Recycling of bio composite façade panels

Exploring the possibilities of recycling bio composites into filler for a new bio composite façade product.

Master thesis report
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Abstract

Bio composites façade panels are an example of circular building products. Using circular products not only decreases embodied carbon, it also contributes not to exhaust natural resources (by recycling them). However if such a building product is a their end of life, they end up as waste (landfill) or are being incinerated, the embodied carbon is released again.

To find an better solution for their end of life, recycling of these bio composite façade panels is researched by recycling the material into filler for a new bio composite façade application that meet the requirements. The main research question focuses on:
"How can bio composite façade panels at their end of life be recycled into new bio composite façade panels while maintaining or increasing their high performance properties and freedom of design?"

In this research this was tested through experimental testing where different recycled fillers were compared to the virgin almond shell filler. The different fillers were tested on mechanical, durability and functional properties that are vital to façade applications.

The results of the experimental testing showed that the recycled filler samples have potential as façade applicants. The mechanical strength is lower compared to the virgin filler sample, but the durability properties are higher. In terms of workability, the higher the filler load the more workable the samples are. In the visual 3D panel testing it became clear that the recycled filler samples have a less smooth finished surface. As a façade panel it is important to withstand wind loads, weathering, impacts and be aesthetically pleasing.

Recycling bio composite façade panels can be realized. Some properties are lower compared to the original product, but with the right adjustments they can be used in a façade applicant. A more functional application such as a corner panel would be more suitable for this material given the visual appearance of the surface.

This research shows promising results, but more research needs to be done on the usage of recycled bio composites in façade panels.

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1 Introduction

1.1 Context

The built environment is a constantly changing environment. New buildings are being built and old ones are repurposed, renovated or demolished. Although adding a lot of value to cities and every days life, the construction industry overall is seen as one of the most polluting industries in the world (Building Renovation: Where Circular Economy and Climate Meet, 2022). Among other things this also has to do with the way materials are treated at the end of their life. A lot of used building materials currently end their life in landfill or are being incinerated. There are a few serious problems involved in this current practice.

It is everything but a circular solution when incinerated embodied carbon is released into the atmosphere and is polluting the environment. Building materials in the EU are making up around 20-30% of the life cycled emissions (Building Renovation: Where Circular Economy and Climate Meet, 2022). To reduce embodied carbon emissions and thereby the negative environmental impact, the life cycle of building products can to be extended.

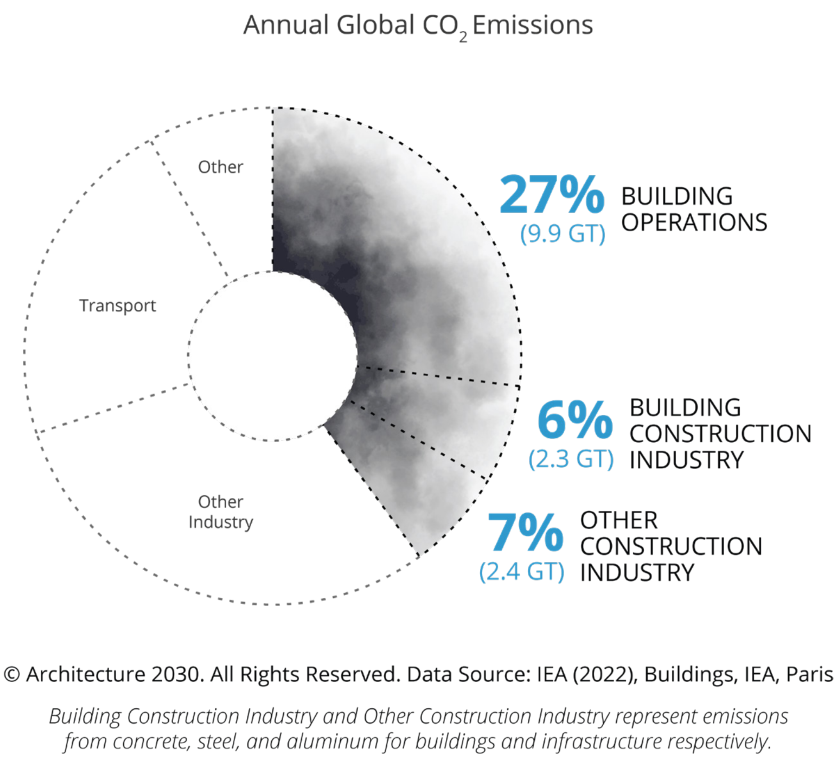


Figure 1. Annual Global CO_2 Emissions (Why The Built Environment – Architecture 2030, n.d.)

Besides environmental impacts there is also an economic problem here, because it is very costly to use only newly produced products and not to reuse usable materials/products. Another problem of not recycling usable materials or products is the danger of depletion of virgin raw materials around the globe. The awareness has grown that we should be careful using (limited) natural resources, and not spill them (Bansard & Schröder, 2021).

Façade cladding are an important aspect of a building. They can take up to almost 20% of a buildings embodied carbon (Ondon et al., n.d.). They are usually made of brick, wood or panels of metal or composite materials. Most façade panels currently are not being reused or recycled. Because of the above mentioned problems, it is relevant to investigate if this would be possible. There are solutions and opportunities that can elongate the materials lifecycle (Goddin et al., 2019). The way to do this is by focusing on the circularity of the materials.

1.2 Problem Statement

The use of bio (based) composite materials in buildings has been on the rise in the last decade (Gurunathan et al., 2015). More research is being done to increase the quality and usability of these products compared to conventional building materials. However until now, not a lot of research has been done on the end of life of bio composite materials. Also **bio composite materials currently end up in landfill and/or are being incinerated at their end of life, considered as waste** (Bensadoun et al., 2016).

The bio composite materials that are being recycled loose mechanical properties (Bhattacharjee & Bajwa, 2018). This is an important reason why the industry chooses for landfill and/or incineration, as it also is the cheapest but least circular end of life option. This raises a question on whether bio composites can indeed be considered circular.

How circular are bio composite building products if they automatically become waste at their end of life?

1.3 Scope

The scope of this research is to investigate the application of recycling bio composite façade panels into filler for new bio composites to increase the circular potential of the product, while maintaining its mechanical and functional properties and increasing its design abilities. The aimed end product of this research is to deliver a prototype that has an optimal mix of these aspects (properties and design abilities).

Objectives

This study aims to bridge the gap between the circular potential of bio composites and its practical application by investigating how bio-composite façade panels can be recycled into new materials. By focusing on innovative recycling processes and design-based research, the study seeks to find ways to transform waste into a valuable resource, setting a benchmark for sustainable construction practices.

This research's objectives are:

Enhance circular potential: Developing and demonstrating a method for recycling bio composite façade panels into filler for new bio composite façade panels, thus extending their lifecycle and reducing waste.

Increase sustainability: Minimizing the environmental footprint of the building product by recycling materials and minimizing the need for finite resources and reducing carbon emissions.

Material Performance: Assessing the mechanical, durability, visual and fire safety properties of recycled materials and comparing them with virgin raw materials.

Design Innovation: Exploring the architectural and functional design potential of the recycled bio composite materials, looking at freedom of design, while ensuring they meet the performance criteria for façade applications.

1.4 Impact

Bio composite materials can become more circular by extending their life cycle through reintegrating and recycling these building materials at the end of their life. By using bio based composites in façade panels and recycling façade panels into ones, waste can be reduced and ultimately also the negative environmental impact of building products.

New research can improve the future building products in the construction industry and discover new techniques for manufacturing or recycling of bio composites. This research aims to contribute to more knowledge of circular and sustainable construction practices by providing research-based evidence on the feasibility of recycling bio-composite materials in façade panels.

This knowledge hopefully stimulates the construction industry to further develop circular and sustainable ways to reuse/ recycle building products (such as façade panels) and thus to reduce waste and pollution in the built environment.

1.5 Outcomes

The ideal outcome would be to create a baseline for recycling bio composite façade panels so manufacturers can increase circularly by recycling of façade panels at the end of their life by:

- Demonstrating the feasibility of using recycled bio composites as high performing materials of façade panels.
- Reducing the overall environmental impact of the bio composite façade panels.

1.6 Outputs

Using experimental testing of different variations of bio composite materials, the materials are compared to the original bio composite material that are made of virgin raw materials.

After the testing and experimental phase, a recycled bio composites façade panel will be realised, with old façade panels used as filler in the new panel.

All the research findings are explained with a description of the performance analysis, manufacturing techniques and design variations of the recycled panels.

1.7 Hypothesis

Using bio based composite materials can increase the circular potential of the façade panel, since these materials can regrow. However, if recycled their mechanical properties decrease, so that problem has to be tackled. Further, it is preferred to increase the design abilities of the material.

The hypothesis of this research is:

'Bio composite façade panels can be effectively recycled into fillers for new bio composite façade panels while maintaining or increasing their high performance properties and design abilities.'

1.8 Research Questions

This research focuses on recycling of bio composite façade panels and implementing them as filler in new bio composites façade panels. The goal is to design and manufacture a (partly) recycled bio composite façade panel. This will be realised with research by design.

The main research question is:

"How can bio composite façade panels at their end of life be recycled into new bio composite façade panels while maintaining or increasing their high performance properties and freedom of design?"

The sub questions are:

- What are the key performance properties of recycled bio composite façade panels, in terms of their mechanical properties?
- How do recycled filler materials compare to virgin raw filler materials used in current bio composite panels?
- How does the weathering of the pre-recycled panel influence the performance of the recycled bio composite façade panel?
- How does using a recycled filler affect the design of a bio composite facade panel?

Methodology

In the methodology the structure of the thesis is outlined. This thesis focuses on design based research, where the functionality, circularity, sustainability and architectural design objectives meet. Before the design phase, literature research needs to be done to understand the full scope of the material and its challenges. After literature research, experimental testing will be done, which in the end will lead to a prototype for the design of a façade product.

2.1 Literature Research

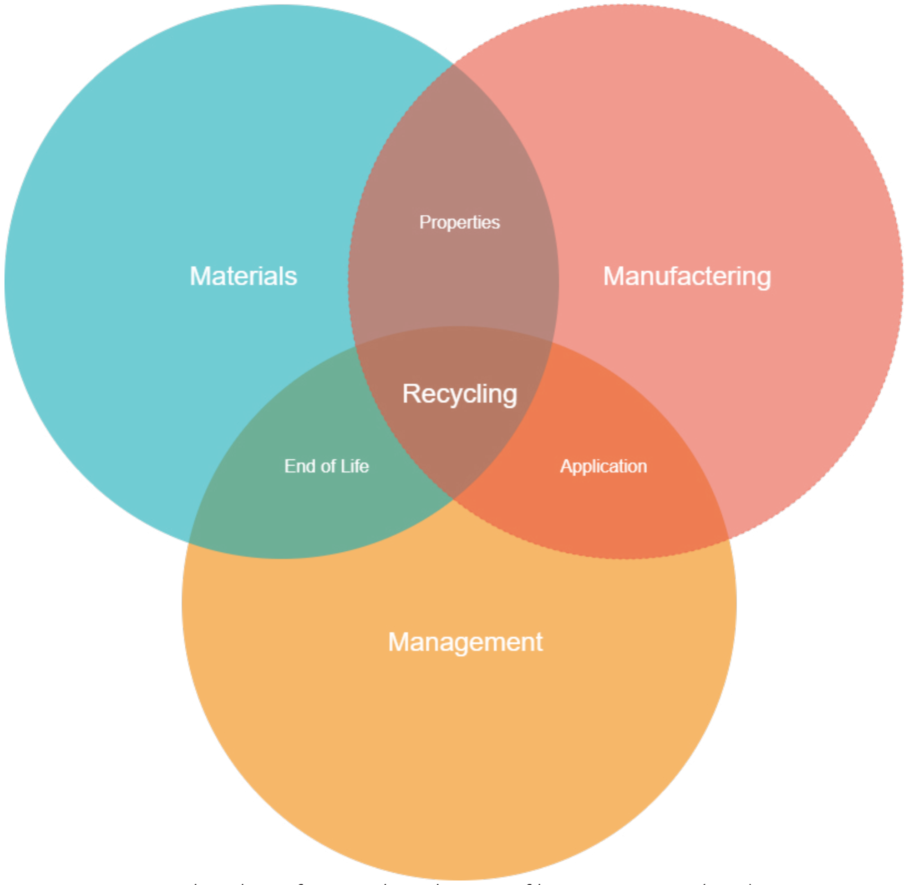


Figure 2. Diagram that shows focus and overlapping of literature review (own)

The literature research focuses on five different aspects; circular building products, bio composites, materials (inside bio composites), manufacturing methods and requirements for the façade application. These aspects will be covered in separate subparagraphs.

The first section concentrates on the circular building products and why they are relevant to today's building industry, while highlighting the R-strategies and which of these strategies will be most relevant for the subject of this thesis. The R-strategies is a framework that shows 10 different ways of incorporating circularity in a (building) product.

Secondly the focus is on bio-composite materials to understand how they are built and of which components they are built. Additionally current studies on bio-composites and their end of life possibilities are explored.

In the third section the component materials within the bio-composites are investigated to further understand the different values and properties of these components.

In the fourth section the bio composite matrix is explained.

Next the manufacturing methods of bio-composites are highlighted and compared each other.

Lastly, the requirements for the façade application are investigated by examining the standards and regulations for mechanical properties, (fire) safety, durability and design abilities.

The chapter will be concluded by a summary of the literature research to outline the most significant findings for the research of this thesis.

2.2 Experimental Testing

The experimental testing will be conducted at NPSP, an innovative Dutch (building) products company, located in the Kabel District in Delft. They are specialised in producing bio composites for façade panels, design products and mobility products. They are providing the space and facilities to conduct the testing. The actual testing relies on the availability of the facilities. For this reason multiple testing protocols are established to ensure that the outcome of the project is sufficient to generate results.

Before starting the testing phase some preparation needs to be done. Bio composite panels need to be made ready for recycling, these panels will be shredded to use them as a filler in the new bio composites panel. The new panels will be made by the current standard composition used by NPSP. NPSP is a company that produces a different range of products, including façade panels made from bio composite material. Their expertise and equipment can be used in this project for the testing and manufacturing of the products.

2.2.1 Testing sequence

The testing sequence is based on three main testing phases and the prototyping phase afterwards.

Phase 1 is focused on comparing all the four different filler to each other. The filler materials properties are examined. These fillers are analysed under the microscope to determine properties about the particles. The density is measured and fractures of the samples are analysed.
These tests should bring some insight in the results of the next phases.

Phase 2 is split into two parts.
The first part, **Phase 2A** is focused on comparing the recycled filler to the raw virgin filler in different ratios to the resin (matrix). By generating 3 different ratios of the filler and matrix, 3 recycled filler samples are compared and tested against 3 raw virgin filler samples. These 6 samples will be evaluated on different criteria, these criteria will be explained in chapter 3.6. The best mechanically performing ratios will be used in the next part of this phase.

Phase 2B focuses on two different recycled filler that are made from panels that have been exposed to weathering for 6 months. These results will give inside to the feasibility of recycling bio composite façade panels after their end of life. These fillers will also be tested on mechanical and functional properties.

All the different fillers will be used in the next phase 3 where they will be tested on their flow and 3D potential. Only the best performing ratio from the bio composites are used in the next phase.

Phase 3 focuses on the 3D potential of the samples. Three different 3D moulds will be tested on their performance and visual defects. The tests will be performed both with 3 different recycled filler and virgin raw filler.

The design phase is the last test phase. In this phase the best performing recipe with recycled filler will be used to show the possibilities of the material in a 3D façade panel, which complies with the criteria and requirements set for façade panels. The process of this prototype will be explained further in the subchapter 2.3 Design.

Workflow testing

Preparation: Bio composite panels for recycling
Objective: Creating a base line product for recycling.
Procedure: Making bio composite panels that will be grind and shredded for recycling purposes. The materials and composition will be the same as current panels made by NPSP.

Phase 1: Filler analysis
Objective: To determine the optimal grain size and ratio between filler and matrix of recycled filler material that focusses on viscosity.

Procedure:
Recycle old façade panels into filler material by grinding them into varying grain sizes.
Assess the viscosity behavior during moulding
Compare the recycled samples performance to virgin materials used in bio-composites.

Outcome: Selection of the best-performing grain size and ratio between filler and matrix for use in subsequent phases.

Phase 2: Comparison Almond shell filler to (weathered) recycled filler & Ratio Optimization

Objective: To determine the possibilities with recycled filler compared to almond shell filler and optimize the ratio between filler and matrix

Phase 2A: Properities Performance
Objective: To determine the possibilities with recycled filler compared to almond shell filler and optimize the ratio between filler and matrix that balances mechanical propeties, impact resistance, durability and visual performance.

Procedure: Recycle old façade panels into filler material by grinding them into varying grain sizes. Evaluate the mechanical properties of test samples. Compare the recycled samples' performance to 'virgin' materials used in bio-composites.

Outcome: Selection of the best-performing ratios between filler and matrix for use in subsequent phases.

Phase 2B: Comparing impact of weathering in recycling panels to fillers
Objective: Determining the influence of weathering and degradtion of the facade panel and what effect it has on the filler used into a bio composite.

Procedure: Recycling two different types of weathering samples, one panel that has been outside for 6 months and one panel that has been inside for 3 weeks in the QUV, that accelerates weathering. Evaluate the mechanical properties of test samples. Compare the recycled samples performance to the results in phase 1A.

Outcome: Assesment on feasability of using 'old' bio composite facade panels and their recyclebility as a filler.

Phase 3: Molding and Flow Analysis
Objective: To test the behavior of the bio-composite material in different mold designs, ensuring suitability for complex geometries.

Procedure:
Use the optimized composition for each different filler type. Test molds with varying shapes and dimensions to evaluate the material's flow rate before curing.
Assess the ability of the bio-composite to fill molds with intricate 3D designs without compromising material integrity. Compare the molded products with existing façade elements for functional and aesthetic quality.

Outcome: Determination of the best molding practices and validation of the material's adaptability for architectural applications.

Figure 3. Testing workflow

2.3 Design

The goal is to design a rain screen façade panel that increases the possibilities of freedom of design. While investigating and testing for the most optimal recipe for the bio composite panel, different design variations will be evaluated. The ability of the dough to flow is defined by the viscosity, the lower the viscosity the more easily the dough can flow. The end product would be a design with a prototype of this façade panel, made out of a recycled bio composite material.

An objective of the design is that recycled bio composites can increase the design freedom of bio composite applications. By giving users like architects more design freedom, the product becomes easier and more relevant for designers to use. And by doing so, more circular products will be used in the built environment.

Designing with bio composites that uses a bulk compression moulding machine have some challenges. Challenges will be discussed in paragraph 3.6 Finding these critical points is important.

2.4 Chapter Conclusion

Through literature research and different phases of regular, alternative experimental testing and prototyping, the opportunities of using recycled filler in bio composites façade panels are explored. The recycled filler is compared on a variety of parameters such as the ratio of the composition in the bio composite and the weathering of the panel before recycling. The final product and prototype is a rain-screen façade panel that is engineered and evaluated on architectural abilities, mechanical and functional properties. The different samples are also compared on their performance properties and freedom of design abilities. The final product is tested on the potential of 3D design of a façade panel.

3 Literature Review

The literature review is divided in five different parts, each parts contributes learning background information or defines requirements for the experimental testing. The first part focuses on understanding the circular economy and how (circular) building products are a huge part of this economy. The R-strategies are introduced and specified which strategies are used in this thesis. In the second chapter bio composites are introduced, the difference between thermoset and thermoplastics are research. In the third chapter the materials inside a bio composite are investigated further. This is done by researching the properties and functions of fibres, matrix and fillers within a bio composite. The manufacturing methods suitable for a bio composite are researched and compared in chapter 5. This thesis also focuses on the design of a application, this application is defined and requirements are set in chapter. All the findings of this research will be summarized and concluded in chapter 6.

3.1 Circular Building Products

Building products are a big part of the embodied carbon profile of a building. If we want to decrease the negative environmental effects of the building industry and decrease its embodied carbon emissions, a difference can be made by using circular building products (CBP) instead of conventional ones .(Building Renovation: Where Circular Economy and Climate Meet, 2022).

Circular building products can be defined by multiple principles, design for dismantle, material reuse and recycling and resource efficiency. These principles all focus on reducing the amount of waste in a products life span and maximizing the utilization of the materials (Circular Buildings and Infrastructure, 2021).

Circular building products show promising results in using what is currently seen as 'waste' streams as building materials (de Graaf & Schuitemaker, 2022). Rest products from other industries, such as agriculture or pruning waste, can be "gold" for manufacturers of circular products. Unfortunately, circular building products are often still more expensive than conventional ones (Braakman et al., 2021), so the industry is reluctant to use them. To get more focus on the circularity of the industry, the building industry needs to be pushed to implement more circular building products. The Netherlands is one of the leading countries within the EU pushing for circular building design (Attia et al., 2021).

The European Union is pushing for a transformation in construction, embracing innovative and sustainable practices to shape a circular future. For this they set up the EU Circular Economy Action Plan (Circular Construction and Materials for a Sustainable Building Sector | BUILD UP, n.d.), which provides a common EU framework to achieve their circularity goals.

3.1.1 Circular building products Canvas

Circular building products can be structured by the Canvas framework. This will be used to define the research and design assignment of this thesis, by helping to navigate through decisions and the different domains that influence each other.

