,9	97,2	99,5	143,6	113,2
	121,6	125,5	98,8	96,5	124,3	103,0
	132,7	120,4	105,8	96,7	125,8	109,6
Mean	**137,7**	**122,5**	**100,1**	**100,7**	**126,9**	**109,7**
S.D	9,7	7,5	2,7	4,7	9,0	8,2

Grasshopper script - Contact Angle



6.1.2 Tables and Graphs - Phase 2

Test results Phase 2 - Particle Size

walnut_250_45	
Date:	240425
Method:	Hotpressing (BMC)
Note:	one plate
(Phase 2)	

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	330	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	16,5	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	11		1,7
Filler	walnut shells	297	powdered, <250µm >125µm	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	43,5	0,9	5,07	118,34	*
2	50,7	0,89	5,83	162,63	*
3	50	0,89	5,78	153,73	*
4	47,2	0,97	5,17	140,4	*
5	47	0,89	5,63	151,07	*
6	52,6	0,92	6	139,84	*
7	55,1	1,0	5,99	174,92	*
8	53,6	0,95	5,92	146,75	*
Mean	**49,96**	**0,92**	**5,67**	**148,46**	
S.D.	3,88	0,04	0,36	16,84	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,1283	2,7788
2	0,1353	2,9242
3	0,1283	2,8094
4	0,1213	2,6601
5	0,1213	2,7621
6	0,0934	2,0960
7	0,1213	2,8796
8	0,1213	2,7524
9	0,1004	2,3323
10	0,0934	2,0619
Mean	**0,12**	**2,61**
S.D.	0,02	0,32

---

walnut_500_45	
Date:	240425
Method:	Hotpressing (BMC)
Note:	one plate
(Phase 2)	

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	330	Biorez(TransFurans Chemicals)	50,4
Catalyst	HM1448	16,5	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	11		1,7
Filler	walnut shells	297	powdered, <500µm >250µm	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	44	0,79	5,67	141,74	*
2	41,8	0,77	5,81	147,06	*
3	40,8	0,73	6,09	136,46	*
4	41,9	0,82	5,33	135,82	*
6	41,8	0,75	5,96	147,99	*
7	43,7	0,76	5,92	147,82	*
8	37,9	0,7	5,4	118,62	*
Mean	**41,70**	**0,76**	**5,74**	**139,36**	
S.D.	2,02	0,04	0,29	10,50	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,1144	2,4648
2	0,1004	2,1692
3	0,0934	2,0211
4	0,1074	2,2714
5	0,1074	2,3116
6	0,0656	1,3941
7	0,1004	2,1195
8	0,1074	2,2567
9	0,1004	2,1140
10	0,0725	1,6074
Mean	**0,10**	**2,07**
S.D.	0,02	0,33

6.1.2 Tables and Graphs - Phase 2

Test results Phase 2 - Particle Size

walnut_blend_45	
Date:	240425
Method:	Hotpressing (BMC)
Note: (Phase 2)	one plate

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	330	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	16,5	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	11		1,7
Filler	walnut shells	297	powdered, mixed grain sizes	45,4

Grain sizes	Filler [%]
<500μm >250μm	21,5
<250μm >125μm	16,5
<125μm	62,0

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	52	1	5,25	221,05	*
2	54,1	1,1	5,15	242,95	*
3	52,5	1,1	4,99	227,56	*
4	49,9	1,1	5,08	210,28	*
5	46,8	0,93	5,38	199,81	*
6	48,4	0,93	5,52	216,29	*
7					
8					
Mean	**50,62**	**1,03**	**5,23**	**219,66**	
S.D.	2,74	0,08	0,20	14,83	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m^2]
1	0,1423	2,8882
2	0,1771	3,1353
3	0,1144	2,0748
4	0,1004	1,8259
5	0,1004	1,8533
6	0,1004	1,8288
7	0,1283	2,3255
8	0,1283	2,3414
9	0,1074	1,9687
10	0,1283	2,3277
Mean	**0,12**	**2,26**
S.D.	0,02	0,45