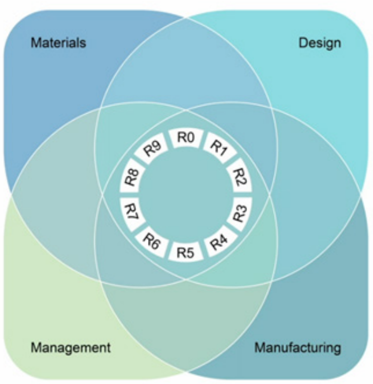


Figure 4. Paradigm of circular products (Circularity for Educators, 2024)

The Canvas (created by the Circular Impulse Initiative of the Architectural Facades & Products (AF&P) group at the TU Delft (Circularity for Educators, 2024)) is a framework that focuses on four different domains of a building product: Materials, Design, Manufacturing and Management. As shown in figure 3 these domains overlap each other in the middle. That is where the R-strategies come into play. The R-strategies are important to reach the goals of a circular economy. Each R-strategy has a different level of circularity and phase where this strategy would be implemented.

3.1.1 Circular building products Canvas

In this research the main focus is on the recyclability of bio composite façade products. This is right in the middle of the Canvas.

The recyclability of the bio composite façade products will be researched from each domain. When looking at it from a **material** focus, a few goals can be set:

- Recycle filler to reduce virgin filler materials
- Recycle filler to elongate materials life

Reducing the need for virgin filler material by replacing it with recycled filler, can help reduce the CO_2 emissions produced by the product. Recycled fillers can also decrease the costs of the product, since raw material resources sometimes have to come from far or have an intensive preparation process. However the use of recycled filler can have an impact on mechanical properties, quality control and consistency of the material that is recycled.

While the **manufacturing** process has an influence on the properties of the material, this can lead to:

- New recycling methods
- Optimizing the manufacturing processes for recycled materials

Using recycled filler material instead of virgin filler materials means that some things need to change in the manufacturing process. The bio composite panels need to be recycled in a certain way that they can be used as a filler. Some steps in optimization of this process will probably take place to find the easiest, cheapest and fastest method to recycle. These factors all have an influence on the energy used and environmental impact that this process has.

An other perspective is looking at it from the **design and management** position, which leads to:

- Choosing disregarded bio-composites that would otherwise be incinerated
- Designing for optimal material use
- Life cycle assessment (LCA) of materials composition

Recycling bio composites into filler can help reduce waste, which would otherwise be incinerated or disregarded at waste facilities. A company can adapt their product management by implementing the use of recycled filler into the manufacturing process. This is very much in line the circular economy principles.

Designing with recycled materials can be different than designing with virgin materials. Since properties of the materials can vary the design parameters can be different. So with recycling design for optimal material use is desired.

3.1.2 R-strategies

The R- strategies define the layers of a circular economy, with the first R being the most and the last R being the least circular option (figure 5). The R ladder can be divided into four main categories. The first category that is the closest to circular economy focuses on the smart way of the product use and manufacturing. These three strategies can be considered in the design phase, they are the most sustainable options.

The second category focuses on the extension of a products life. These products are already used in or on a building and need extra attention to ensure a longer life span.

The third category is focused on the end of life of the product and how this product or its materials still can still have value. This value can be energy recovery or recycled material that has a similar or lower quality.

The last category is if no circular option is considered, where the product ends up in landfill or is being incinerated. This category needs to be avoided, unless there is no other option.

In this thesis the main focus is on R8: Recycle, which is the scope of the project, although R2: Reduce also plays an important role (less waste and less virgin raw materials).

"R8: RECYCLE, BECAUSE TRASH IS TREASURE"

(Malooly & Tian, 2023)

The strategy Recycle tested in this project will save the product from being incinerated (two layers lower) by using old bio composite façade cladding and recycling it as filler into a new façade cladding.

Also in the new manufacturing process fewer virgin raw materials are used, replacing them by secondary or recycled bio-based materials, so the second strategy R2: Reduce is also applicable.

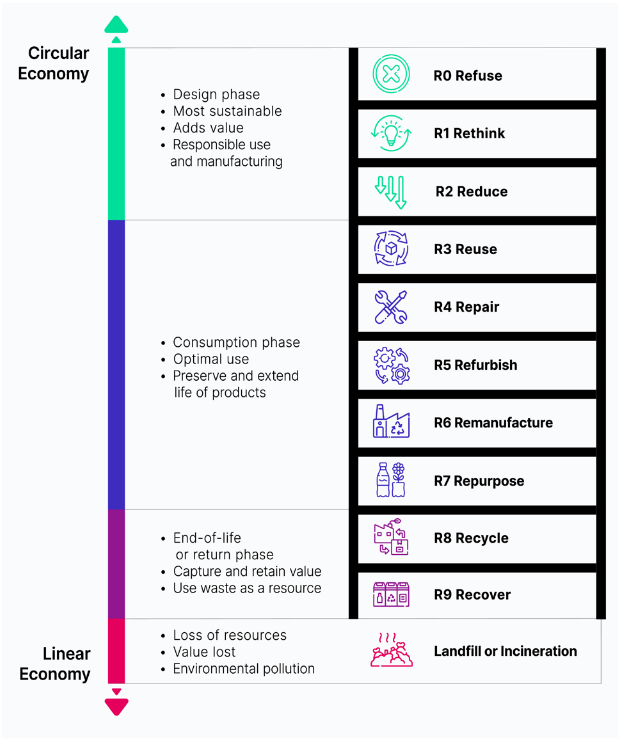


Figure 5. R-strategies (Malooly & Tian, 2023)

3.1.3 Bio composite (building) products

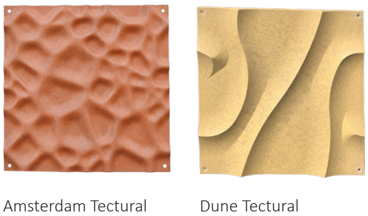


Figure 6. Bio composite facade panels made by NPSP (Nabasco , n.d.)

Choosing the material used in a building product has an influence on the circularity of the product. It can influence the recyclability and reusability of the product. But this is not so obvious, since not all materials can be recycled or reused. The recyclability of bio composites will be discussed further in section 3.1.5.

Composites as important building products are generally used in different industries; such as aerospace, automotive, and for windmills and marine applications, but not so much in the construction industry yet. However, using composites can be a very interesting option, because of their characteristics like being relatively lightweight materials, strong and durable. This makes them a very versatile materials (Bhong et al., 2023).

Figure 7. Pastoe chair made out of flax (Indulge & Explore Natural Fiber Composites, 2015)

Choosing for a bio based material is a more circular option. Bio based materials are partly or totally derived from a biological origin, such as plants, animals or microorganisms. They are often renewable, which makes them a good alternative for fossil based materials (Biobased, Biodegradable and Compostable Plastics - European Commission, n.d.).

Bio composites are similar compared to traditional or fossil based composites, but instead of fossil resources, renewable bio based materials are used to make the bio composites (European Bioplastics e.V., 2023).

The application of bio based composites is still quite new, and there is a lot of potential to increase circularity in the industries by using bio composites. It can be expected to grow as a trend, because more industries want and also have to change to more sustainable ways of developing and applying non fossil-based materials (Kähler et al., 2021). This is the first step in the direction to get the building industry to innovate. For innovating these industries at lot of change in manufacturing processes is required, which costs a lot of money (Surgenor et al., 2019) (Manu et al., 2022).

Figure 8. Composite materials (Introduction to Composite Materials and Processes: Unique Materials That Require Unique Processes, n.d.)

Bio composites are currently used at a small scale to make diverse products. NPSP already makes bio composite façade panels and other products in collaboration with other companies and institutions. One of these collaborations is the classic Pastoe chair design by Maarten van Severen and Fabian Schwaerzler, figure 7. This chair is made of flax and sisal fibres combined with polyester resin and fabrication by close mould vacuum injection (Indulge & Explore Natural Fiber Composites, 2015) .

And there are other examples of companies that also make products using bio composite materials, with applications such as furniture, packaging, automotive and architectural elements (NaturoMer ® (Natural Fiber Biocomposite) | Godavari, n.d.).

Figure 9. Bio composite aplications (NaturoMer ® (Natural Fiber Biocomposite) | Godavari, n.d.)

3.1.4 Embodied energy

A way of measuring the environmental impact of a product is the embodied energy. With a life cycle assessment of materials the embodied energy and carbon emissions can be calculated. Bio-based composites normally perform better than non-biobased composites, since they are better recyclable and leave less harmful rest materials behind (Shanmugam et al., 2021).

Comparing for instance plant fibres to synthetic fibres shows a lot of possibilities for reducing the environmental impact of a product, while reducing the need for technical or highly processed materials. As shown in table 1, natural fibres use a lot less energy while being produced and are carbon neutral (Singh et al., 2017).

Replacing fossil based materials in composites with bio based materials to create bio composites can reduce the carbon emissions and the environmental footprint of composites a lot.

Looking at the matrix, it shows that using a bio based matrix instead of a fossil based matrix can reduce the carbon footprint of the composite between 50-70% according to the study by (Vink et al., 2003).

The use of a natural filler will increase the sustainability and circularity of the products, compared to conventional fillers.

Table 1. Comparing plant fibres and synthetic fibres (adapted Singh et al., 2017)

Properties	Natural fibres	Synthetic fibres
Resource	Infinite	Limited
Renewability	Renewable	Non-renewable
Recyclebility	Good	Moderate
Bio-degradability	Bio-degradable	Non-biodegradable
CO2 neutral	Yes	No
Mechnical properties	Moderate	High
Toxicity	Non-toxic	Toxic
Cost	Low	Higher than natural fibre
Energy consumptions	Low	High

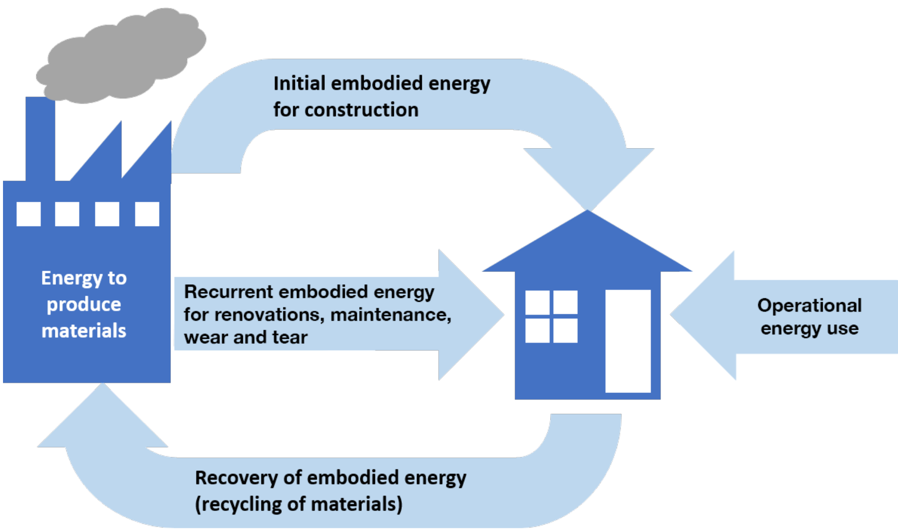


Figure 10. Embodied energy and operational energy of a building and buildproduct (source: Murray Hall, 2020)

3.1.5 End of life for bio composites

The end of life (EOL) of a building product currently mostly means that they end up in landfill or are incinerated (Jacob, 2011). This is not a sustainable solution and a waste of resources, especially if a product (or parts of a product) has the potential to be recycled or reused into something new. The reuse or recycling of a bio composite material at its EOL however is still a challenge, since it is made out of different materials with different properties (Chaitanya et al., 2019). For thermoset-matrix composites which will be applied in this research multiple methods can be used to recycle the composites. The three main methods are thermal, chemical and mechanical recycling (Yang et al., 2012).

Thermal recycling uses high temperature to separate filler and fibres while decomposing the resin. Sadly the quality of the fibres and filler materials is almost always lower than before. In this process of thermal recycling, thermal energy can be recovered through pyrolysis, gasification or combustion (Yang et al., 2012).

Chemical recycling uses chemical depolymerisation or removes of the matrix, so that the fibres are separated from the rest for further recycling (Rybicka et al., 2016) (Yang et al., 2012). Chemical reactions are used to separate the different components, where the solvent is determined by the matrix used in the (bio)composite (Shanmugam et al., 2021) (Grigore, 2017).

However, **biological recycling** is the most natural way of recycling. This method starts at the beginning of a products lifecycle, by using biodegradable thermoset materials. This method would use fungi or other natural synthesis to degrade the product. This method uses less energy and causes less damage to the fibres during recycling (Ma & Webster, 2018). This method is relatively unknown and won't be the main focus of this project.

Mechanical recycling is when the materials are grinded into smaller parts. To reach certain grain sizes a sieves is used to get the right size (Oliveux et al., 2015).

Although all of these methods work and are a possibility, mechanical recycling has proven in multiple studies to be the easiest way to recycle bio composites (Xu et al., 2018). This method will be applied in this research.

Table 2 Recycling methods adapted from (Yang et al., 2012)

Thermoset matrix composites	Recycling methods	Technology features	Status
	Mechanical recycling	• Comminution – grinding – milling • Products: fibres and fillers • Degradation of fibre properties	Commercial operation
	Thermal recycling	• Combustion/incineration with energy recovery • Fluidised-bed thermal process for fibre recovery • Pyrolysis for fibre and matrix recovery	Promising technology
	Chemical recylcing	• Chemical dissolution of matrix • Solvolysis (supercritical organic solvent)/hydrolysis (supercritical water) • Product of high quality fibres, potential recovery of resin • Inflexibility of solvent and potential pollution	Only laboratory studies Promising

3.2 Bio Composites

Bio composite materials are made out of different components. These components have their own properties to ensure the strength, cohesion and more. Bio composites are composed of materials from biological origin in one or more phases. Bio composites are made of reinforcement (fibres), matrices (resins) and fillers.

Reinforcement can be plant fibres such as hemp, flex, bamboo or from recycled wood.

Matrices can be polymers, which can be produced from fossil resources or from renewable resources (Fowler et al., 2006). These polymers can come in multiple forms, as thermoplastics or as thermosets. The main focus here will be on thermosets polymers as furan resin matrix.

Fillers can bio based powders from plants or food waste. A filler can have a lot of different functions, these functions will be elaborated on in paragraph 3.3.3.

Mixed together the fibres, matrices and fillers form a dough which can be compressed and heated into a mould where the dough will harden. In chapter 3.3 the materials of the bio composites structure are researched more in depth.

3.2.1 Filler as main focus

Fillers have multiple functions in a bio composite. The main function is to reduce the costs of the total material, but they also add tensile strength and stability by reacting with the matrix (Shanmugam et al., 2021). The different function of fillers will be further elaborated on in section 3.3.3 Fillers. Mechanically recycling a bio composite results in a powder, which can be used as a filler. This possibility will be investigated further in the testing phases. Previous research shows that recycling composites into fillers, decreases the mechanical properties of a new composite. Investigating the limitations of recycled fillers and how they can be used in new bio composite materials.

3.3 Materials

3.3.1 Fibres

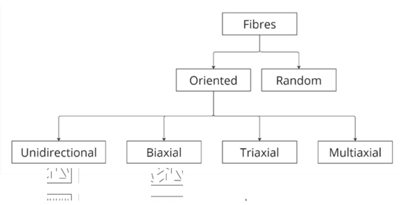


Figure 11. Fibre distribution (Indulge & Explore Natural Fiber Composites, 2015)

Figure 12. Natural fibres for bio composites (Midani, 2022)

Fibres work as a reinforcement inside the composite material. It gives strength and stiffness. These properties of the composite material are passed over from the fibres (Fowler et al., 2006).

Fibres can take different forms and compositions in a composite. They can be divided in two main categories; oriented and random. Oriented fibres are actively laid in a direction or pattern. The subcategories are shown in figure 12. Random fibre distribution means the fibres are mixed with other ingredients without a specific direction (Indulge & Explore Natural Fiber Composites, 2015).

Bio composites use natural fibres which can be divided in different categories, plant based, animal based or mineral based. All plant-based fibres are built from three main components; cellulose, lignin and matrix polysaccharides (Fowler et al., 2006).

Natural fibres that are stiff and strong enough for reinforcement of a bio composite are flax, hemp and jute (Michaeli, 1989).

However in the testing phases fibres will not be used, the reason for this is that at NPSP it was concluded that adding fibres to the bio composite reduces the mechanical properties of the product. This behaviour hasn't been explained scientifically, it could be that the fibres are not interacting with the resin as much as the filler does. Although adding fibres would help reduce the shrinkage of the product. For the sake of this research the fibres will be left out of the testing phases.

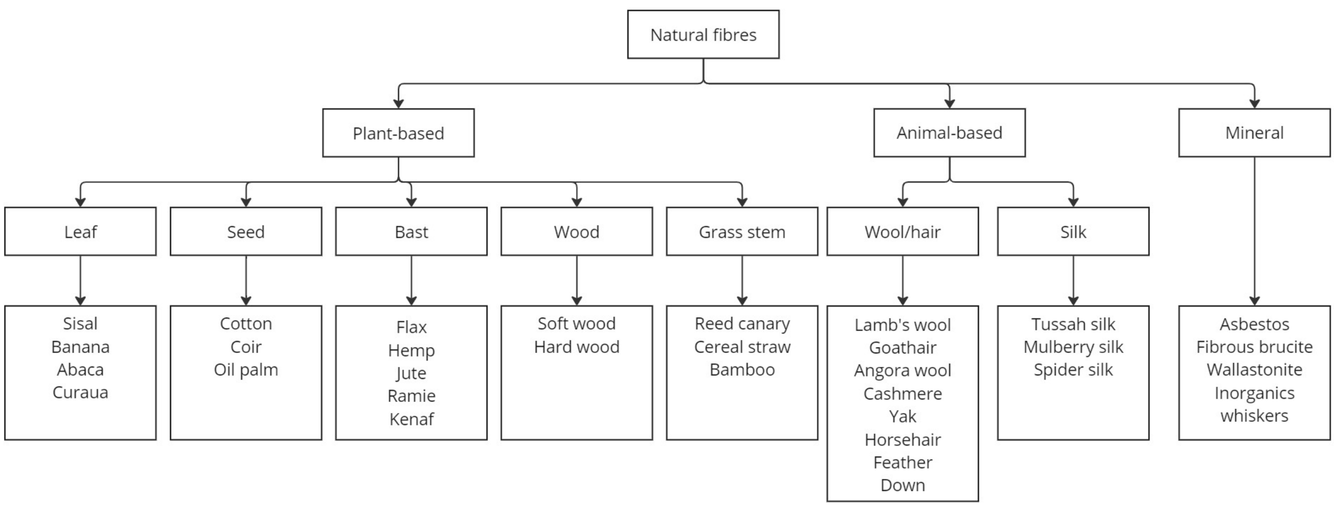


Figure 13. Range of natural fibres (source)

3.3.2 Resins

Furan resin

Furan is used as a resin matrix in the bio composite material. Furan can be derived from corn cobs, sugar cane, wood products and more natural sources that have vegetable cellulose (Abhiram et al., 2021). Furan used as a resin matrix for curing are based on 2-furfuryl alcohol (Gandini & Belgacem, 2022). Furan is a bio based material, but it is not bio degradable. This makes it more difficult to recycle in a natural way.

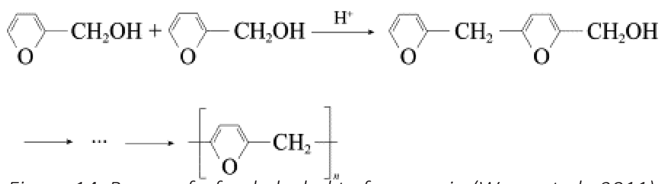


Figure 14. Process furfuryl alcohol to furan resin (Wang et al., 2011)

Lignin Resin

Another biobased resin is lignin. Lignin is natural polymer that is one of the three main building blocks of wood, cellulose and hemicellulose are the other two building blocks. It is ensures the mechanical structure of the wood and plants (Gioia et al., 2020). Lignin decreases porosity and increases stiffness and adds biological resistance (Shaily et al., 2023).

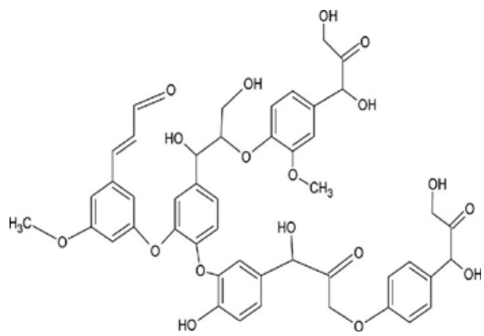


Figure 15. Lignin chemical structure (Mahmood et al., 2018)

Polyester resin

Polyester resin is a commonly used resin in composites. It is a synthetic resin which is made created by the reaction of polyhydric alcohols and dibasic organic acids. This resin is also used to make composites at NPSP. (Nabasco, n.d.).

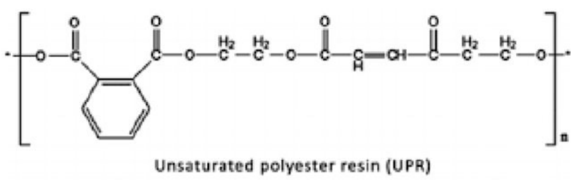


Figure 16. Unsaturated polyester resin (Islam et al., 2019)

These three different resins are used by NPSP in their bio composite materials. For the experimental testing the focus will be on furan resin to discover more about its recyclability (still quite unknown). Another reason it that furan resin is a biobased resin, which falls in the scope of this thesis on circular products.

3.3.3 Fillers

Figure 17. Examples of additives, pigments (https://www.meghmaniglobal.com/) and release agent (linseed oil (https://vitalbix.com)

Fillers can have multiple functions inside a composite material. Bulk fillers are meant to reduce the costs of the overall material (Indulge & Explore Natural Fiber Composites, 2015). Functional fillers are a very low part of the composition of the bio composite. These fillers are added to add specific characteristics or enhance the resins properties. Functional fillers can also be called an additive, and additives can be synthetic and natural (Additives & Fillers - Composite Materials | CompositesLab, n.d.).

Some of these additives can be added to the matrix :

- Pigments & Colorants (colouring)
- Fire Retardants (combustion resistance)
- UV Inhibitors & Stabilizers (protect against UV radiation)
- Release Agents (removal from moulds)
- Conductive Additives (conduct electricity)

Bulk fillers

Bulk fillers are fillers that can be added to reduce the costs of the composite material. Fillers can also increase the tensile strength of the bio composite (Tan et al., 2022). Fillers can reduce the shrinkage that happens during curing, since the resins are more filled. Bulk fillers can fill around 40-65% of the composite by weight (Additives & Fillers - Composite Materials | CompositesLab, n.d.).

Bulk fillers are now mostly inorganic materials (mineral) such as:

- Calcium carbonate
- Kaolin
- Alumina trihydrate
- Calcium sulfate

All these bulk filler are mineral materials, to increase the sustainability of composite. Some of these materials also have an extra added values, such as a higher fire resistance. Bulk fillers can be bio based.

3.3.3 Fillers

Bio based fillers

Figure 18. Biobased fillers top: wood flour bottom: spent coffee bean powder

Bio-based filler is a great opportunity to increase circularity, because of its substance and weight percentage. Bio based fillers are relatively new. Some testing has already been done with food-waste as fillers (Neuhaus, 2024). The results are promising on the use of food waste fillers for low carbon products.

The most common 'organic' fillers fall into the following three categories;

- Wood flour (made from wood dust, shavings etc.)

- Lignocellulosic fillers (can be agricultural waste such as spent tea leaf powder, spent coffee bean powder, eggshell powder, banana peel powder, tamarind nut powder, almond shell and turmeric powder) (Senthil Muthu Kumar et al., 2020)

- Carbon-based nanofillers

During the testing phase the main focus will be on **almond shell** as a lignocellulosic filler. This filler is already used in combination with furan resin, which makes the two ingredients compatible.

Material requirements for fillers

Fillers in bio composites can help improve mechanical properties, thermal and dimensional stability (Senthil Muthu Kumar et al., 2020).

Different properties of the filler can have an effect on the performance as a filler:

- Filler composition
- Filler size
- Filler surface/texture
- Filler concentration
- Shape of the filler
- Dispersion in the matrix

Bio composites can have different functions, which require different properties which a filler should add to the material.

Filler size and amount

Filler size and the amount of filler can affect the mechanical properties of the bio composite. Smaller grain sizes have a larger surface area to connect to the matrix. When adding more filler into the bio composite, the impact strength increases, but the tensile strength decreases (Senthil Muthu Kumar et al., 2020). However, adding too much filler (which decreases the amount of resin) will make the material more brittle.

3.3.3 Fillers

LCA filler

Almond shell filler needs to be processed and grinded to get fillers that are the size of less than 125 µm. This costs energy and resources. To investigate if using recycled bio composites as a filler is more circular and sustainable than a virgin filler a Life Cycle Assessment (LCA) needs to be performed.

Almond shells are a co-product of the production of almonds. In the production of almonds, 1 kg raw almonds and its co-products use 35MJ of energy which emits 1.6kg CO2-eq of GHG emissions (Kendall et al., 2015). Almond shells are often used in electricity generation and livestock bedding. To remove the almond from the shells and hulling energy is needed, this takes around 0.59 MJ per kg of almond kernel (Kendall et al., 2015).

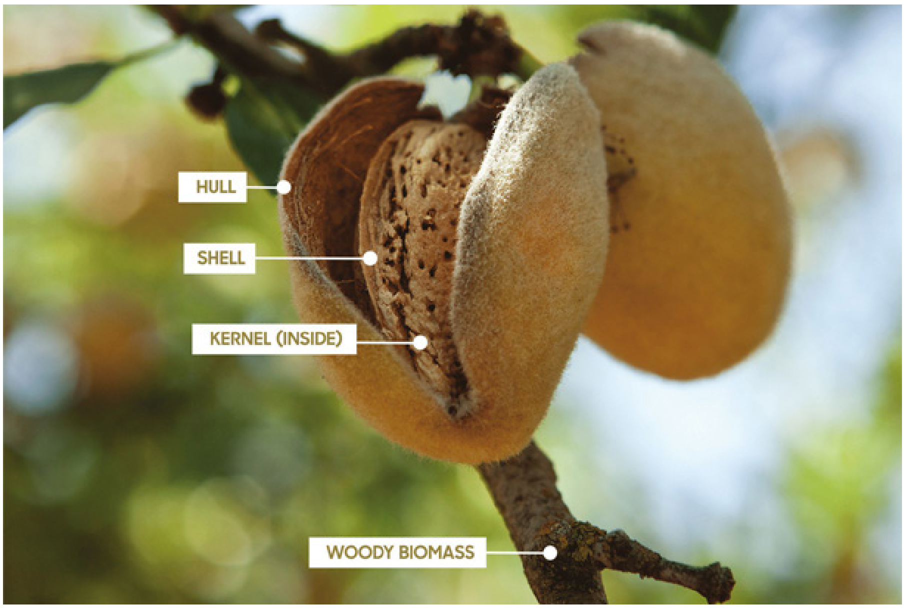


Figure 19. Almond components (Good for You, Good for the Earth, n.d.)

3.4 Bio composite matrix

3.4.1 Matrix of bioplastics

The matrix in bio composites are described as bioplastics. Bioplastics are either biobased, biodegradable or both. Bioplastics are obtained from renewable recourses, which means these materials can grow back. Biobased materials are partly or fully derived from biomass, plant based material. Biodegradable means that the materials can be broken down into natural substances due to a process caused by microorganisms (Rosenboom et al., 2022). Not all biobased materials are biodegradable and vice versa.

In figure 20 is the system shown of bioplastics. Furan resins fits in the biobased category, but it is not biodegradable.

Bioplastics are a more sustainable option than conventional plastics, with two main advantages: biobased materials reduce the use of fossil fuel resources because these materials are regeneratable, and further they can store carbon instead of emitting carbon (European Bioplastics e.V., 2023).

The matrix of a composite material can either have a thermoset or thermoplastic structure.

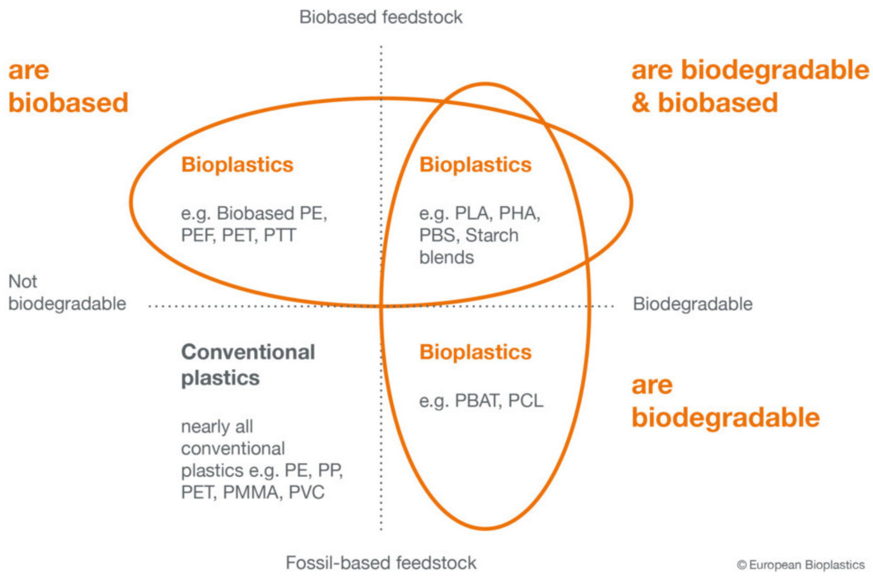


Figure 20. Bioplastics (European Bioplastics e.V., 2023)

3.4.2 Matrix - Thermosets vs Thermoplastics

Thermosets are more difficult to recycle compared to thermoplastics. Thermosets generally have better mechanical, thermal and structural properties than thermoplastics (Kula et al., 2014). A thermoset is a long chain of molecules that are chemically cross-linked. The chain is formed during a curing reaction, caused by heat, radiation or both (Kula et al., 2014) (Ma et al., 2016). They can't be remoulded when cured, since they are permanently cured (Ma & Webster, 2018). A solution to the difficulty of recycling could be the use of degradable thermosets instead of non-degradable thermosets. These degradable thermosets are actually quite new to the research field, so a lot is still unknown (Ma & Webster, 2018).

Thermoplastics are also made form a long chain of molecules that are interlinked, but when heated these links will disappear. This makes the materials easily fixable when broken (Kula et al., 2014). This makes is easier for thermoplastics to be recycled. Thermoplastics are representing around 83% of the plastics industry, they can be found in food packaging, household products and more (Kula et al., 2014). Thermoplastics are very well performing on impact resistance, but not really well on heat (Brandrup et al., 1999).

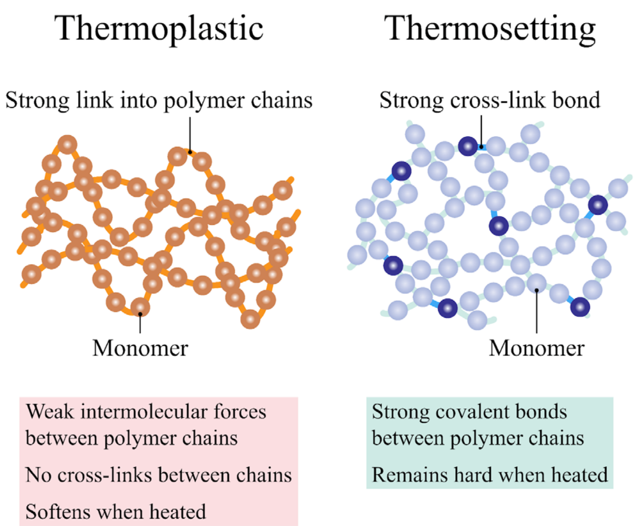


Figure 21. Thermoplastic vs Thermoset (Melito, 2022)

Table 3. Typer of Polymers in composite matrix (Indulge & Explore Natural Fiber Composites, 2015)

Thermoplastics	**Thermosets**
Polypropylene (PP)	Polyester (PE)
Polyethylene (PE)	Epoxy (EP)
Polyvinyl Chloride (PVC)	Phenolic (PF)
Biobased PE, PVC, etc.	Polyurethane (PUR)
Thermoplastic starch blends	Furan Resins
PLA	Various bio resins

3.5 Manufacturing Methods

For fabricating bio-composites different manufacturing methods are used in the industry. The same methods are used for the manufacturing of plastics and composites. The specific methods used to produce bio composites methods are injection compression moulding, resin transfer moulding, cast-moulding, thermoforming and bulk compression moulding (Fowler et al., 2006) (Abhiram et al., 2021).

Comparing the different manufacturing methods used to make bio-composites is useful to define the best method for the product.

3.5.1 Injection compression moulding

Injection compression moulding is a process where molten resin is injected into the mould, which is shaped by compressing the mould closed. This ensures a uniform distribution of the resin inside the mould. Due to holding pressure and high temperature for around 3 to 5 minutes the product is hardened and cooled. The process has to be repeated at least 3 times to get the right result, the first three products are disregarded. The screw extruder should be cleaned before and after using the injection moulding, to minimize the chances of contaminations of other products (Kula et al., 2014; Masri et al., 2021).

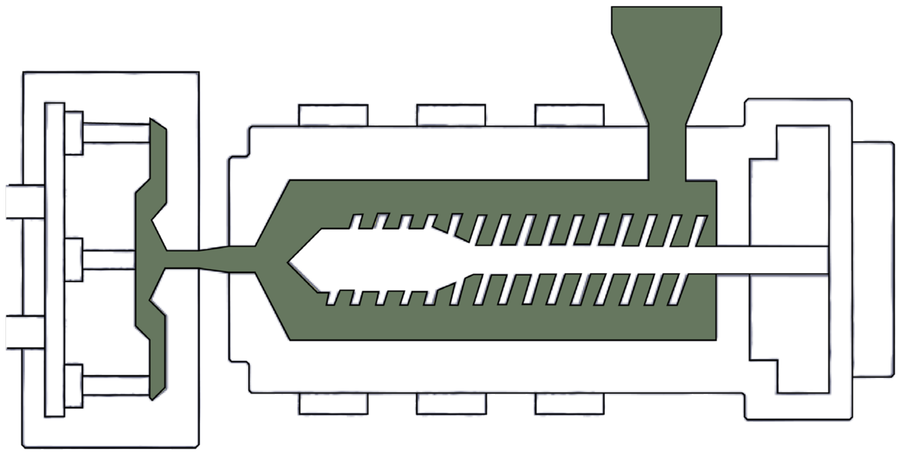


Figure 22. Diagram Injection compression moulding (based on (Kula et al., 2014))

3.5.2 Resin transfer moulding

Resin transfer moulding (RTM) is a manufacturing process for composite materials. Preformed fibres or woven fibre are placed into the mould cavity. The mixture of epoxy resin is injected into the mould together with hardener, pressure (160 bar) and high temperature (220 °C) is applied via the mixing head. Reinforcement is added to the mould. Through the cavity in the mould the resin impregnate the fibres in a vertical direction, due to the vertical injection of the resin (Masri et al., 2021).

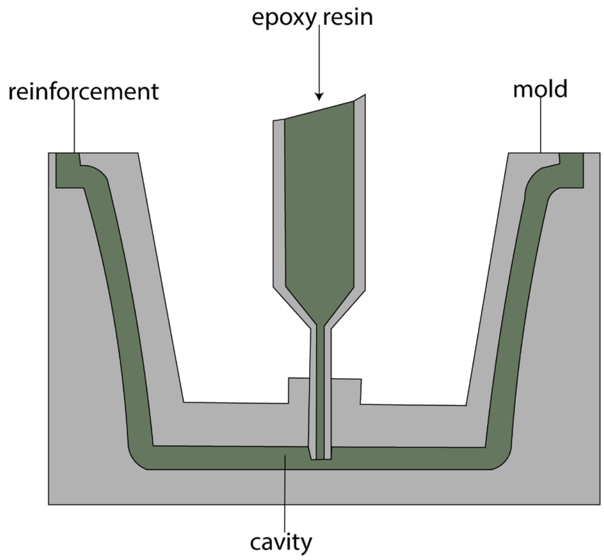


Figure 23. Diagram Resin transfer moulding (Mwesigwa et al., 2022)

3.5.3 Cast-moulding

There are two different types of cast-moulding; open mould casting and closed mould casting. A mould is made from a desired end-product, this leaves a 'negative' of the product. This mould is then used to make the new product. Thermoset resins are used as a catalyst to solidify the product (Kula et al., 2014). This process creates opportunities for complex shapes.

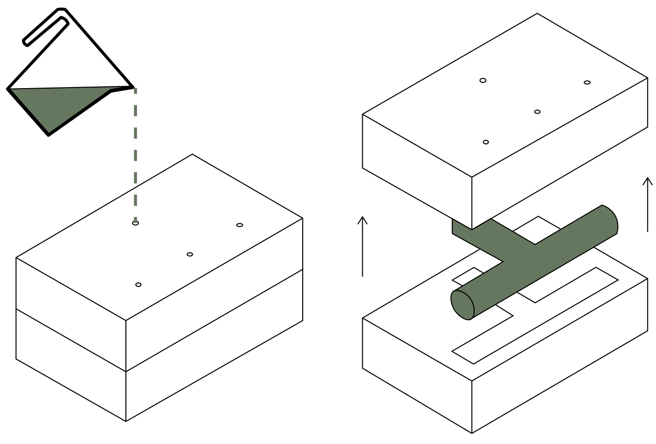


Figure 24. Diagram Cast-moulding (based on (Kula et al., 2014))

3.5.4 Bulk Compressing moulding

Bulk Compression moulding (BCM) uses a mould with two sides that are compressed together and heated. To ensure the right thickness of the composite, the right curing temperature and pressure are applied, while keeping the resin's velocity in mind (Mahendran et al., 2021). Mechanical properties of the manufacturing process are really good, although it has limited freedom in form. This technique can produce high quality products with little porosity This technique can produce high quality products with little porosity (Kula et al., 2014)

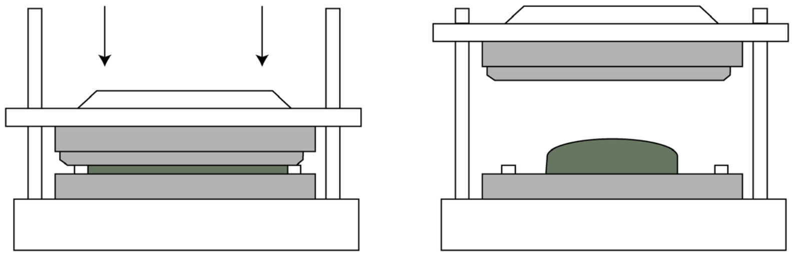


Figure 25. Diagram Bulk Compression Moulding (based on (Mahendran et al., 2021))

3.5.5 Conclusion

All these different manufacturing processes have their advantages and disadvantages.

Injection moulding gives a clean finish and has a low material loss, but the mould are expensive and lead to a lower strength of the product.

Resin transfer moulding gives a clean finish, but has a size restriction for the products that can be manufactured this way.

Cast moulding is low in costs, but has an higher porosity of the manufactured material.

BCM gives high quality products, can be used for big shapes, however the processing times is longer compared to the other methods.

Comparing all these manufacturing processes and keeping in mind the available resources at NPSP, it was decided to use the bulk compression moulding machine for this project.

3.6 Requirements Application

3.6.1 Application

The application of the façade panel chosen in this project will be a rainscreen type of façade, which is aiming to protect the building from weather conditions.

The rainscreen façade is the most outer layer of the building, so the requirements for the product are:

- Protection from **weather** conditions (rain, snow , heat, UV and hail)
- **Impact** resistance
- Aesthetic **appearance** (freedom of design)
- **Fire** protection (not easily spread over façade)

Buildings can be categorized in different parts (Brand, 1994), each having their own life span. As shown in figure 20 the "skin" of a building, also known as a façade, generally has a life span of 20-50 years. So the durability of a façade panel is important to define and test.

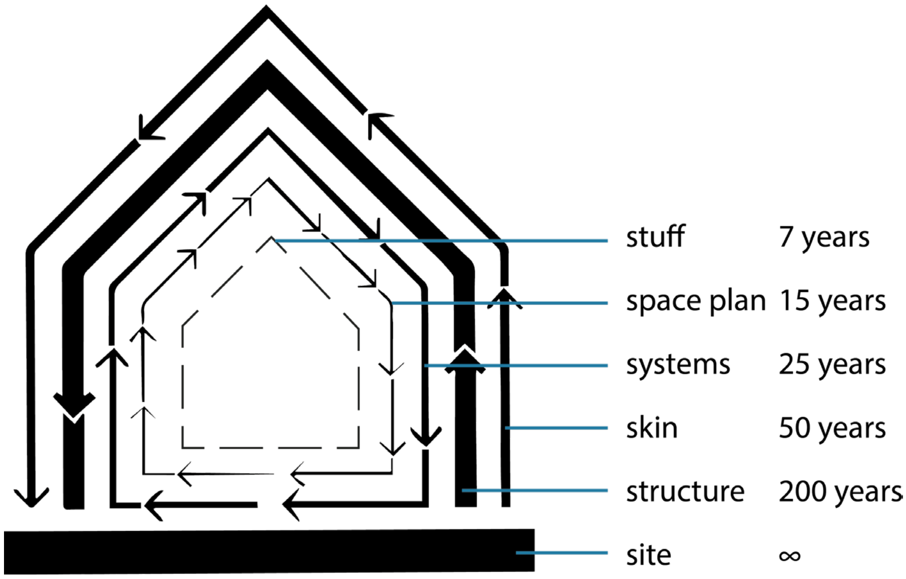


Figure 26. Scheme of shearing layers model, based on (Brand, 1994)

Rainscreen façade panels are often made from sheet material produce with moulds manufacturing techniques. This makes it easier to mass produce them, while still leaving room for design freedom and more complicated geometries. The application of this project will be designed for a standard size panel used by NPSP, with a size of 200 mm x 200 mm.

3.6.2 Application requirements

The following criteria are defined after the previous mentioned requirements of a rainscreen façade panel:

- Mechanical strength, to withstand wind load and self-weight
- Impact resistance
- Weather resistance (water and frost)
- Flow (viscosity of dough)

These criteria will be tested on a sample size of the product.