---

spent_coffee_250_45	
Date:	240425
Method:	Hotpressing (BMC)
Note: (Phase 2)	one plate

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	330	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	16,5	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	11		1,7
Filler	spent coffee grounds	297	powdered, <250μm >125μm	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	34,7	1,1	3,3	148,77	*
2	39,4	1,3	3,48	171,25	*
3	32,5	1	3,33	133,9	*
4	32,7	1	3,63	138,43	*
5	29,4	0,9	3,44	128,8	*
6	34,7	1,1	3,43	141,91	*
7	30,3	0,9	3,61	126,59	*
8	32,1	0,96	3,59	143,56	*
Mean	**33,23**	**1,04**	**3,48**	**141,65**	
S.D.	3,11	0,13	0,13	14,11	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m^2]
1	0,0795	1,4693
2	0,0795	1,4730
3	0,0865	1,5990
4	0,1004	1,8574
5	0,0934	1,7152
6	0,1283	2,3712
7	0,0865	1,5961
8	0,0795	1,4637
9	0,0865	1,6413
10	0,0865	1,6192
Mean	**0,09**	**1,68**
S.D.	0,01	0,27

6.1.2 Tables and Graphs - Phase 2

Test results Phase 2 - Particle Size

spent_coffee_500_45	
Date:	240425
Method:	Hotpressing (BMC)
Note: (Phase 2)	one plate

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	330	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	16,5	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	11		1,7
Filler	spent coffee grounds	297	powdered, <500µm >250µm	45,4

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	32,6	1,1	3,5	102,87	*
2	33	1	3,6	115,27	*
3	35,3	1,2	3,51	111,39	*
4	32,4	1,1	3,46	111,76	*
5	23,6	0,71	3,76	76,61	*
6	31,2	0,92	3,78	99,57	*
7	27	0,8	3,78	87,69	*
8	32,9	0,98	3,76	106,18	*
Mean	**31,00**	**0,98**	**3,64**	**101,42**	
S.D.	3,81	0,16	0,14	13,26	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,0586	1,2938
2	0,0934	2,0467
3	0,0656	1,4759
4	0,1074	2,4292
5	0,0586	1,2902
6	0,0516	1,1420
7	0,1004	2,2448
8	0,0934	2,0453
9	0,0795	1,7662
10	0,1004	2,1887
Mean	**0,08**	**1,79**
S.D.	0,02	0,46

---

spent_coffee_blend_45	
Date:	240425
Method:	Hotpressing (BMC)
Note: (Phase 2)	one plate

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	330	Biorez (TransFurans Chemicals)	50,4
Catalyst	HM1448	16,5	(2-hydroxyethyl) ammonium nitrate	2,5
Releasing Age	linseed oil	11		1,7
Filler	spent coffee grounds	297	powdered, mixed grain sizes	45,4

Grain sizes	Filler [%]
<500µm >250	24,0
<250µm >125	18,5
<125µm	57,5

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	24,9	0,8	3,35	109,6	*
2	33,1	1,1	3,22	149,93	*
3	28,9	0,86	3,63	124,73	*
5	27,3	0,82	3,46	117,76	*
6	16,1	0,47	3,5	70,44	*
7	36,4	1,2	3,33	153,69	*
8	28,8	0,9	3,43	125,79	*
Mean	**27,93**	**0,87**	**3,42**	**121,71**	
S.D.	6,45	0,23	0,13	27,80	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,0725	1,3285
2	0,0795	1,4328
3	0,0656	1,1953
4	0,0725	1,3211
5	0,0725	1,3095
6	0,0795	1,4617
7	0,0865	1,5976
8	0,0795	1,4485
9	0,0795	1,4346
10	0,0865	1,5688
Mean	**0,08**	**1,41**
S.D.	0,01	0,12

6.1.2 Tables and Graphs - Phase 2

Test results Phase 2 - Composition

walnut_blend_35	
Date:	240502
Method:	Hotpressing (BMC)
Note: (Phase 2)	one plate