To meet the set criteria some tests need to be performed. These tests will determine mechanical properties, durability, fire safety properties and design abilities. The results will be evaluated against property data of virgin bio composite materials and visual inspections.

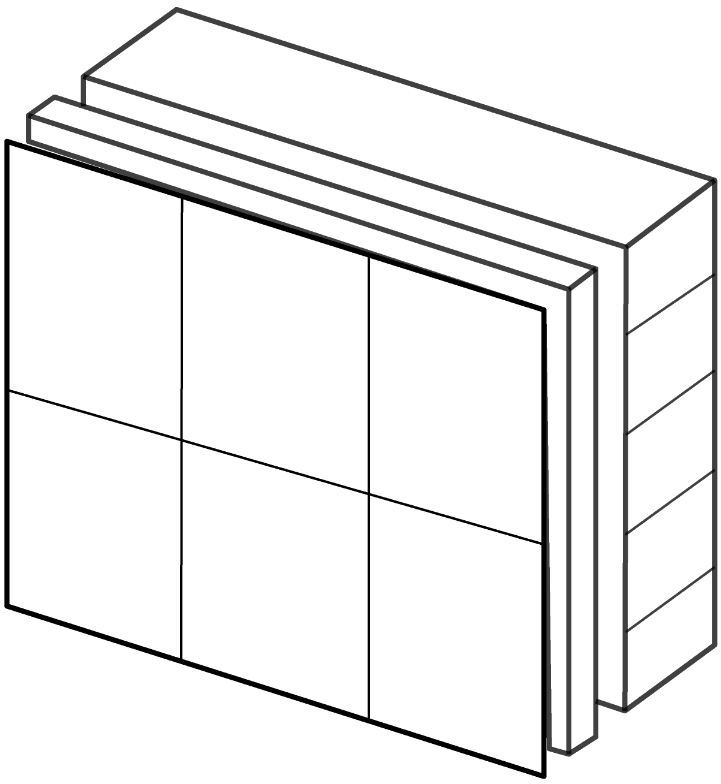
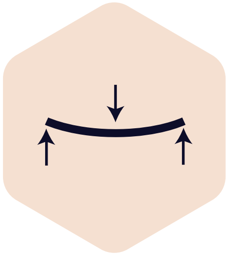
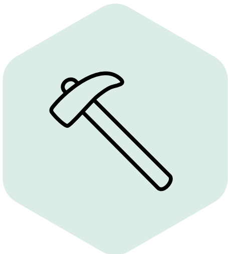


Figure 27. Rainscreen facade concept (own)

3.6.3 Testing methods

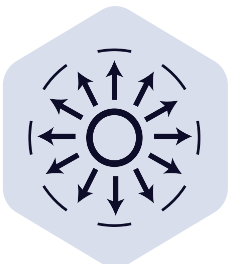


Strength:
The flexural strength of the samples can be calculated by using the sizes of the sample and the relation between the forces. Then comparing the deflection between the different samples and maximum deflection allowed by standards. The tensile strength is tested for. The compressions strength will be tested to see if the product can hold its own weight. For the testing the standard for composites: ISO 14125A is used.



Impact resistance:
Impact can happen in different ways, humans vandalizing, nature like hail or animals. To evaluate the impact resistance the Izod & Charpy impact test will be used. In this test the sample is hit with a pendulum with an applied force that will break the sample. The sample will be prepared as the NEN-EN-ISO 179-1:2023 EN prescribes. This test will be done in phase 1 and 2 where the pendulum equals 1 joule.

Durability & Weather exposure:
The durability of the product will be tested with exposure to UV, temperature changes and moisture. There are two options for testing this on the samples. The first option is the weather machine that simulates a sped up exposure to the environments. The second option is submersing the samples in water for 24 hours and freezing for 24 hours. (ISO 62)
The methods to be applied in this project will be chosen based on the availability of the machines.



Flow:
Viscosity of the dough before curing is important for freedom of design. During the curing process the dough will have to reach around corners or difficult shapes. The lower the viscosity of the dough the higher the form freedom of the material.

Appearance:
The samples are tested on appearance, this is done by seeing if there are any visible defects; such as cracks, unfilled edges, holes and other marks.

3.7 Chapter Conclusion

Bio composites are a circular building product, that integrates bio based materials in a façade panel. An advantage of a circular building product is that it has less embodied carbon in a product. A disadvantage is that circular building products can have a shorter lifetime compared to conventional materials such as bricks and metals. Looking at the R-strategies for extending the life cycle of the material, two strategies stand out, Recycle and Reduce. By recycling the materials at their current EOL and implementing them in a new bio composite, the life cycle of the materials is prolonged. Also virgin material usage is reduced. The way for recycling a bio composite that fits best with the characteristics is mechanical recycling, where the material is shredded and grinded in to small particles, which can be used as filler in a new composite. For this reason mechanical recycling will be used in the experimental testing phases.

Recycling bio composite materials into fillers for a new composite could be the solution to prolong the materials life. Fillers can have multiple functions in a bio composite materials. Bulk fillers are mostly added for the reduction of costs. However they also add to the tensile strength and can have potential to reduce environmental impact when using recycled filler. Functional fillers can have a variety of different functions, such as adding colour, easy release from the mould, catalysing the process. These fillers mixed together with the matrix, furan, a thermoset resin is necessary for the curing of the bio composite.

Different manufacturing techniques were investigated, due to the available resources it resulted in the bulk compressions moulding (BMC). This process uses heat and pressure to cure the bio composite in the desired shape and thickness.

The application of a rain screen façade is assessed against some criteria. These criteria are based on regulations and architectural impressions.

For the experimental phase the following elements are selected:

- Mechanical recycling
- Furan resin
- Almond shell filler
- Bulk Compression Moulding (BMC)

Testing

The experimental design chapter is divided into:

Phase 1 looks more intensely into the fillers material properties.
Phase 2A Compares almond shell filler to the recycled filler & optimize the weigth ratio of the recycled bio composites on mechanical properties & durability.
Phase 2B investigates the effects of recycling weathered bio composite panel as a filler it new bio composites.
Phase 3 investigates the 3D possibilities with the recycled fillers.

All these phases will lead to determine design criteria for a rain sceen facade panel that can be manufactered with recycled fillers.

4.1 Workflow

Shown in figure 28 is the workflow of the different testing phases and how they influence each other. Testing starts at phase 1 where the fillers are researched on its properties. These properties influence the second phase were they are used together with the matrix to make a bio composite. Each filler is tested with different ratios between the filler and matrix to find to the optimal combination. These bio composites are tested on mechanical and functional properties. This will lead to a selection of bio composites that are used for the next phase, where they are tested on their flow. This is a functional property, to see the usability of the material in a façade product. All these findings regarding their properties will be used in a design proposal.

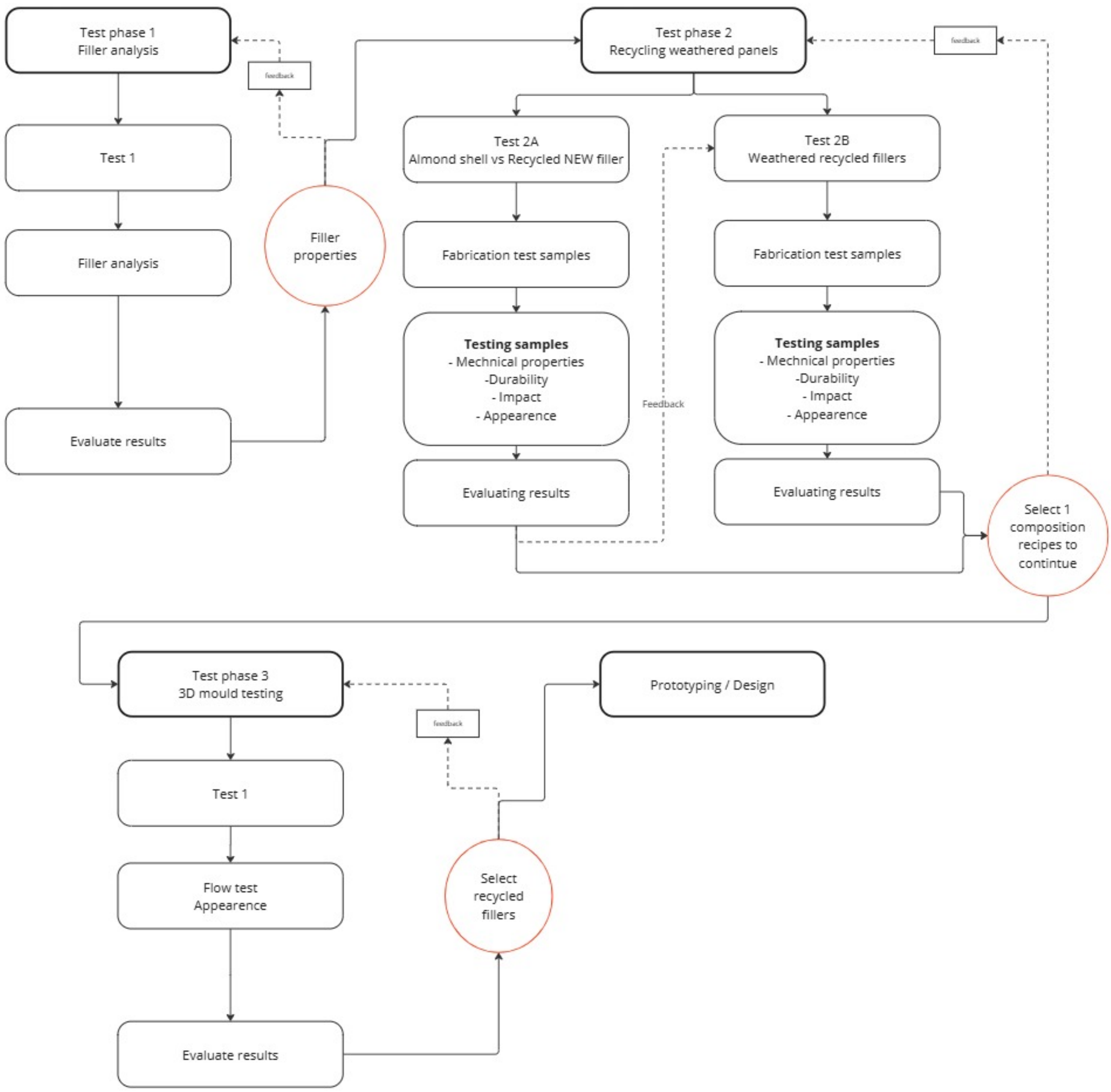


Figure 28. Testing process

4.1.1 Objectives

The objective of the testing phases is to investigate the possibilities of recycling of bio composite façade products. Bio composite panels that are weathered in different stages are recycled into filler materials and used into new bio composites. These 'new' bio composites are tested on mechanical and functional properties to ensure that they can be used for a rain screen façade cladding.

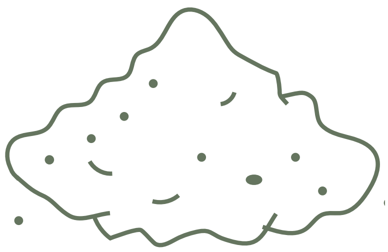
The ratios between the recycled fillers and resin are tested to find the optimal ratio that meets all the requirements. The recycled fillers are also compared to the 'original' almond shell filler, used by NPSP.

The different fillers are testing in a 3D mould to investigate the flow and workability of the recipes.

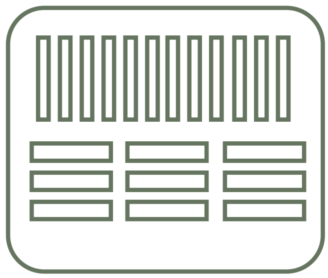
The outcomes of the testing phases will determine the recyclability of the bio composite façade panels into fillers for a new panel.

4.1.2 Structure

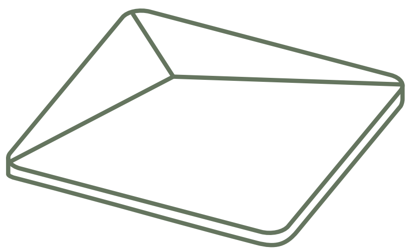
The testing phases are structured based on size of the test samples, starting with the research and analysing of the filler materials and its properties. Continuing with the interaction between the fillers and the matrix (resin), and testing the functional and mechanical properties. One step larger is looking at the product scale, were the material is tested on a functional level and aesthetics.



Raw material resources



Material sample



Product

4.1.3 Evaluation criteria

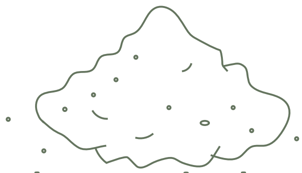
The evaluation criteria vary during each phase of the experimental testing.

The first testing phase is looking at the filler material itself and this properties. These properties are analyses and compared.

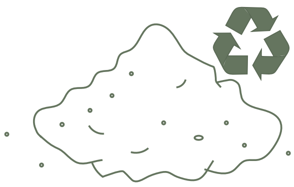
The second phase focusses on the sample level, where the filler material is mixed together with the matrix. These samples will be evaluated on the way they interact with each other. This phase was split into two parts to research the different fillers interacting with the matrix. The sample will be evaluated on mechanical, functional and durability properties.

In the third phase the different fillers are compared based on their ability to flow in 3D moulds. This can define the workability of the recycled filler in a later stage.

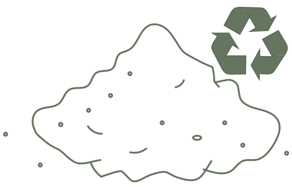
4.1.4 Filler selection



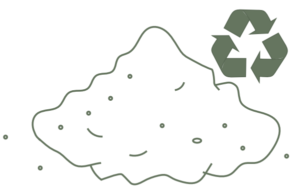
Almond Shell



NEW



OUT



QUV

In the testing phases four different types of fillers are tested and analysed. A reference filler, almond shell filler, to compare the recycled filler to. The remaining three fillers are recycled fillers from different panels made from the almond shell filler and furan resin.

Filler types:

- ASF: Almond shell filler , which is currently used in the base recipe of NPSP.

- RF_NEW: Recycled filler of sample plates that have been newly manufactured and recycled right away.

- RF_OUT: Recycled filler from a natural weathered panel (OUT is abbreviations from outside)

- RF_QUV: Recycled filler from an artificially weathered panel

4.2 Preparation of fillers

Prior to starting the experimental testing phases, some preparations needs to be made. In the experimental testing phases, fillers are used that are made from recycled 8040 panels. These panels are recycled at 3 different moments in weathering or usage. These panels have to be made before recycling. Some panels are recycled right after making them. While other are placed inside the QUV for a time period of 3 weeks. One panel was already hanging outside for 6 months.

4.2.1 Equipment

Equipment for mixing

Kneader - Linden, Type K Double-Z-Kneader

Measuring - Measuring cups, scale

Safety gear - Goggles, gloves, labcoat, safetyshoes and mask

4.2.1 Equipment

All steps of the testing production were performed at the company NPSP under partial supervision of the lab supervisor and lab assistant.

Ingredients:
Filler Material: Almond shell, supplied by NPSP.

Furan Resin: NPSP provides Furan resin

Catalyst Agent: supplied by NPSP, is used to accelerate the curing process.

Releasing Agent: Linseed oil, supplied by NPSP, ensures easy removal of the piece from the mould.

Equipment for pressing

Hot-press - Bucher, Hydraulic Press

Removal - Suction cup and gloves

4.2.2 Procedure

Before starting phase 1, preparations need to be made. In phase 1 bio composites recycled into filler will be used for testing. Since there are no available panels to shred into fillers, new panels need to be made. These panels are made with the ‘base’ recipe used by NPSP.

Table 4. Recipe of bio composite panels for recycling

Component	Description	Weight%
Resin	Furan	45
Filler	Almond shell <125 µm	45
Catalyst		7
Releasing agents	Linseed oil	3

The manufacturing procedure is as following

Step 1: Dry filler
First the wet materials are measured in measuring cup by weighting them on a scale. All materials are weighted in their own cup. The filler is measured just before adding it to the mixer.

Step 2: Measuring the ingredients
First the wet materials are measured in measuring cup by weighting them on a scale. All materials are weighted in their own cup. The filler is measured just before adding it to the mixer.

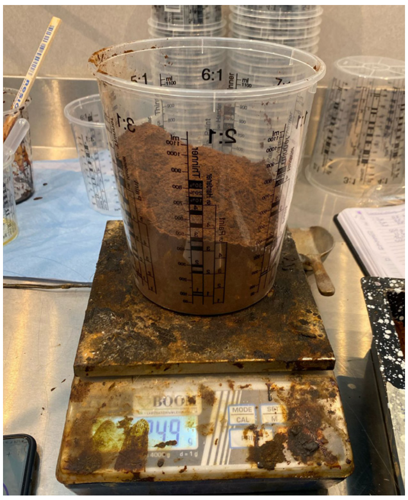


Figure 29. Measuring of the ingredients.

Figure 30. Adding liquids to the kneader

Step 3: Adding liquids to the kneader
The resin is added to the kneader and mixed for 15 minutes, the kneader is heated to 95°C to make mixing easier. After 15 minutes the catalyst is added to the kneader and mixed with the resin for 5 minutes. The last liquid ingredient is added and mixed for 5 minutes.

4.2.2 Procedure

Step 4: Adding filler to the kneader
After all the liquid ingredients are mixed in the kneader, the filler is added in two parts. This takes around 6 minutes of mixing in total.

Step 5: Taking out the dough
After everything is mixed properly. The dough is taken out of the kneader and stored in a labelled bag.

Figure 31. Taking out the dough

Step 6: Moulding
The bulk compression moulding machine is pre heated to 150°C, before adding the dough in the mould. The mould is brushed with oil, so the panel can be easily released from the mould. The dough is placed into the mould and cured under 150°C with 80 bar pressure for 15 minutes. The panel is cooling under a weight to limit deformation during cooling.

Figure 32. Pressing the sample plates

4.2.3 Making Recycled filler

Equipment for grinding filler

Shredder - Retsch Cutting Mill SM 300

Rotor mill - Retsch Rotor Beater Mill SR 300

Hammer

Sieving tower - Fritsch, Analysette 3 Spartan

Plastic bags

Oven - drying filler

Safety gear - Ear protection, gloves, safety glasses and mask

Measuring - Measuring cups, scale

Cleaning - Brush, vacuumcleaner and paper

4.2.3 Making Recycled filler

The panels made in the previous steps are recycled into filler. In total 7 panels were produced during the preparation phase. To use these panels as filler into new bio composites the panels need to be shredded and grinded into small particles.
The different panels need to be recycled to filler. The three different stages of weathering are recycled separately. For the recycled filler new, 7 samples plates are recycled.

Step 1: Hammer panels
Since the panels are too big to go straight in the shredder, the panels have to be broken down into smaller pieces. The panels are placed in a plastic bag, to collect all the fly away pieces. After being placed into the plastic bag the panel is hit with a hammer until the pieces are smaller than ±5 cm.

4.2.3 Making Recycled filler

Step 2: Shred filler
The smaller pieces are then shredded further in the cutting mill SM300 to around a few millimetres.


Step 3: Rotor milling filler
The shredded panel is grinded into a filler in the rotor mill SR300, that has a size around 50 µm.


Step 4: Sieve filler
The filler is sieved to extract the right grain size <125 µm. This size is extracted until there's enough for a dough. Step 2 and 3 are repeated until the desired amount of filler size is achieved.


4.2.3 Making Recycled filler

Step 5: Weight filler
After sieving the filler is weighted to check the total amount of filler extracted from the plates.

Step 6: Storing
The filler is stored into a container and labelled. Ready to use in the next phases.

4.2.4 Observations

Grinding:
The total amount of shredded filler that came from the 7 panels is 3207 grams. The first grinding conducted in the SM300 mill that grinded the particles lower than ±0.5 cm. To get smaller particles the SR300 mill is used which grinds the particles smaller than <50 µm. Both machines took some time to grind all the panels, since only small amounts of the filler can be grinded at once. During grinding some loss of material has to be taken into account, dust and particles stay attached to the machine or when moving the particles from one beaker to another some material is lost.

Sieving:
To check the grain sizes of the fillers, the sieve tower was used. While sieving the grinded particles, a lot of particles suck together. This led to clumps which wouldn't pass through the sieve. To try something different to see if the particle would pass through the sieve, the filler was dried in the oven for 2 hours to see the filler particles would pass through the sieve. The drying of the filler had no positive effect on sieving the filler. The particles still stuck together and didn't go through the sieve where they should.

4.2.5 QUV panels

The second recycled filler was made from panels that were placed in the QUV machine for 3 weeks. In this accelerated weathering machine samples are exposed to UV radiation and half water. This artificial weathering panels where grinded down to filler material with the same procedure as described in paragraph 4.2.3.

To calculate the amount of UV exposure over 3 weeks (21 days) in the QUV weathering machine, the following formula was used:

$$x\ light\ hours = \frac{1}{3{,}6} * \frac{a * \frac{kJ}{m^2}}{0{,}89 \frac{W}{m^2}}\ at\ 340nm$$

The light hours in the QUV were 504 hours.
The amount of exposure to solar radiation a = 1615 kJ/m2.
To compare this to the amount of solar radiation it would be enduring outside in the Netherlands for 21 days in the same period of time would equal = 55.5 kJ/m2.

Calculating the difference factor = 1615/55.5 = 29
So the QUV machine would equal 609 days outside or 1 years and 8 months.