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	393	Biorez (TransFurans Chemicals)	60,2
Catalyst	HM1448	19,5	(2-hydroxyethyl) ammonium nitrate	3,0
Releasing Age	linseed oil	11		1,7
Filler	walnut shells	229	powdered, <125µm	35,1

Grain sizes	Filler [%]
<500µm >250µm	21,5
<250µm >125µm	16,5
<125µm	62,0

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	34,8	1,1	3,42	141,29	*
2	37,1	1,2	3,46	156,93	*
3	37,2	1,1	3,66	160,8	*
4	38,7	1,1	3,83	166,69	*
5	35,6	1,1	3,65	147,28	*
6	32,8	0,98	3,51	147,51	*
7	35	1,0	3,52	158,14	*
8	28,9	0,84	3,56	129,52	*
Mean	**35,01**	**1,05**	**3,58**	**151,02**	
S.D.	3,06	0,11	0,13	12,01	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,0975	1,7517
2	0,1116	2,0654
3	0,0869	1,6238
4	0,0833	1,4906
5	0,0869	1,5849
6	0,0798	1,4223
7	0,0904	1,6170
8	0,0869	1,5554
9	0,0939	1,6910
10	0,0869	1,5452
Mean	**0,09**	**1,63**
S.D.	0,01	0,18

---

walnut_blend_55	
Date:	240502
Method:	Hotpressing (BMC)
Note: (Phase 2)	one plate

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	262	Biorez (TransFurans Chemicals)	41,195
Catalyst	HM1448	13	(2-hydroxyethyl) ammonium nitrate	2,044
Releasing Age	linseed oil	11		1,730
Filler	walnut shells	350	powdered, <125µm	55,0

Grain sizes	Filler [%]
<500µm >250µm	21,5
<250µm >125µm	16,5
<125µm	62,0

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	52	1,1	4,96	226,56	*
2	47,9	1	4,73	218,74	*
3	52	1,1	4,98	229,24	*
4	46,7	0,93	5,14	194,79	*
5	47	0,96	5,44	201,06	*
6	46	0,94	5,07	203,41	*
7	48,8	1,0	5,43	216,32	*
8	51,4	1	5,23	243,34	*
Mean	**48,98**	**1,00**	**5,12**	**216,68**	
S.D.	2,49	0,07	0,24	16,34	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,1610	2,7997
2	0,1610	2,8742
3	0,1292	2,2875
4	0,1257	2,3067
5	0,1186	2,1146
6	0,1222	2,1728
7	0,1116	1,9949
8	0,1398	2,4878
9	0,1116	1,9622
10	0,1257	2,2567
Mean	**0,13**	**2,33**
S.D.	0,02	0,31

6.1.2 Tables and Graphs - Phase 2

Test results Phase 2 - Composition

spent_coffee_125_35	
Date:	240502
Method:	Hotpressing (BMC)
Note:	one plate
(Phase 2)	

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	393	Biorez (TransFurans Chemicals)	60,3
Catalyst	HM1448	19,5	(2-hydroxyethyl) ammonium nitrate	3,0
Releasing Age	linseed oil	11		1,7
Filler	spent coffee gr	228	powdered, <125µm	35,0

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
1	34,1	1,2	3,02	115,99	*
2	36,9	1,3	3,11	122,23	*
3	33,2	1,3	2,99	125,13	*
4	27,8	1,1	2,91	101,22	*
5	29,2	1,1	2,9	103,79	*
6	32	1,3	2,84	115,93	*
7	29,9	1,1	2,92	110,53	*
8	37,9	1,4	3,18	129,59	*
Mean	**32,63**	**1,23**	**2,98**	**115,55**	
S.D.	3,61	0,12	0,12	10,02	

* Tensile fracture at outermost layer

Impact Testing ISO 179

	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,1292	2,6712
2	0,1328	2,8036
3	0,1010	2,1648
4	0,0975	2,0735
5	0,0869	1,8066
6	0,0727	1,5416
7	0,1292	2,7251
8	0,0833	1,7433
9	0,1151	2,4174
10	0,0869	1,8276
Mean	**0,10**	**2,18**
S.D.	0,02	0,45

---

spent_coffee_125_55	
Date:	240502
Method:	Hotpressing (BMC)
Note:	one plate
(Phase 2)	

Recipe				
	Name	Ammount [g]	Specification	Ratio[%]
Resin	furan resin	262	Biorez (TransFurans Chemicals)	41,2
Catalyst	HM1448	13	(2-hydroxyethyl) ammonium nitrate	2,0
Releasing Age	linseed oil	11		1,7
Filler	spent coffee grou	350	powdered, <125µm	55,0

Flexual Testing ISO 14125A

	Flexural Strength	Flexural Strain	Flexural Modulus	Force at Max. Flexure load	Failure mode
	[Mpa]	[%]	[Gpa]	[N]	
2	29,9	0,82	3,69	129,16	*
3	34,6	1	3,85	149,47	*
4	23,6	0,62	3,93	99,48	*
5	28,3	0,76	4,06	116,37	*
6	35,2	0,92	3,87	148,13	*
7	29,5	0,8	3,88	123,74	*
8	42,9	1,0	4,52	177,9	*
Mean	**32,00**	**0,85**	**3,97**	**134,89**	
S.D.	6,20	0,14	0,27	25,79	

* Tensile fracture at outermost layer

Impact Testing ISO 179

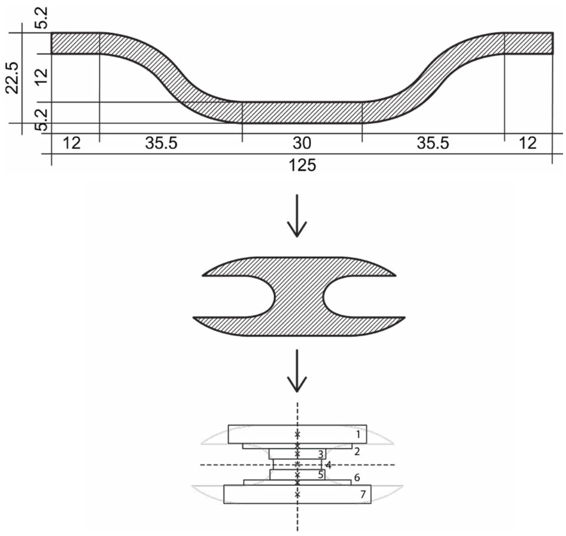
	Energy	Charpy impact
	[J]	[kJ/m²]
1	0,0727	1,3246
2	0,0869	1,5835
3	0,0763	1,3983
4	0,0833	1,5574
5	0,1116	2,1057
6	0,1045	1,9106
7	0,0904	1,6509
8	0,0621	1,1339
9	0,0833	1,5455
10	0,0586	1,0881
Mean	**0,08**	**1,53**
S.D.	0,02	0,32

6.1.3 Tables and Graphs - Phase 3 - Structural Verification

Structural Verification

Calculations

Moment of Inertia
Iz = 36515,97 mm4
A = 660.561 mm²
y (bottom to centroid) = 11.1 mm



Simplified cross-section:

Shape		width [mm]	height [mm]	area [mm2]	Ii [mm4]	y [mm]
	1	39,7	5,25	208,425	478,73	8,79
	2	31,4	1,5	47,1	8,83	5,41
	3	16,3	3	48,9	36,68	3,16
	4	13,8	3	41,4	31,05	0,16
	5	15,8	3	47,4	35,55	2,84
	6	30,8	1,5	46,2	8,66	5,09
	7	42,2	5,25	221,55	508,87	8,46
total					36515,97	

Bending Moment/ Bending Strength

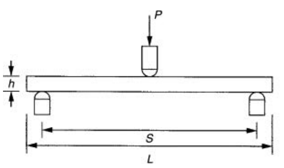
Example Specimen 1

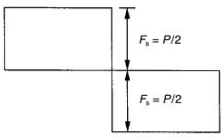
Iz = 36515.97 mm4
y = 11,1 mm
L = 180 mm
F = 2.368 kN