4.2.6 Next steps

After preparing the recycled fillers, phase 1 can start. In phase 1 all the fillers will be examined on a microscopic level to find the filler properties.

In phase 2, these recycled fillers will be used in new bio composite recipes to test the mechanical and functional properties, which are compared to almond shell filler which is normally used by NPSP.

In phase 3, all fillers will be tested in an 3D mould to test their flow. These samples will determine boundary conditions for the design of the façade panel.

PHASE 1

4.3 Phase 1 - Filler analysis

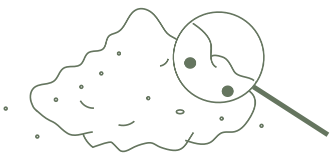
In phase 1 all the fillers will be examined on a microscopic level to find the filler properties. The following tests were executed to obtain more data about the properties and differences between the different filler types:

1. Measurement of filler density

2. Microscopic analysis of filler powders

These tests were done after the mechanical testing of the bio composite materials. To gain some more insight in the materials properties of the used fillers, different test were executed.

Each of these tests mentioned above will clarify some behaviour of the filler inside the bio composite. The density for instance and explain the materials porosity.



4.3.1 Density

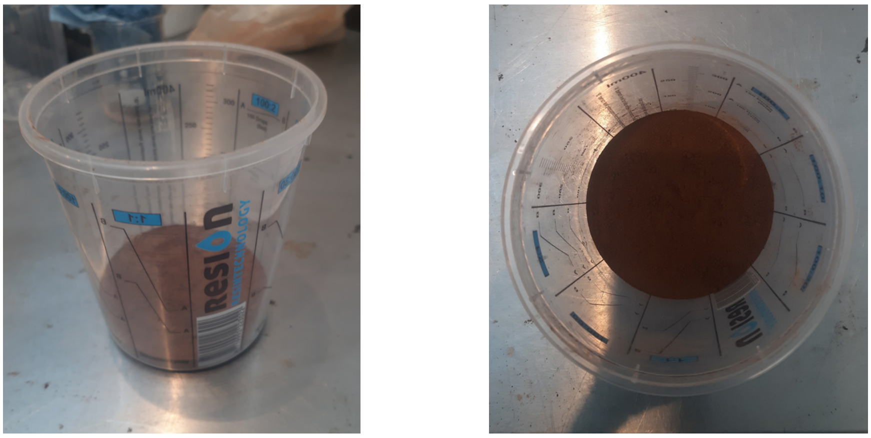
Procedure
The filler material is weighted on a precise scale. The filler is added to a measuring cup, which is tapped and compressed to get a flat surface. As the surface is flat and level the volume is noted.. This procedure is repeated 3 times to get an accurate result.

Equipment: Cylinder, scale & water

Measurements:
To measure the bulk density of the different fillers, weight of the filler is divide by the volume. As shown in the formula below:

$$Density\ [kg/m^3] = W / V_f$$

V_f: Volume filler



Measuring cup to measure the balk density

Findings
It is interesting to see that the recycled fillers have a lower density compared to the almond shell filler. Another interesting pattern is that the more weathered the panel the lower the density of the filler. This could be correlated to each other. The bulk density of the tested fillers are shown in table 5.
Since there is data available on the almond shell fillers density, the measure density can be compared to the data provided by from a professional density tester.

Table 5. Bulk Density

	Average Bulk Density [kg/m^3]
Recycled NEW	609
Recycled OUT	589
Recycled QUV	450
Almond Shell filler	666

4.3.1 Density

Seeing that the density reduces in the recycled fillers, is not really surprising. The recycled fillers consist of a combination of resin, filler and additives. The density of the resin, which make up around half of the composite (before recycling), is lower than the almond shell filler. The densities of the materials provided by the manufacturer are shown in table 6.

Table 6. Density according to NPSP

	Density [kg/m3]
Linseed oil	930
Catalyst	1200
Furan	1210
Almond shell	1500

Discussion & Conclusion

It can be stated that these measurements are not that precise, the measuring cup was able to measure every 10 ml. The method also mean that the readings were done manually, which has its limitations. The almond shell filler density test was compared to the density data that was obtained with a professional test. Although the value measured from the test was much lower than the actual density, value were in line with the expectation that the recycled filler have a lower density. It could be explained by the lower density of furan, which is around have of the components inside the recycled fillers. Knowing the density of the filler could help indicate the amount of filler added into a new bio composite recipe. It shows that the RF_NEW composites need more filler compared to the other components to achieve the same density of the material. Looking at the weathered recycled filler even more filler needs to be added to the other components to achieve the same density of the composite.

4.3.2 Filler Particles

Procedure

Using the digital microscope, Keyence VHX-7000, available at the faculty of Architecture the different fillers from Phase 2 were observed. The fillers were photographed at two different enhancements 250 µm and 500 µm.

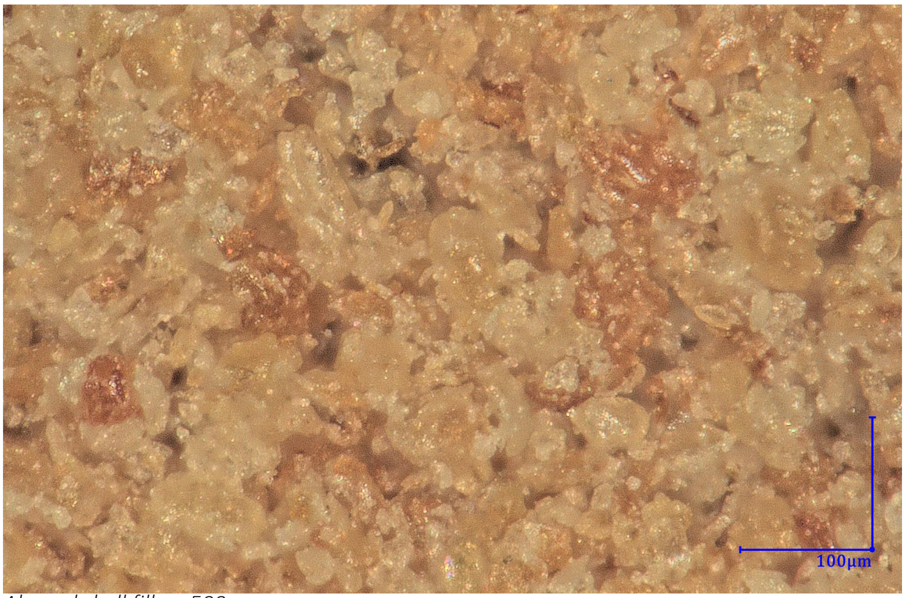
Measurements

The filler are analysed based shape, size, colours, size distribution and abnormalities.

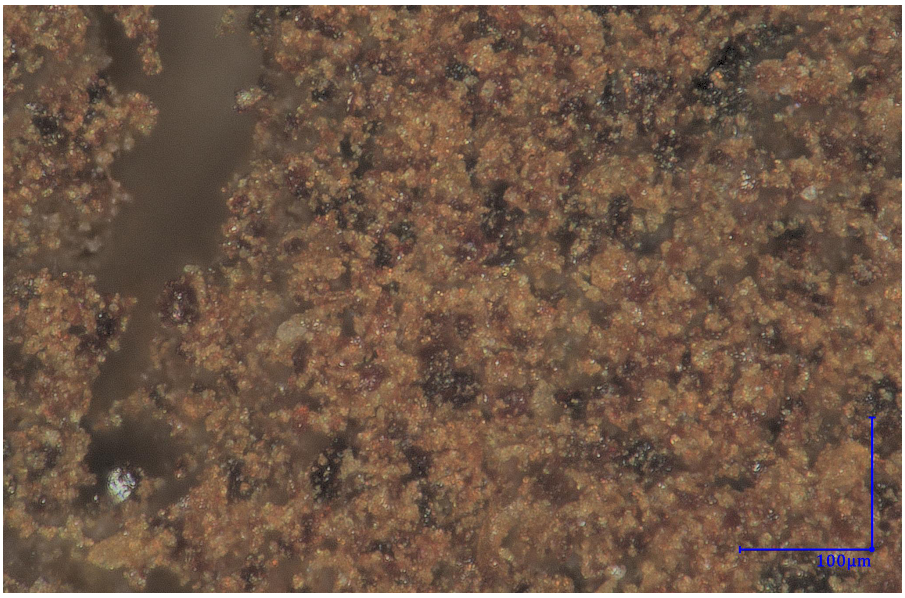
Observations

Particle shapes

The different powders vary in shapes. The particle shape of the almond shell filler is sharp and not uniform. The recycled fillers (NEW, OUT & QUV) are quite similar to each other, both are milling in the same way which could explain the same shape. They seem more round as a shape, but they also stick together. The different colour within the filler really shows that they agglomerate.



Almond shell filler x500



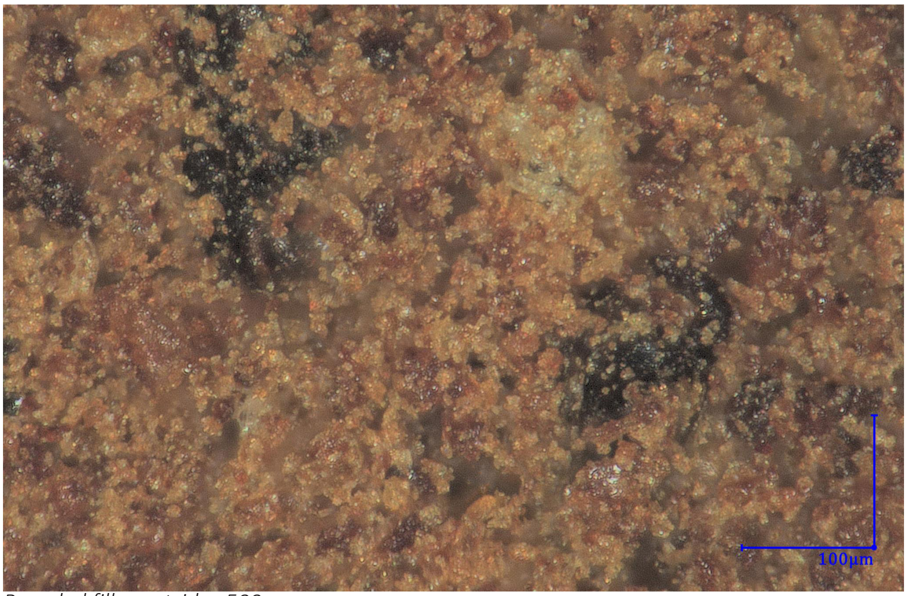
Recycled filler new x500

4.3.2 Filler Particles

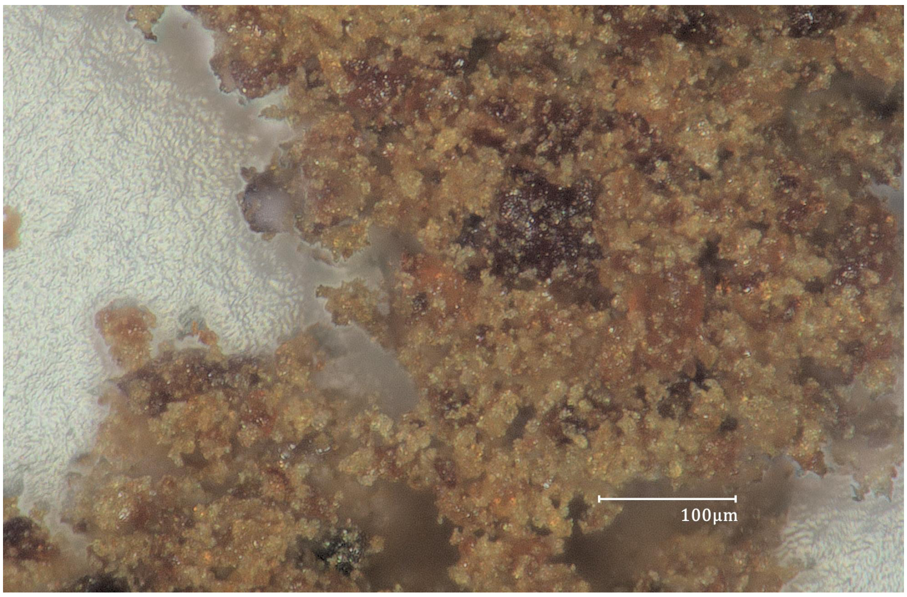
Particle size mixture
The almond shell filler really stands out, these particle sizes are more than twice as big compared to the recycled fillers. The almond shell filler has some different filler sizes, some particles are quite big. While the recycled fillers are much smaller. The cutting mill used for cutting the recycled filler, has a final fineness of < 50 µm. Since the recycled fillers have a smaller practice size, it has a bigger total surface area which can bind with the resin.

Colours
The main difference in colour is seen between the almond shell filler and the recycled fillers. Since the recycled filler are made from furan, almond shell filler and some additives. The colour is darker compared to the almond shell, since the furan is cured really dark brown, almost black.

Within the recycled filler, both NEW, OUT and QUV are different colour variations are seen. In the recycled fillers some agglomerate of furan resin is seen and some lighter parts. The cured furan parts that are inside the filler, could have difficulty binding with the furan resin.



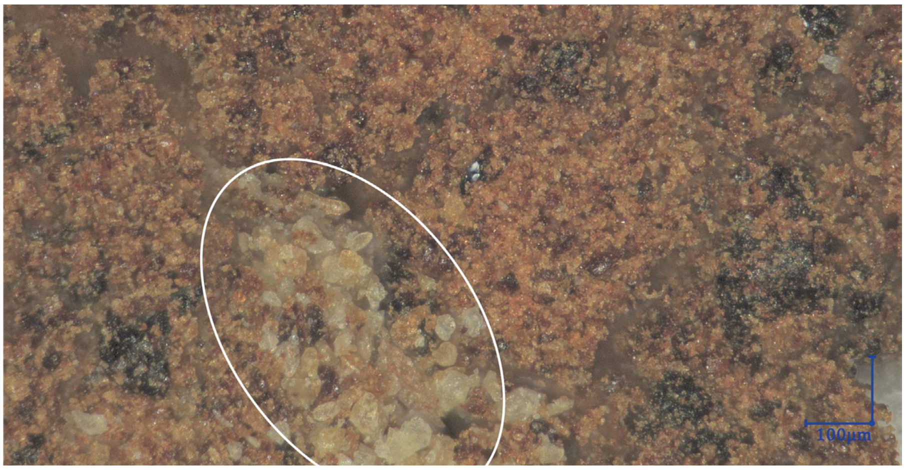
Recycled filler outside x500



Recycled filler QUV x500

4.3.2 Filler Particles

Sieving issues
While sieving the fillers the particles stick together and form agglomerates. This made it difficult to estimate the particle size of each filler. In the microscopic photo's a rough estimation can be made.



Recycled filler new, with almond shell x250

Discussion & Conclusion
The main take away from this microscopic analysis of the fillers is that the almond shell filler a much bigger particle size has compared to the recycled filler. This can be explained because of the manufacturing method of recycling. Since the recycled fillers have a smaller particle size, they will have a larger surface area. Keeping this in mind it is expected that less filler is needed to bind with the resin. However, the recycled filler also show that they are not as homogenous as the almond shell filler. The photo's clearly show the different material components inside in the recycled filler. Especially the cured furan particles tent to stick together, which could be an issue when mixing together with the new resin and additives.

These two findings contradict each other, so this will be examined further in the next phases.

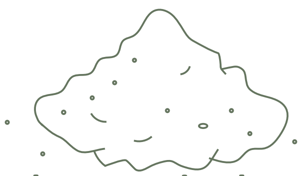
4.3.3 Discussion & Conclusion

Analysing the fillers resulted in some interesting findings, these results give more insight into the filler material properties. Even though the density testing was not very precise due to the testing method, a comparison between the fillers could still be made. As expected the recycled filler had a lower density, because the filler was made half out of furan and this has a lower density compared to almond shell filler.

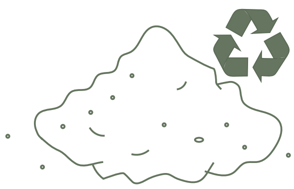
During the microscopic analysis, this became clear that the recycled filler had a smaller particle size compared to the almond shell filler. It became also clear that the recycled filler was not that homogeneous, a clear distinction could be made between the different components inside the fillers. The smaller particle size would suggest that the filler has a bigger surface area so bond with the resin. Which could mean that less filler is needed to make a new composite.

This leads to some contradicting findings between the particle size and materials homogeneity, which still needs to be investigated further in the next phases.

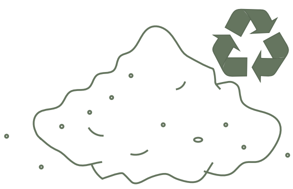
PHASE 2



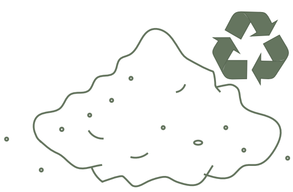
Almond Shell



NEW



OUT



QUV

4.4 Phase 2

Phase 2 is split into two parts, the first part researches the difference between used almond shell filler and recycled filler from newly manufactured furan bio composite panels. The second part researches the influence of weathering the panels before recycling them into filler for new bio composites.

4.4.1 Making sample procedure

For all fillers and ratios in this phase the same manufacturing procedure was used:

Step 1: Dry filler
The almond shell filler is dried on a tray in the oven at 110°C for approximately 2 hours, to remove any moisture that is still remaining. Before adding the filler to the mixer the moisture is checked with the moisture meter.

Step 2: Measuring the ingredients
First the wet materials are measured in measuring cup by weighting them on a scale. All materials are weighted in their own cup. The filler is measured just before adding it to the mixer.

Step 3: Adding liquids to the kneader
The resin is added to the kneader and mixed for 15 minutes, the kneader is heated to 95°C to make mixing easier. After 15 minutes the catalyst is added to the kneader and mixed with the resin for 5 minutes. The last liquid ingredient is added and mixed for 5 minutes.

Step 4: Adding filler to the kneader
After all the liquid ingredients are mixed in the kneader, the filler is added in two parts. This takes around 6 minutes of mixing in total. After everything is mixed properly, the dough is taken out of the kneader.

Step 5: Moulding
The bulk compression moulding machine is pre heated to 150°C, before adding the dough in the mould. The mould is brushed with oil, so the panel can be easily released from the mould. The dough is placed into the mould and cured under 150°C with 80 bar pressure for 15 minutes.

Step 6: Cooling
The panel is cooling under a weight to limit deformation during cooling.

Step 7: CNC-milling
After the sample plates are cooled down, the plates are placed into the CNC-milling machine to get the test specimen for 3 point bending test and the impact test.

4.4.2 Testing protocols

In the subphases A & B all the samples have been tested on their mechanical and functional properties. These tests were performed with the end application in mind, to see the possibilities of recycling bio composites and their usability.

The materials properties were tested on the following:

- Flexural strength
- Impact resistance
- Weathering resistance
- Surface texture and appearance
- Defects

Preparation of Specimen
The sample plates of the different recipes were cut with the CNC mill to two sizes of specimen, as shown in figure 33.

The specimen were tested according to standards. For flexural strength the standard ISO 14125A and the impact test ISO 179 were used to cut the right amount of specimen.

Another size specimen is needed for the QUV, water absorption, frost resistance. These specimen need to fit in the QUV machine slots. A larger surface area is needed to analyse the weathering.

During cutting of these sample plates into specimen for testing, some of the specimen were not cut completely, so the excess pieces had to be removed by hand.

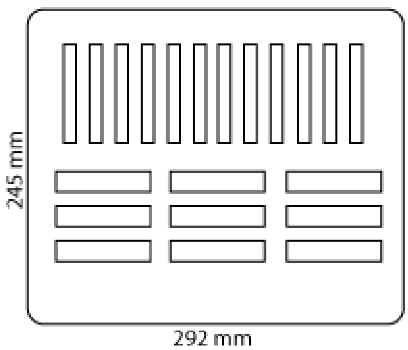


Figure 33. Specimen mechincal properties cutting out of sample plate

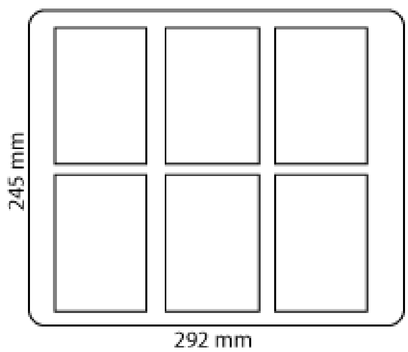


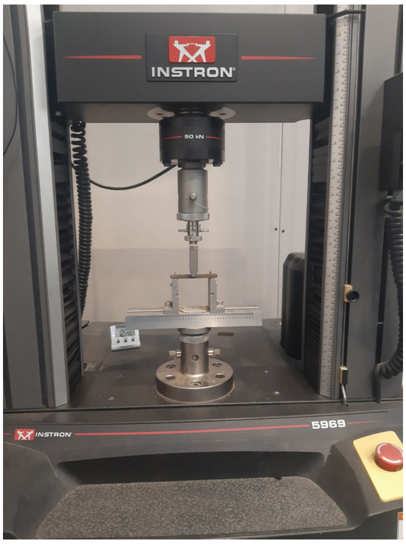
Figure 34. Specimen QUV cutting out of sample plate

4.4.2 Testing protocols

Three point bending

Procedure
Before starting the tests, the temperature and humidity are noted and entered into the system. The specimen samples are weighted and measured with a scale and calliper. The specimen is placed on the 3 point bending setup, where they are bent until fracture. For this test at least 5 to 9 specimen samples are tested on a universal testing machine, depending on the material loss during CNC milling.

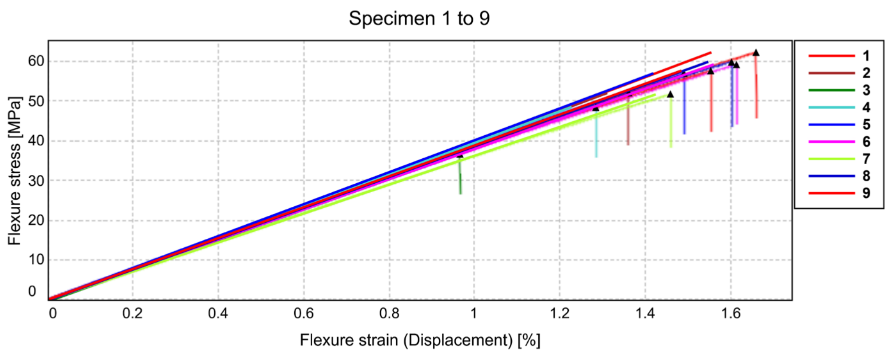
Sample Size: 5mm x 15mm x 80mm
Equiptment: Instron 5969 testing system, scale, electronic calliper



Instron 5969 testing system

Measuring with electronic calliper

Measurements
The universal testing machine gives a deadline report on all tested specimen of the same material, such as deflection, flexural modules, strain and flexural strength and modules.



Graph 1. Stress and strain diagram of RF_NEW_55

Observations
Furan is a brittle material, so when the material is bended until facture the specimen breaks completely and fly away. Also edge defects can have an influence on the strength of the material. If the specimen samples were not cut completely with the CNC, it could have an influence on the mechanical properties.

4.4.2 Testing protocols

Charpy Impact test

Procedure
Before starting with the impact testing, the Charpy Impact machine needs to be calibrated to find the correct results. The Charpy pendulum is swung 10 times and the angle is noted, to get reliable results for the swinging angle without any specimen. This test calculates the amount of energy absorbed by the specimen when hit with the pendulum. The first step in the testing cycle is measuring the thickness and the width of the specimen. The specimen is then placed on the testing stand and the pendulum of 1 joule is released. The swinging angle the pendulum made is noted and later calculated to the absorbed energy. To test according to the standard at least 10 specimen need to be tested.

Sample Size: 5mm x 10mm x 80mm
Equiptment: HY4251 Charpy impact tester & electronic calliper

Charpy impact machine

Fractures of impact

Measurements
The swinging angle measured from the Charpy Impact machine can be calculated into energy (J) and Charpy Impact (kJ/m2). This is done with the following formulas:

$$\text{Charpy Impact} = \frac{\text{Absorbed energy}}{\text{Smaple cross section}}$$

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

Observations
Just like with the bending test also in the Charpy Impact test all specimen fractured. The fractures did differ from each other. Some of the pieces fractured into two parts, while other fractured into three of more pieces.

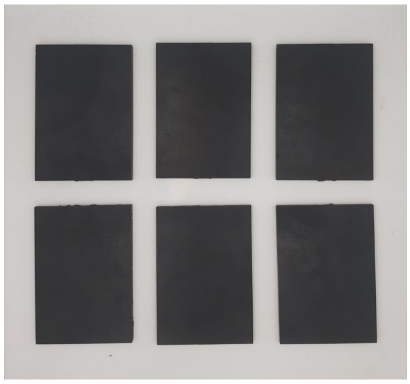
4.4.2 Testing protocols

QUV weathering test

Procedure
The QUV machine has spots for small samples 8 samples of 4 different fillers are placed into the QUV for 3 weeks. Since this is an accelerated weathering machine the samples are thus exposed to 6 months of weathering conditions. The samples are cut with the CNC milling machine.

Sample Size: 75mm x 100mm
Equiptment: Q-LAB, QUV - Accelerated Weathering Tester

QUV - Accelerated Weathering Tester


Samples for weathering machine

Measurements
The QUV samples are photographed before and after the testing cycle of 3 weeks. The visual texture and discolouration are analysed and measured.

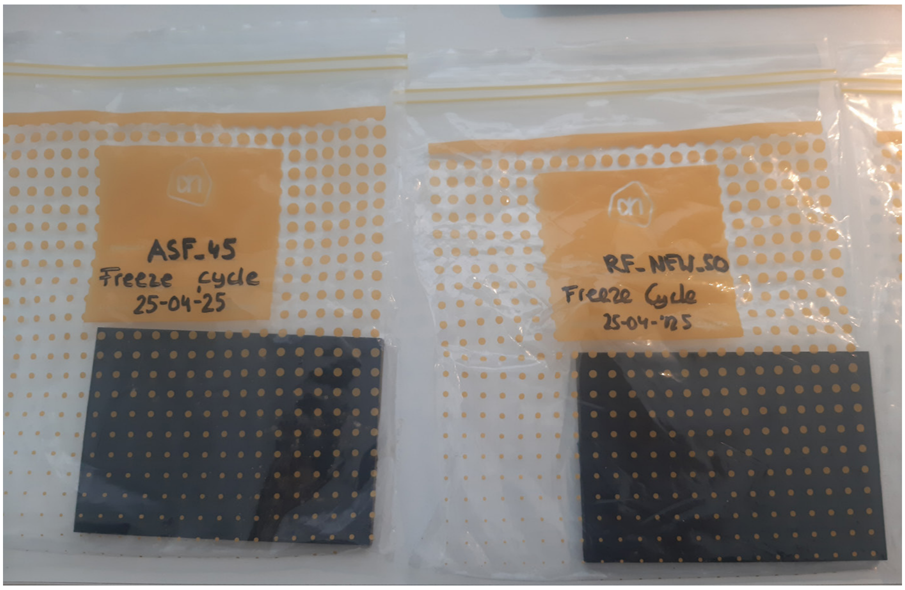
Observations
The machine is emitting solar radiation and heat to accelerate the weathering of the materials. When checking on the materials, it is noticeable that the samples are hot. After 2 weeks in the QUV the samples did not show a lot sign of weathering, only some watermark spots.

4.4.2 Testing protocols

Frost resistance

Procedure
For this testing procedure 1 sample of each recipe will be used. The samples are weighed before every cycle. The samples are placed inside an individual zip lock bag, which are placed inside the freezer at -18 °C for a period of 8 hours. After 8 hours the samples are thawed outside the freezer in around 18 °C (room temperature). This cycle is repeated for 10 times.

Sample Size: 75mm x 100mm
Equiptment: Freezer, plastic bags, scale



Test set-up for frost resistance

Measurements
The samples are weighed before the experiment and after all the test cycles to note the changes in the weight. The samples are photographed after the test cycles next to an untested sample of the same material. The samples are analysed on the change in texture, crack and bumps after the freezing cycles.

Observations
After the 10 test cycles were completed the samples were analysed on bumps, deformations and cracks. All samples show a little deformation due to the freezing and thawing. Comparing them to reference samples that haven't been used in a test, shows that some of these samples have a bit of discoloration or spots on the surface.

4.4.2 Testing protocols

Water absorption

Procedure
Each material provides two samples that are tested on water absorption. First the samples are put into the oven for 2 hours at 90 °C to fully dry the samples. Each sample is weighed to get the dry weight and submersed in water in small containers. After 24 hours the samples are measured again after being dried with a towel. This is then repeated every 24 hours until the samples are fully saturated.

Sample Size: 75mm x 100mm
Equiptment: Freezer, scale

Test set-up for water submersion

Measurements
The average of the two samples is taken for each material. The water absorption is determined by the difference in weight, calculated to a percentage.

$$\text{Water absorption [\%]} = \left(\frac{W_w - W_D}{W_D}\right) * 100$$

W_w: Wet weight; W_D: Dry weight

Observations
Measuring the weight of the sample was done with a scale that measured every gram, but this measurement is not precise enough to draw any conclusions on the water absorption. However this test can still be used to test the materials behaviours when exposed to water for a long period of time. A rough estimation of the water absorption can be done comparing the dry weight to the heaviest the sample was during that time period.

4.4.2 Testing protocols

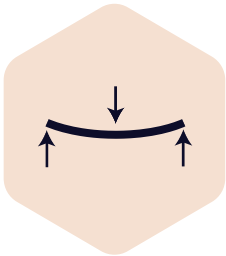
Bending fractures

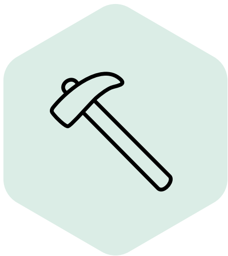
Procedure
The 3 point bending fractures and impact of the tested specimen were analysed with the digital microscope, Keyence VHX-7000.

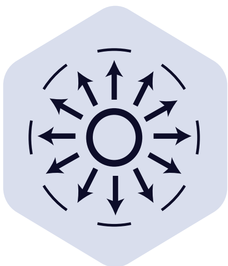
Measurements
The photos taken by the microscope were analysed, looking at the texture and different patterns of the facture. The microscope was used to zoom in 250x and 500x to get an overview of the sample and a more detailed part of the sample.

Test set-up for bending fractures

Observations
The samples were illuminated with a spotlight to expose all the parts of the sample. However the operator of the microscope did not use the same settings each time, which let to different colour lighting and angles. This made it sometimes difficult to compare to each other.







4.4.3 Comparison methods

After each material sample is tested with the previous mentioned methods, the samples are compared to each other by using a grading system. This grading system is explained in table 7. This grading system, creates a scale for each property test result. The flexural strength is graded based on a range between 0-80 MPa, where below 40 MPa the material is very weak. The impact resistance is graded based on scale range from 1-6 kJ/m2, the higher the number the more resistant the material is. Workability and durability grading are more based on my own observations and experience when working with the materials. Workability can be explained by the ease of handling the materials in the process of manufacturing. This is measured by the texture and consistency of the dough, the more sticky and liquid the dough is the more difficult the material is to work with. If the material is drier and crumbly it is easier to work with.

The durability of the samples is tested through three tests where the average is used as a base line. In these tests the samples are exposed to 'extreme' weather conditions to see if there are any visible changes in the surface texture or colour of the samples.

Table 7. Grading system (own)

Evaluation scale	1. Flexural Strength (MPa)	Resistance (kJ/m^2)	3. Workability	4. Durability
	Scale 0-80	Scale 1-6	Scale 0-5	Scale 0-5
	0 = 0-16	0 = 1-2	0 = liquid not workable	0 = total destruction
	1 = 17-32	1 = 2-3	1 = thick liquid	1= cracks and all of above
	2 = 33-48	2 = 3-4	2 = super sticky	2= deformation
	3 = 49-64	3 = 4-5	3 = sticky	3= visual change (coloration)
	4 = 65-80	4 = 5-6	4 = thick crumble (a bit sticky)	4= minimal visual change
	5= 80	5= 6	5 = crumble	5= no visual change

PHASE 2A

4.5 Phase 2A - Recycled vs Almond shell

4.5.1 Samples

The bio composite materials are fabricated in a sample sheet format that have the dimensions of 245 x 292 mm.

Filler types:

- ASF: Almond shell filler , which is currently used in the base recipe of NPSP.

- RF_NEW: Recycled filler of sample plates that have been newly manufactured and recycled right away.

The naming of the samples is structured as the following:

“RF_NEW_50”

Filler type — State of recycling — Filler load (w%)

In Phase 2A the following samples were produced and tested:

- ASF_45
- ASF_50
- ASF_40
- RF_NEW_50
- RF_NEW_55
- RF_NEW_45

In this phase three different ratios of Recycled filler panels are compared to three different ratios of Almond shell filler.

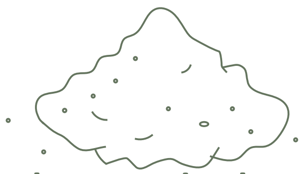
The following wight ratios were used:

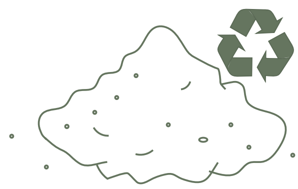
Table 8. Almond shell bio composite filler (ASF)

Composition / grain size	<125 µm
45w%	ASF_45
40w%	ASF_40
50w%	ASF_50

Table 9. Recycled bio composite filler (RF-NEW)

Composition / grain size	<50 µm
50w%	RF-NEW_50
55w%	RF-NEW_55
45w%	RF-NEW_45


Almond Shell


NEW

4.5.2 Process changes

Mixing:
For the first testing with the recycled filler, the right ratio needed to be found. Three different doughs were made. The first one was a test dough where the filler would be gradually added to see the reaction with the resin. This was done the make sure the dough was not too difficult to take out of the mixer. First only 100 grams of recycled filler was added to the mixture, this was far too little for the composition. The mixture was still too wet to work with. More filler was added in 3 steps, until the texture of the dough was similar to the texture of base recipe of ASF_45. This is now referred to as RF_NEW_50, so 50wt% recycled filler was added to the matrix.

Pressing:
The different recipes were pressed in the BMC machine. The first plate was cracked when opening the machine after 15 minutes. After checking the temperature of the moulds it was discovered that it was 5 degrees too high. The temperature was reduced 5 degrees to avoid this from happening again.

4.5.3 Observations

Mixing:
Comparing the colour of the dough with recycled filler showed already a much darker brown colour than the almond shell filler doughs. Another observation was the consistency of the dough. The recycled filler dough was far more sticky compared to the almond shell filler dough.

Changing the ratios between the filler and resin showed different amount of stickiness or dryness. The RF_NEW_45 was much more sticky and compact which made it not really workable. While the ratios of RF_NEW_50 & RF_NEW_55 were more dry, this made it more comparable with the 'original' recipe with the almond shell. The workability of these two doughs was a lot better compared to the RF_NEW_45 dough.

Mixture 50wt% RF (RF-NEW_50)

Mixture 50wt% ASF (ASF_50)

Mixture 45wt% RF (RF-NEW_45)

Mixture 45wt% ASF (ASF_45)

4.5.3 Observations

Pressing:
Due to too high temperatures of the mould, one plate cracked. The dough is pressed for 15 minutes, the combination of heat and pressure helps liquify the resin, which can then flow to all the parts in the mould. However some of the plates showed some signs of defects in the corners of the plates. This meant that the flow or distribution of the dough is not sufficient enough. This could have led to the cracks and defects.

Observations CNC milling:
During the CNC-milling of the plates, the recycled filler plates were more brittle than the almond shell plate (ASF). These plates produced a lot more dust and small bits compared to the ASF. Also when taking the samples out of the frame the ASF it was very easy to take out with the pliers, but the RF samples were much harder to get out. While breaking the specimen from the sample plate the edges of the specimen could have been impacted. Looking at some of the specimens that where not completely cut by the CNC machine a difference in colour and texture could be noticed.

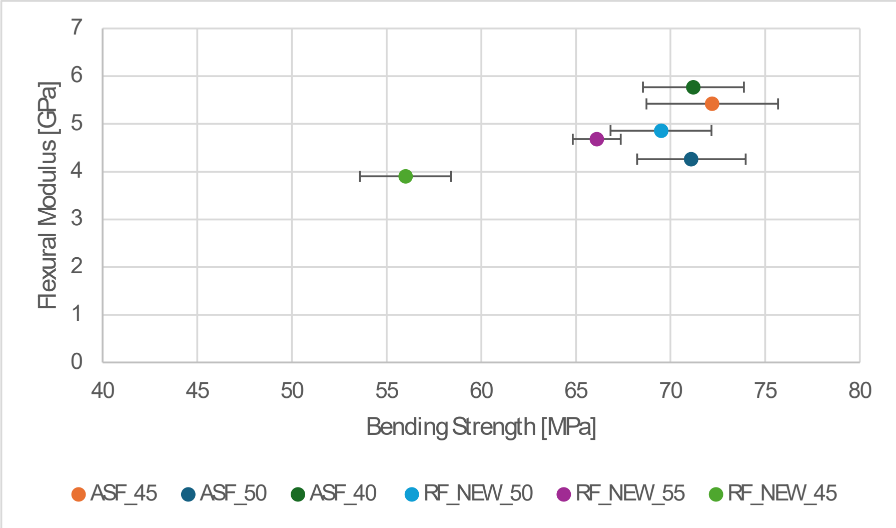
CNC milling sample plates for testing

Sample plate with CNC specimen

4.5.4 Results

Flexural strength

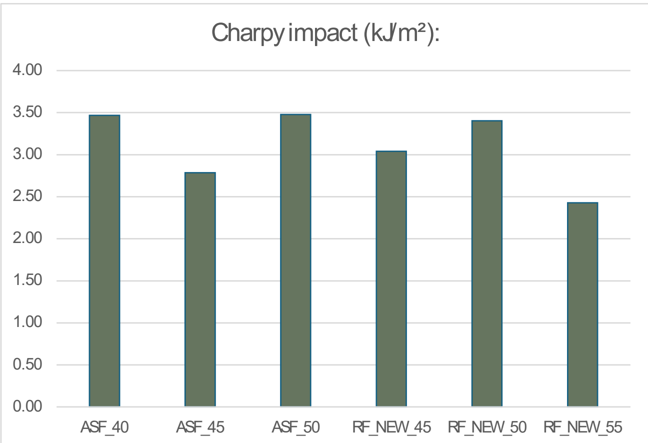
The flexural strength of all the samples is in the range of 55-75 MPa. The previous results of the Almond shell filler with 45wt% (ASF_45) were around 80 MPa. All the results are quite clustered and similar, the only results that were much lower was for the RF_NEW_45, which had a flexural strength below 60 MPa and a flexural modulus. Based on this observation, it was decided that all the samples above 60 MPa will be used into the next phase.



Graph 2. Results bending strength testing

Impact strength

The impact testing showed that all the samples were brittle fractures. The results show that using 50wt% of filler in both cases is the best resistance against impact. The differences between the samples is not that high. Also interesting to see is that there is not a trend between adding more or less filler to the resin, for in the impact resistance it does not really matter.



Graph 3. Results impact strength testing

Name sample	Bending strength (mean)	Bending strength (S.D.)	ƒk (bending strength)	Flexural modulus (mean)	Flexual modules (S.D.)	Charpy impact (kJ/m^2):
ASF_45	72.2	6.94	60.82	5.42	0.13	2.79
ASF_50	71.1	5.73	61.70	4.26	0.16	3.48
ASF_40	71.2	5.33	62.46	5.77	0.2	3.47
RF_NEW_50	69.5	5.34	60.74	4.86	0.13	3.40
RF_NEW_55	66.1	5.45	57.16	4.68	0.22	2.43
RF_NEW_45	56	4.8	48.13	3.9	0.1	3.04