M_{max} = (1/4) * F * L
M_{max} = **0.107 kNm**

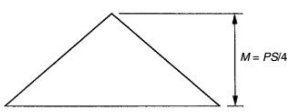
σ = (M*y)/I
σ = **32.39 MPa**

Specimen Nr.	Deformation at break [mm]	Force at Break [N]	Mmax [kNm]	σ Bending strength [Mpa]
1	2,81	2367,78	0,107	32,39
2	2,26	2092,23	0,094	28,62
3	2,34	2318,99	0,104	31,72
4	2,53	2288,65	0,103	31,31
5	2,36	2275,45	0,102	31,13
6	2,46	2290,85	0,103	31,34
mean	**2,46**	**2272,32**	**0,102**	**31,08**
SD	**0,18**	**85,97**	**0,004**	**1,18**
Area	731,6	mm²	σ = M*y/I	
Support Span L	180	mm	M = (1/4) * F * L	
Thickness d	5,02	mm		
Iz	36515,97	mm4		
y	11,1000	mm	<- distance centroid to underside	





Shear force diagram

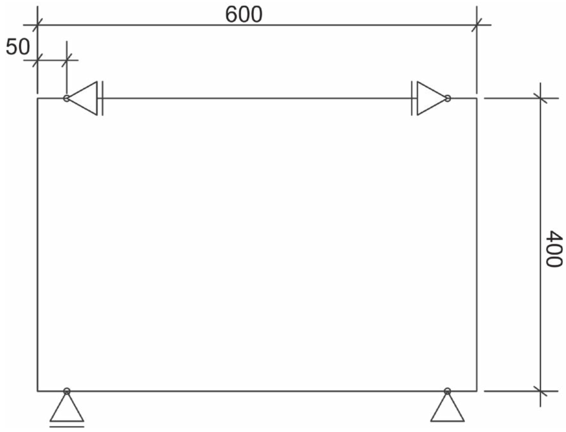


Bending moment diagram

6.1.3 Tables and Graphs - Phase 3 - Structural Verification

Sustainability Comparison

Calculations - Bending Moment

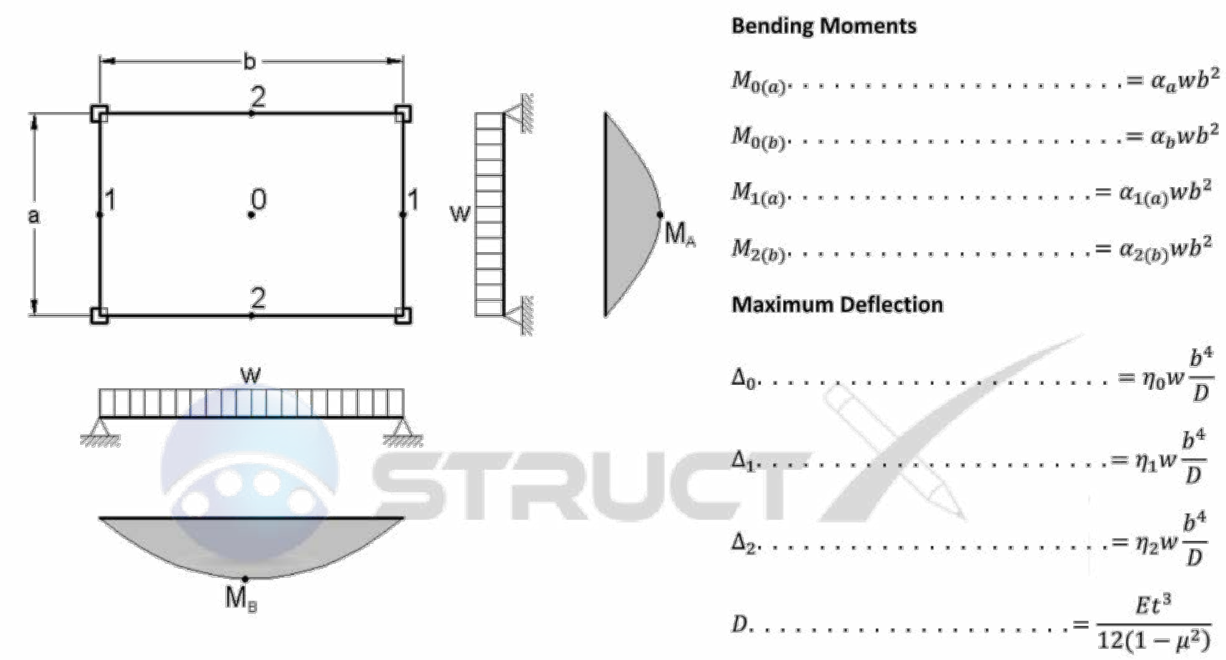


Loads:

- Wind pressure; w = 1,30 kN/m2
- Self-weight

Material safety factor: $\gamma_m = 1,5$
Max Deflection at SLS: $\Delta_{max} = b/200 = 0.3$ cm

Bending moment:
a = 40cm
b = 50cm
w = W*a = 0,52 kN/m
$\alpha_{(b)} = 0.1078$
$M_{0(b)} = \alpha_{(b)} * w * b^2$
$M_{0(b)}$ = 0,014 kNm