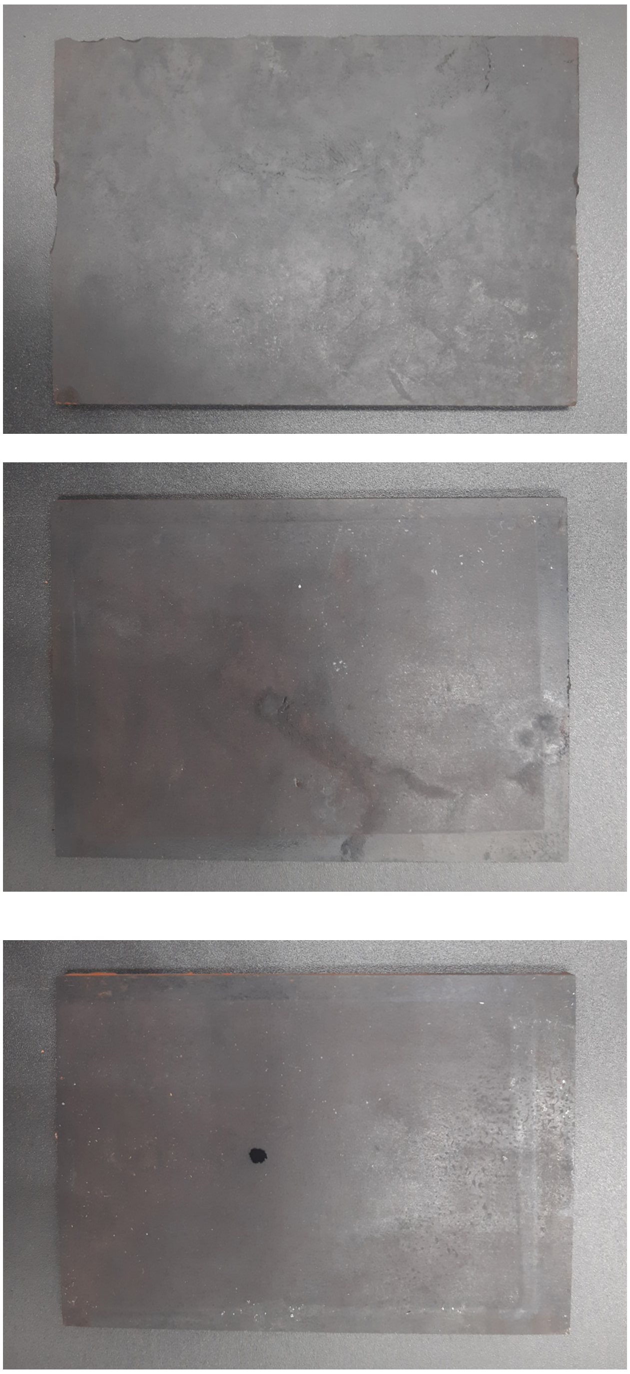
Table 10. Results mechanical testing

4.5.4 Results

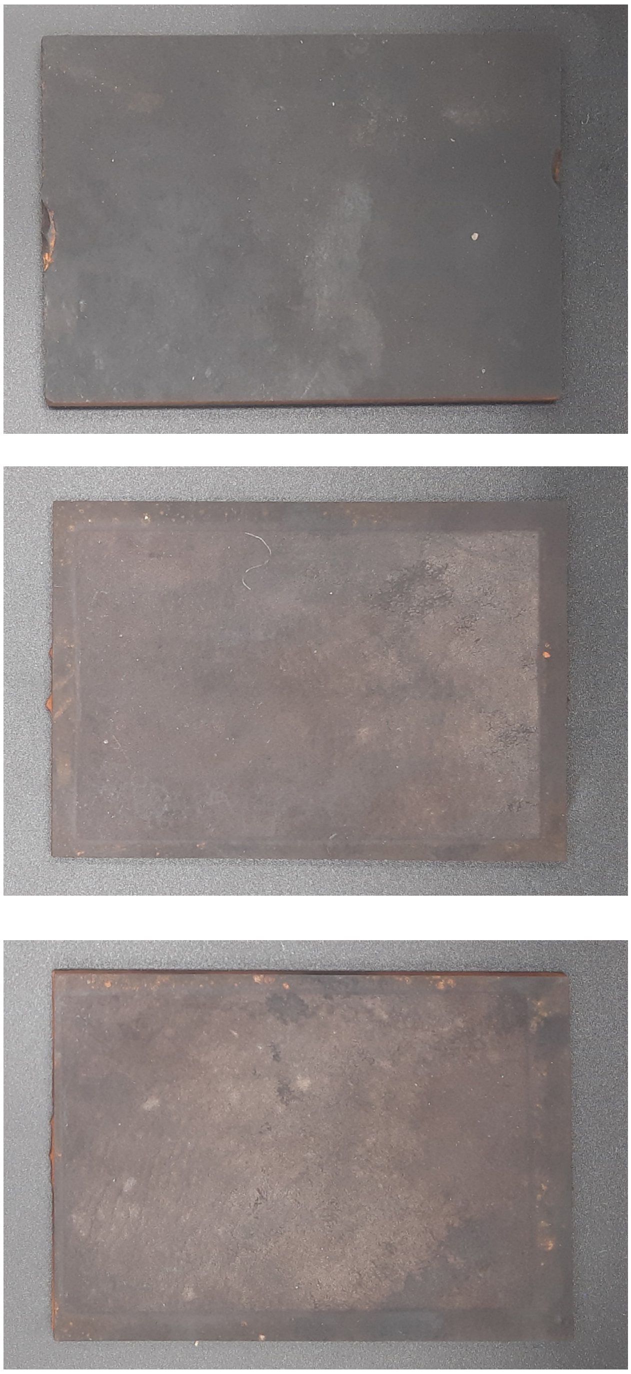
QUV

Both the ASF_45 & RF_50_NEW samples were put into the QUV weathering machine. The samples were compared to a reference sample from the same plate. This shows the weathering of these samples. Looking at the RF_NEW_50 it shows a slight discoloration of the sample. Still some condensation marks are visible on the surface.

Looking at the ASF_45 samples that we placed in the QUV for 3 weeks, they show clear signs of discolorations. The surface has a lot of spotting. The texture looks more rough compared to the reference sample. These visible changes suggest that the durability of this materials is not that good.



Above: Reference RF_NEW_50
Below: QUV sample RF_NEW_50



Above: Reference ASF_45
Below: QUV sample ASF_45

4.5.4 Results

Frost resistance

Comparing the frost resistance of the almond shell filler to the recycled filler showed some interesting results. The ASF sample showed some signs of colorations and spots, while the RF_NEW didn't show a lot of spots or that is affected. In this test the RF_NEW comes out as best performing sample.

Above: Reference RF_NEW_50
Below: Frozen sample RF_NEW_50

Above: Reference ASF_45
Below: Frozen sample ASF_45

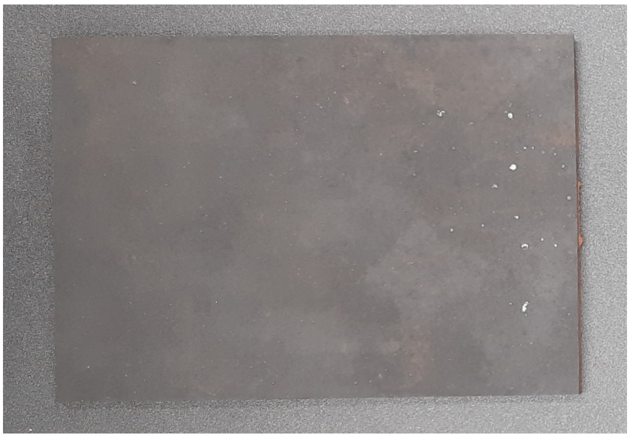
4.5.4 Results

Water submersion

Over the time period of 28 days the samples were submersed in water and weighted every 24 hours to see the water absorption of the samples. Looking at the samples of the RF_NEW_50, they show small signs of discoloration, but the differences are minimal.
ASF_45 samples show some white spots due to the water submersion. The surface texture is overall not that different from the reference sample.








Above: Reference RF_NEW_50
Below: QUV sample RF_NEW_50

Above: Reference ASF_45
Below: QUV sample ASF_45

4.5.4 Results

Discussion

The test regarding QUV, water absorption and frost resistance were only performed on the best mechanically performing samples. This was due to the limited amount available of recycled filler material. Testing the other ratios, RF_NEW_45 & RF_NEW_55 on durability would have been insightful to see if the filler content would have an influence on the durability of the material. This choice that was made could have excluded well performing samples that could have been performing overall better than the tested samples. However, since mechanical strength is an important property of a façade panel this was a risk I was willing to take.

For the almond shell filler, it would not make a huge difference since the ASF_45 is the recipe NPSP already uses. They already have tested multiple options to find the best performing recipes, keeping in mind various requirements for façade panels. However testing all the samples I would have set a base line of data that was acquired with the same method. This could have given more information of the effect of filler load on the durability properties on the base recipe.

Some of the mechanical testing was repeated since the results were not in line with previous tests of the same material. This gave a more precise overview of the materials properties.

The ratios for the recycled filler were chosen based on my own observations during mixing of the first dough and the existing data used from NPSP.

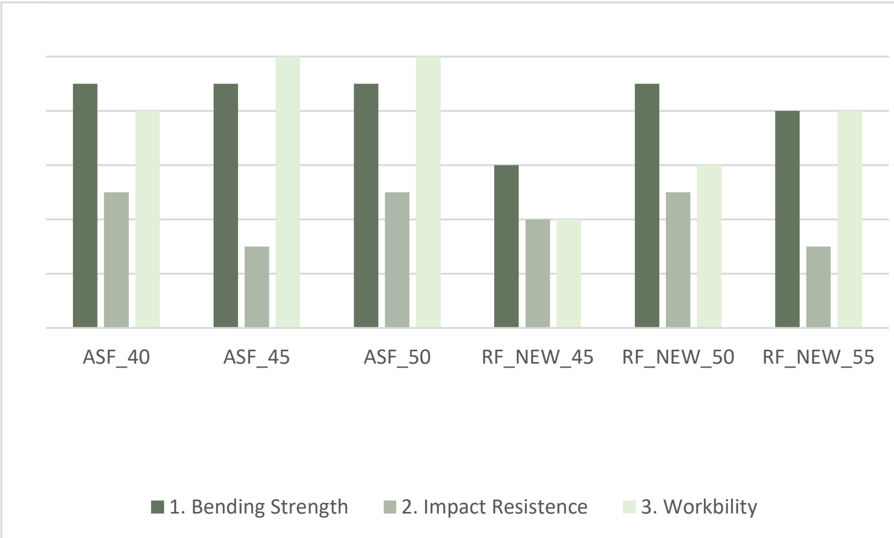
It would be very interesting to research the combination of ASF and RF_NEW to see how the mechanical properties of this combination perform. This would bring a combination of different size range of particles as well as still keeping a higher level of sustainable recycled material. It could also improve the durability of the base recipe by adding the recycled filler.

4.5.4 Results

Conclusion

Comparing the recycled filler to the almond shell filler, shows that there is potential in the use of recycled filler. The mechanical properties are a little bit lower, but still within the range that is acceptable, above 60 MPa. Looking at the impact resistance all recycled filler ratios perform less than the almond shell filler, but the RF_NEW_50 comes close to the almond shell ratios. Looking at workability the doughs is still relatively easy to work with. Compared to the almond shell the dough is a bit more sticky, but that can harden after a few days.

In graph 4 a comparison between the filler ratios and test results is shown, which gives an overview of the potential of the recycled material. For the next step the best two ratios of the recycled filler will be used in the weathered filler testing. For the recycled fillers those ratios are 50wt% and 55wt% filler.



Graph 4. Comparison between filler properties

PHASE 2B

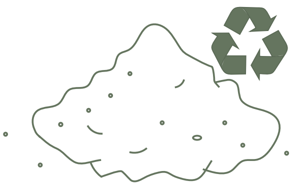
4.6 Phase 2B - Weathered recycled fillers

Phase 2B focuses on comparing the recyclability of two different types of weathered panels. Both panels are weathered naturally and artificially.
The first panel is a panel that hanged outside for 6 months before removing and recycling it into filler. This panel was placed on the south side of the building, where it would be exposed to the highest amount of sun.
In figure 35 is shown how the panel was mounded.

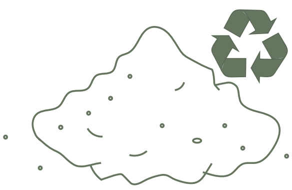
Figure 35. Furan panel placed on the south façade.

This panel already discoloured significantly during these 6 months. Since the panel was only attached with 2 bolts, the panel also deformed quite much. These observations show the degradation of the panels.

The second recycled filler was made from plates that were put into the QUV, an accelerated weathering machine that can expose samples in 3 weeks.



OUT



QUV

Figure 36. Plates placed in weathering machine for 3 weeks

4.6.1 Samples

The bio composites are fabricated in sheet format with the dimensions of 245 x 292 mm with 450g of dough, which results in a plate of about 5mm thickness.

Filler types:

- RF_OUT: Recycled filler of façade panel that has been outside for 6 months.

- RF_QUV: Recycled filler of sample plates that have been in the QUV weathering machine for 3 weeks.

In Phase 2B the following samples were produced and tested:

- RF_OUT_50
- RF_OUT_55
- RF_QUV_50
- RF_QUV_55

In this phase a choice was made to only make two different ratios of the recycled filler, 50wt% and 55wt%.

The in phase 2A tested ratio 45wt% filler showed poor workability and mechanical properties. Because of this in combination with the limited amount of filler it was decided to excluded this ratio from this and further testing phases for recycled fillers. Out of experience the workability is really important, since this determines the material loss during production as well as distribution of the dough in the mould, is could lead to a better performing product.

The two different ratios of 6 months old recycled filler panels and the artificial weathered recycled filler are compared to the recycled filler panels and the almond shell filler panels from phase 2A.

Table 11. Recycled bio composite filler ("6 months exposed outside") (RF-OUT)

Composition / grain size	<50 µm
50w%	RF-OUT_50
55w%	RF-OUT_55

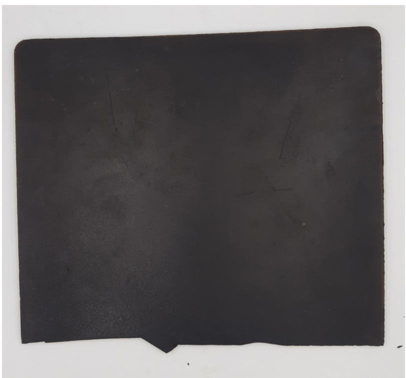
Table 12. Recycled bio composite filler ("3 weeks exposed QUV") (RF-QUV)

Composition / grain size	<50 µm
50w%	RF-QUV_60
55w%	RF-QUV_55

4.6.2 Process change

Since the RF-OUT was recycled from a façade panel of 60cm x 60cm the procedure took a bit longer than with the smaller test plates. The façade had to be hammered in two rounds to get small enough pieces for the shredder. As shown below the process of hammering.

Before recycling the plates, the plates were placed in the QUV weathering machine to speed up the weathering process. This had a lot of effect on the plate’s warping and discolorations.



4.6.3 Observations

Grinding & shredding:
RF-OUT was a full façade panel which had to be hammered down to smaller pieces. This process was quite easy, since the 3D shape makes it easier to break. After hammering the pieces where shredded into smaller bits and milled into powder.

RF-QUV panel were warped during the time in the QUV, also a bit off decolouration already happened. Breaking these panels into smaller pieces with the hammer was easier than the panel in phase 2A.

This process was time consuming due to the limited amount of material that could pass through the shredder and mill at once. **If recycling these materials is going to happen on a large scale a more efficient and sufficient method is needed to ensure a speedy process.**

Mixing:
For both fillers two recipes were made, with 50% and 55% weight of the fillers.

RF_OUT_50 and RF_QUV_50 dough was similar to mixing with the RF_NEW filler, the doughs came out quite sticky. This made these recipes less workable. The doughs could be taken out of the mixer, but it took more time and they left some residue behind in the mixer.
RF_OUT_55 and RF_QUV_55 doughs were a lot more crumbly and easier to handle. These doughs were a lot more workable compared to the 50wt% doughs.

What is interesting is that the workability of the weathered recycled filler OUT compared to the newly recycled filler is different in the same filler load.

Before making the RF_QUV doughs the mixer was cleaned, so no furan layer was left on the blades and inside walls of the mixer. This layer was working as an insulation, so the mixture would get less heated. After removing it the mixture would get much more heated. This could have had effects on the results.
Mixing in larger batches will be even more time consuming, so proper equipment is needed to manage this type of dough mixing. Also keeping in mind that if dough is left behind in the mixer, because of its stickiness cleaning the mixer is more time consuming. This is not ideal in the optimization of the process.

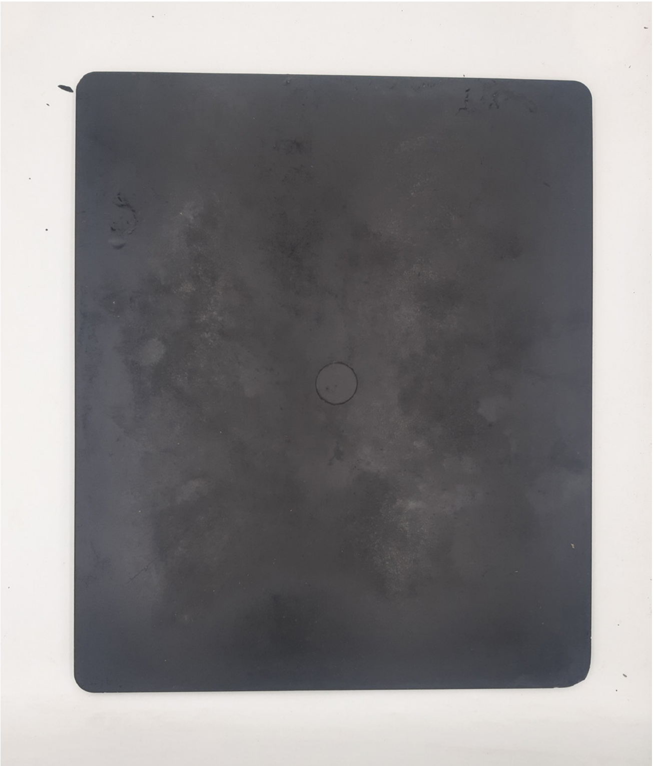
RF_OUT_50

RF_OUT_55

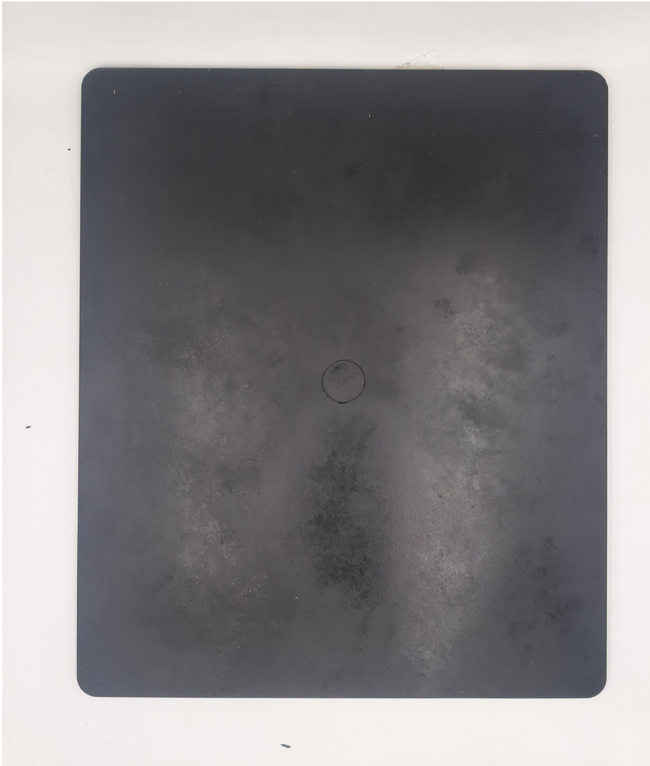
4.6.3 Observations

Pressing:
RF_OUT pressing both plates was easy and during pressing the dough flowed to each place in the mould. The doughs were both easy to spread around in the mould. This could be an important factor in the flow especially when there is a higher filler load.

RF_QUV pressing was also easy but there were some inconsistencies in the plate, the dough did not reach all the corners of the mould.



RF_OUT_50



RF_OUT_55

RF_QUV_50

RF_QUV_55

4.6.4 Results

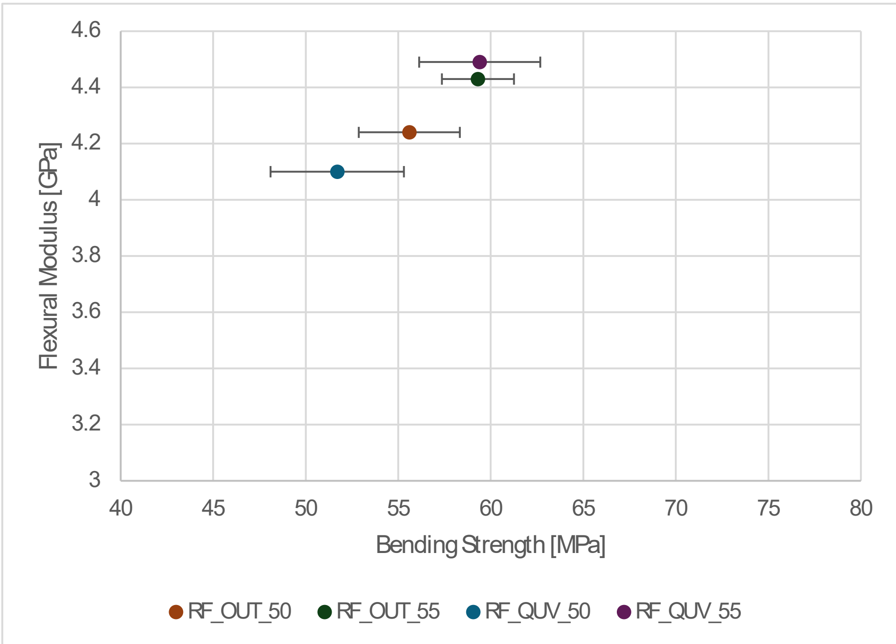
Flexural bending

RF_OUT_50 & RF_OUT_55 performed relatively good compared to the ASF and the RF_NEW fillers in the previous phase. This could be explained by the bamboo fibres that were in this panel before being mechanically shredded.

RF_QUV_50 performed much less than the other recycled filler with 50wt%. The mechanical properties were lower than expected if following the trend set by the previous samples. This could be explained by the mixing temperature, as pointed out in the observations.

RF_QUV_55 performed similar to the other 55wt% recycled filler samples. It seems the more recycled filler added to the composite the higher the flexural strength.

As seen in graph 4, the flexural strength of the weathered recycled fillers are all in the same range of 50 to 60 MPa. However the 55wt% filler has a higher flexural strength and flexural modulus than the 50wt% samples. Both the artificial and natural weather panels follow the same trendline and have almost similar results.