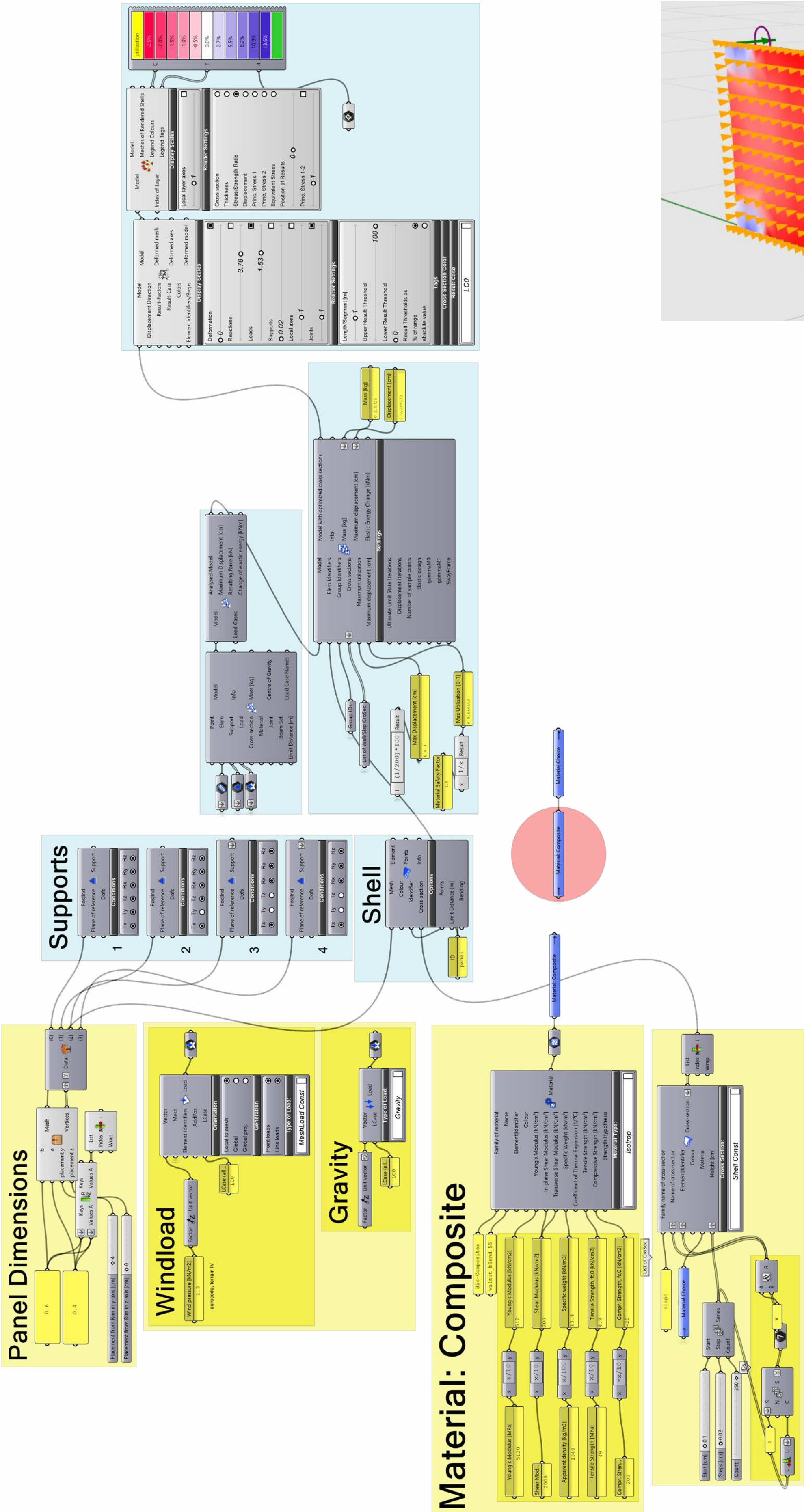


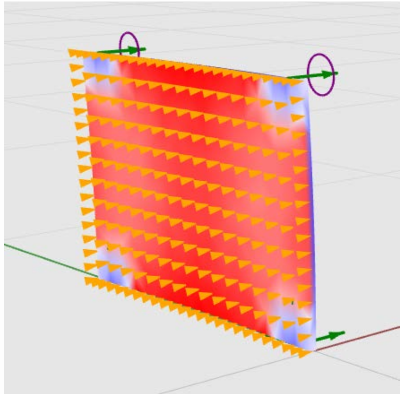
a/b	$\alpha_{0(a)}$	$\alpha_{0(b)}$	$\alpha_{1(a)}$	$\alpha_{2(b)}$	η_0	η_1	η_2
1.0	0.0947	0.0947	0.1606	0.1606	0.0262	0.0172	0.0172
0.9	0.0689	0.1016	0.1367	0.1541	0.0218	0.0119	0.0164
0.8	0.0047	0.1078	0.1148	0.1486	0.0180	0.0079	0.0157
0.7	0.0289	0.1132	0.0955	0.1435	0.0158	0.0050	0.0151
0.6	0.0131	0.1178	0.0769	0.1386	0.0148	0.0030	0.0146
0.5	0.0005	0.1214	0.0592	0.1339	0.0140	0.0016	0.0141

source: structX

6.1.3 Tables and Graphs - Phase 3 - Sustainability Comparison

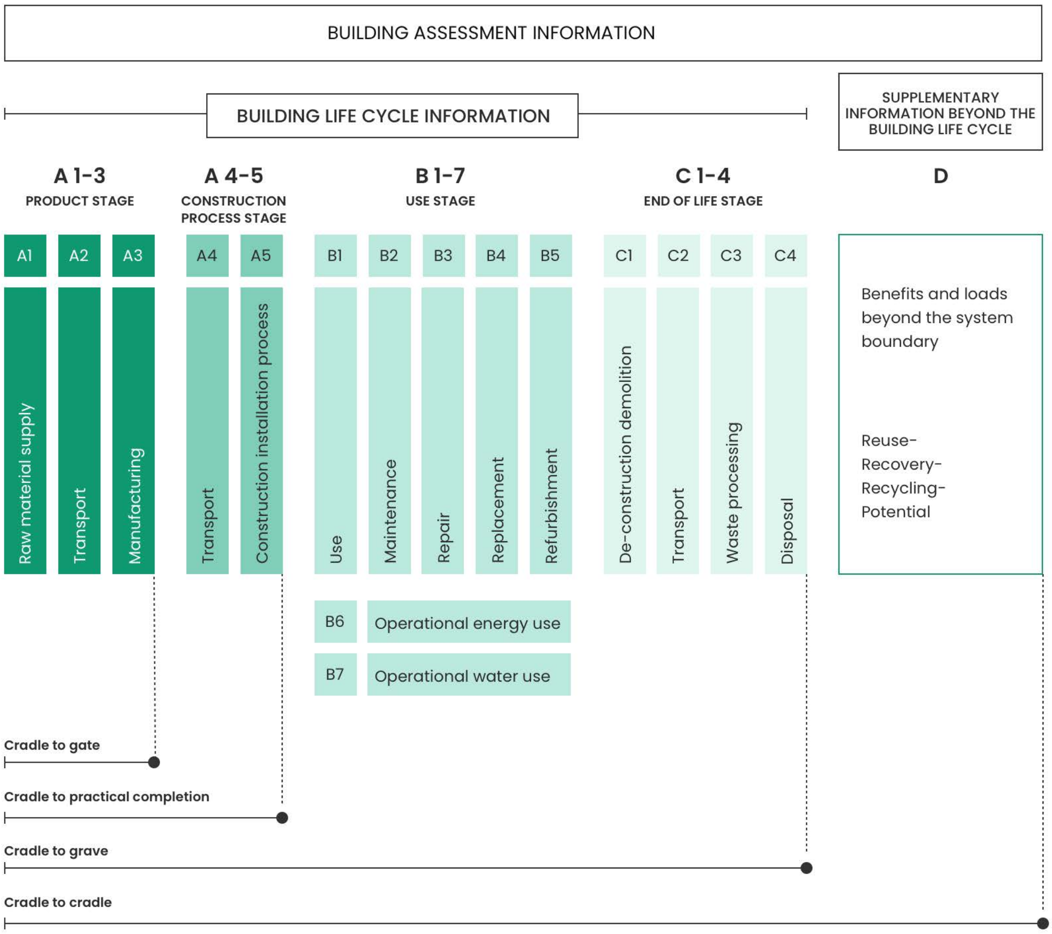
Calculations - Grasshopper





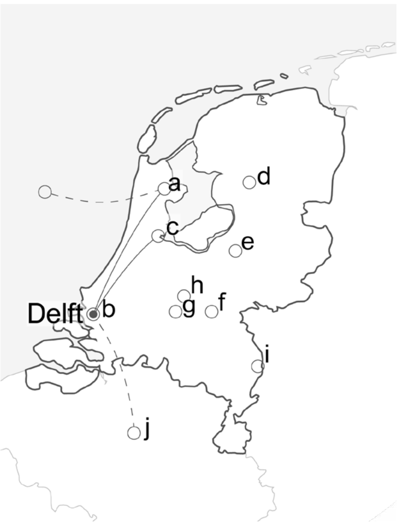
6.1.3 Tables and Graphs - Phase 3 - Sustainability Comparison

Live-cycle Stages



graphic: oneclick LCA

Example Suppliers for different Waste Products



a. Crown of Holland BV
Agriport 161,
1775 TA Middenmeer

b. Espressobar
BK-Faculty, TU Delft

c. Caffe Inc.
Schaafstraat 26K,
1021 KE Amsterdam

d. Notengaard Bisschop
Kallenkote 59,
8345 HH Kallenkote

e. De Smallekamp
Hardenbrinkweg 24,
8071 SM Nunspeet

f. Boomkwekerij 't Herenland
Bonegraafseweg 64a,
4051 CH Ochten

g. Kersenteeltbedrijf Hakkert
Kornedijk 15,
4197 RN Buurmalsen

h. Kersen & Theetuin Molenweg
Molenweg 28,
4111 KP Zoelmond

i. Aarts Conserven B.V.
Houthuizerweg 20,
5973 RG Lottum

j. Transfurans bvba
Leukaard 2,
2440 Geel, Belgien

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