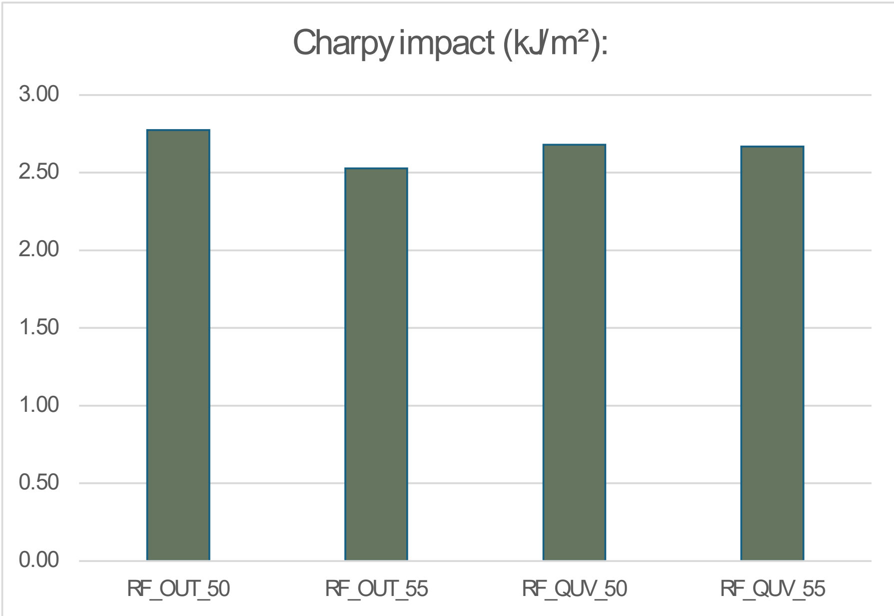


Graph 5. Results Bending strength weathered testing

4.6.4 Results

Impact resistance

Comparing the impact testing of the different samples show that all the panels have a consistent impact resistance. They are all in the range between 2.5 and 3 kJ/m2. The impact resistance is a little bit higher in the samples with 50wt% fillers. So the lower the filler load the higher the impact resistance. The differences are minimal, however the impact resistance would ideally be higher.



Graph 6. Results impact resistance weathered testing

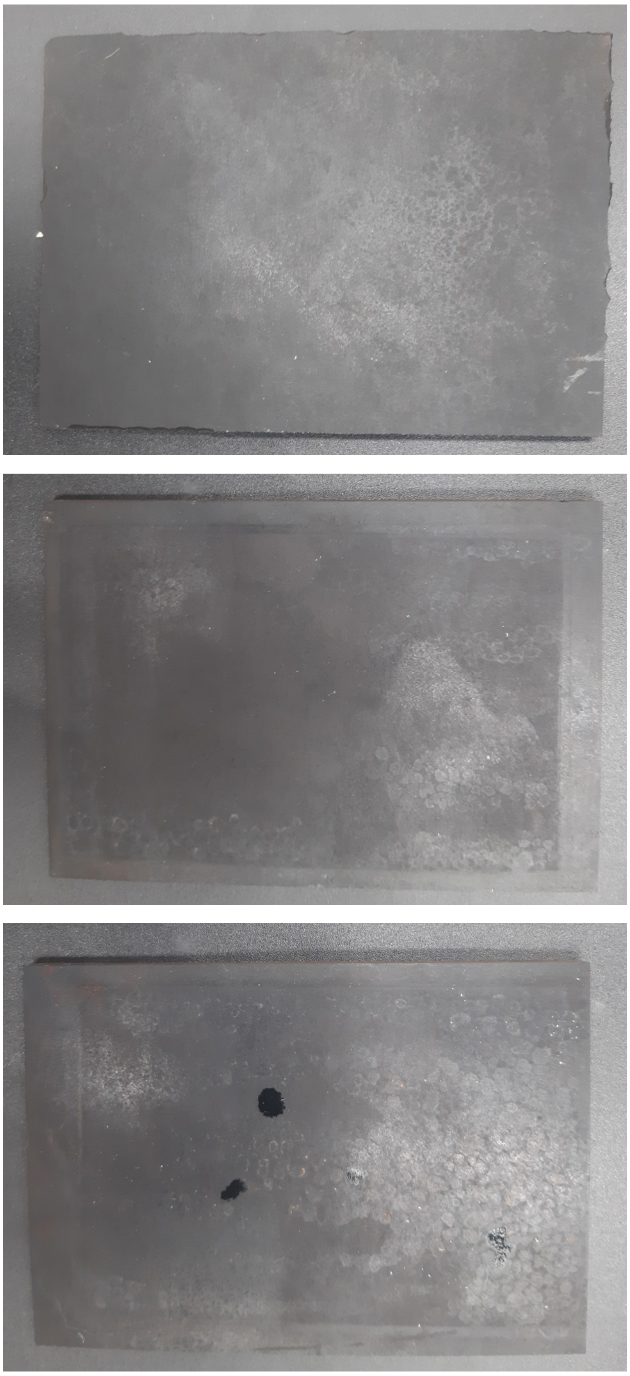
Name sample	Bending strength (mean)	Bending strength (S.D.)	ƒk (bending strength)	Flexural modulus (mean)	Flexual modules (S.D.)	Charpy impact (kJ/m^2):
RF_OUT_50	55.6	7.06	44.02	4.24	0.11	2.79
RF_OUT_55	59.3	3.89	52.92	4.43	0.05	3.48
RF_QUV_50	51.7	2.28	47.96	4.1	0.05	3.47
RF_QUV_55	59.4	2.24	55.73	4.49	0.17	3.40

Table 13. Results mechanical properties

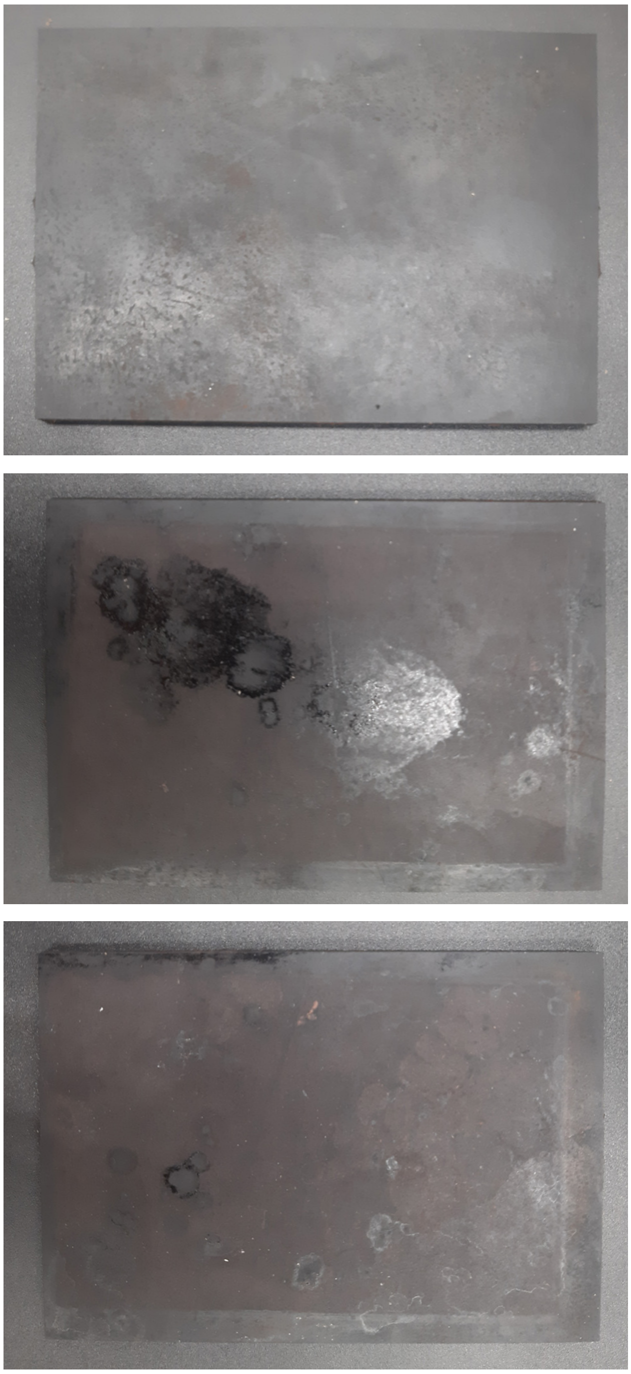
4.6.4 Results

QUV

Two different ratios of the RF_OUT were tested in the QUV. Analysing the RF_OUT_55, it is visible that the sample put in the QUV has a print of the inner rectangle. The difference is not that significant, especially when compared to the RF_OUT_55. This sample is clearly weathering, the inner rectangle is a lighter brownish colour compared to the outer edge. Also some spots of condensation are visible. The only difference between the two samples is the amount of filler load, so the higher the filler load the faster the weathering of the material.



Above: Reference RF_OUT_50
Below: 2x QUV sample RF_OUT_50



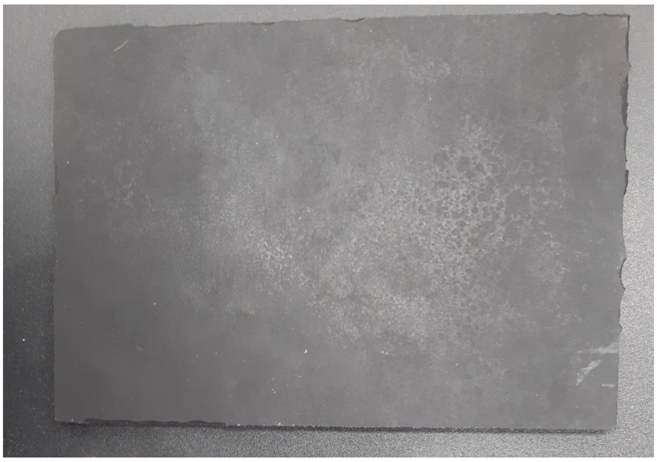
Above: Reference RF_OUT_55
Below: 2x QUV sample RF_OUT_55

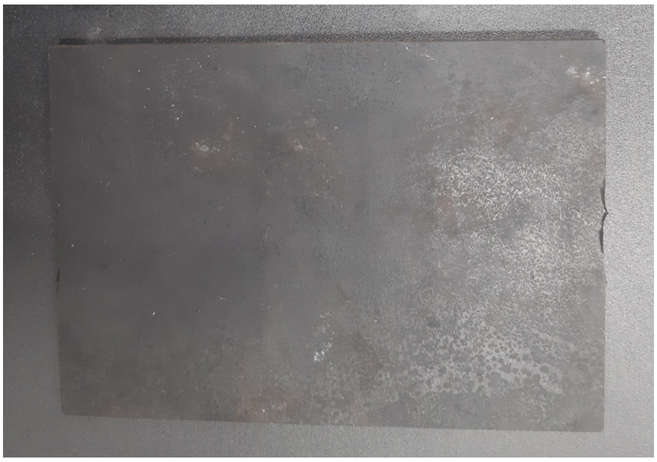
4.6.4 Results

Frost resistance

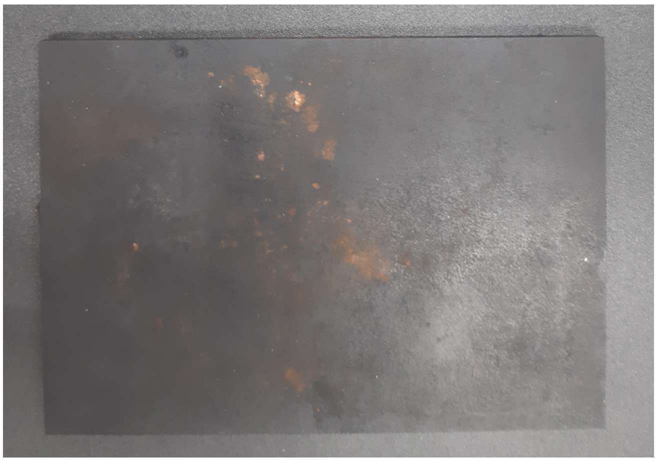
Comparing the frost resistance of the two ratios of RF_OUT showed barely any difference between the two samples. The RF_OUT_55 showed a bit more spots on the sample.

The frost resistance test show limited amount of change in the samples, it could be that the testing wasn't long enough for the effect to take place. It could be considered to elongate the test for future testing.





Above: Reference RF_OUT_50
Below: Frozen sample RF_OUT_50

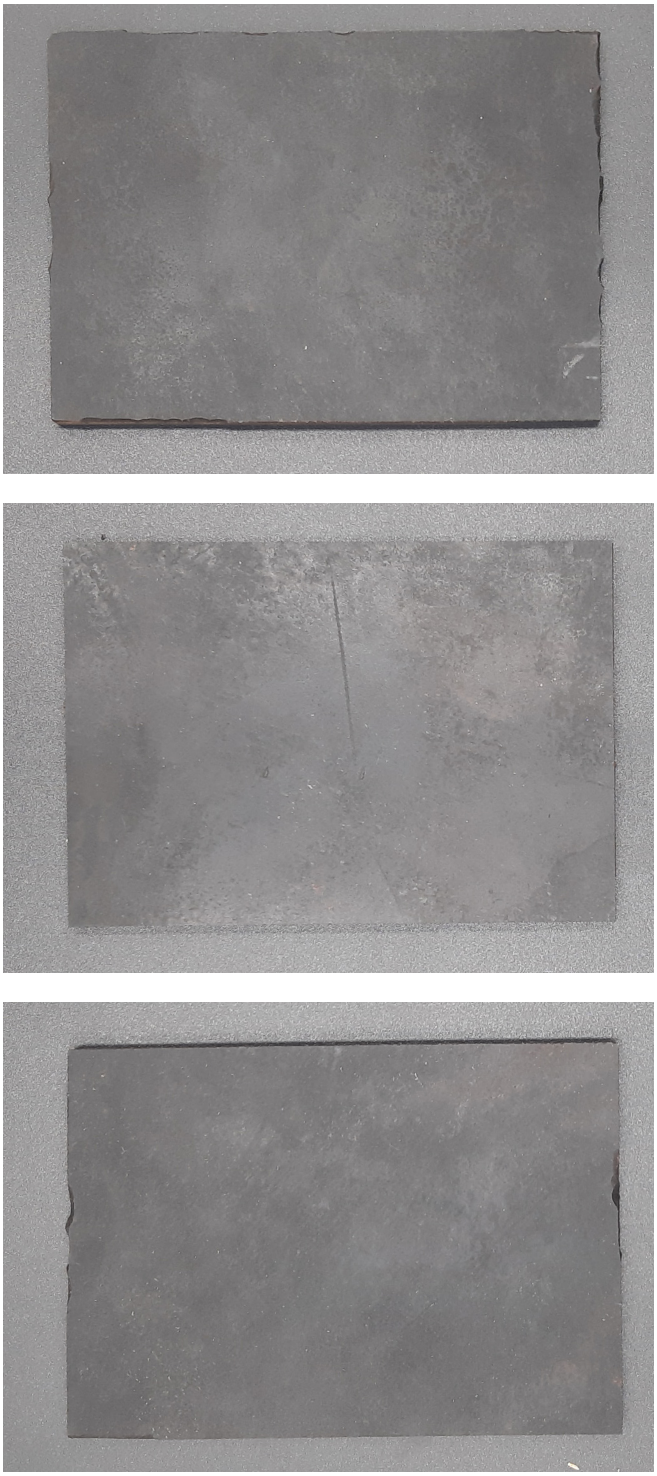


Above: Reference RF_OUT_55
Below: Frozen sample RF_OUT_55

4.6.4 Results

Water absorption

The samples from the RF_OUT_50 & RF_OUT_55 were placed underwater for 28 days to test their water absorption and durability. RF_OUT_50 just like in the other durability test not weathered much compared to the reference sample. RF_OUT_55 just like the QUV sample already weathered a bit, some slight discoloration were visible. However this is a minimal change compared to the changes that happened in the QUV testing.



Above: Reference RF_OUT_50
Below: 2x Watersubmersion sample RF_OUT_50

Above: Reference RF_OUT_55
Below: 2x Watersubmersion sample RF_OUT_55

4.6.4 Results

Bending fractures

Observations

Crater texture

All the fractures have a similar texture. All are crater like textures, this supports the assumption that the material is brittle. While the specimen were tested on strength, when failure occurred the specimen broke in two or more pieces and flying away everywhere.

Uneven filler distribution

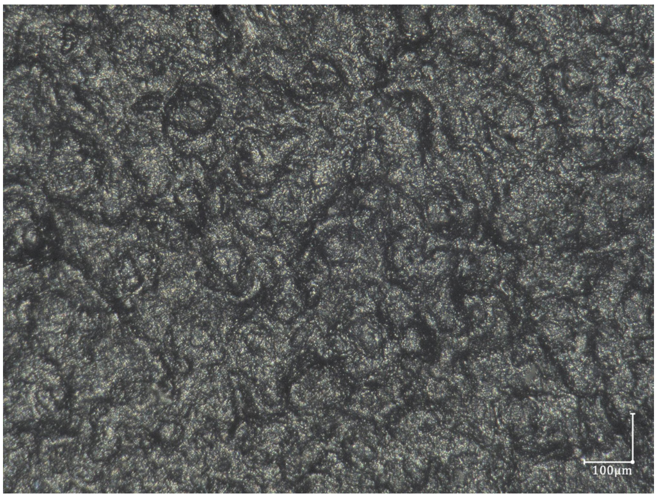
In the bending facture of the RF_QUV sample is visible that the filler is not that well distributed. Still some dark brown spots are seen of filler particles that have not interacted with the resin. This is compared to the other fractures a lot higher.

Marks

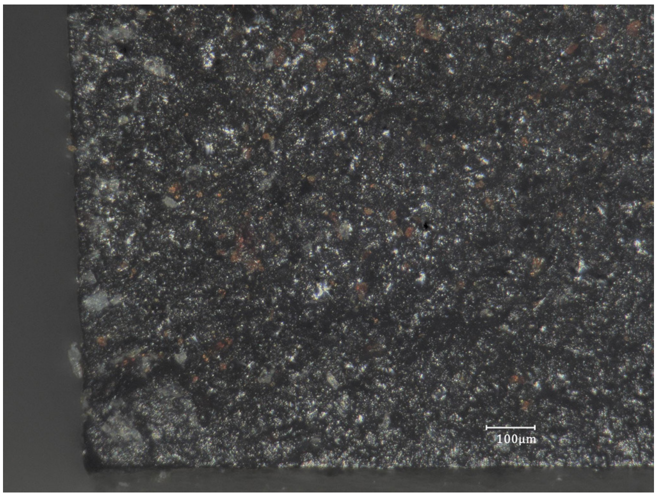
In the impact fracture of the RF_OUT there appears a big imprint of a hair or fibre structure. It could have happened that a hair from the brush used during the recycling of the filler was mixed with the filler. And added during the mixing of the bio composite. The imprint is very clear, which could mean that the hair / fibre did not interact with the resin. This made it a weaker point in the composite.

Conclusion & Discussion

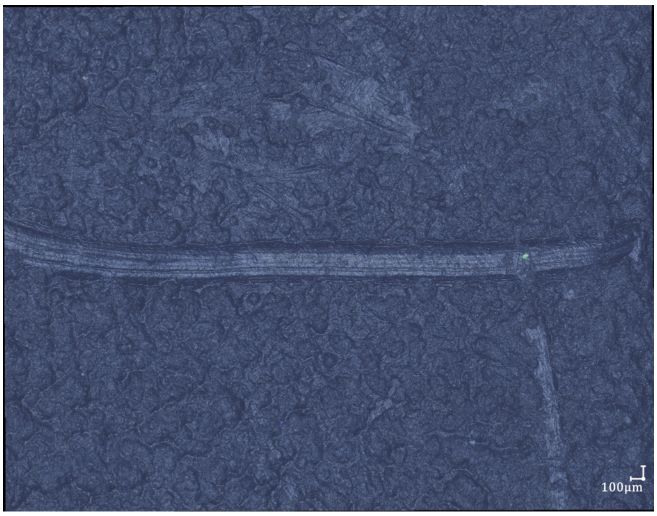
Looking at the fractures, confirms that this composite material with furan as a resin is a brittle material, no matter what filler is used in the composite. The texture of all the samples are similar to each other. The main differences is if the filler is mixed well and bonds together in the composite. The only composite that didn't mixed well together is the RF_QUV. This could be coincidental or the filler is not bonding with the resin.



Bending fracture - RF_NEW x500



Bending fracture - RF_QUV x500



Impact fracture - RF_OUT x250

4.6.4 Results

Some of the tests regarding QUV, water absorption and frost resistance could not be performed due to the lack of recycled filler from the QUV panels. A choice was made to focus on the mechanical properties and workability of the doughs. This makes it more difficult to compare the two weathered fillers to each other. However this material won't be a material that will be recycled much in reality, since this method, QUV weathering, is only used for testing materials on durability. As explained in the observations the mixer circumstances changed regarding the cleaning of the mixer. This could have had an influence on the mechanical properties of the samples from RF_QUV.

The performed tests on the weathered recycled filler show promising results that they can be incorporated into a new bio composite material, where the mechanical properties are within reasonable standards. The samples with a larger filler content of 55wt% show a higher flexural strength, while the impact resistance is a bit less than the 50wt%. With these results it can be concluded that even the natural weathered panels can be recycled to be used as a filler in a new bio composite panel. However some more optimization of the production processes (grinding & shredding and mixing) and further research would be beneficial to obtain optimal results.

Graph 7. Comparison sample properties

In graph 7 is shown how the different properties of the sample compare to each other. Overall the RF_OUT samples have a more stable distribution of the results. The 55wt% performs the best overall, so this sample will be used in the next phase where the materials are tested on 3D moulding.

PHASE 3

4.7 Phase 3 - 3D Moulding

In this phase the different fillers will be tested on the usability in 3D shapes. The best mechanically performing samples will be used and tested in 3D moulds.

4.7.1 3D Moulds

One mould will be used to test the 3D application of the recycled fillers.

- Tile mould (20x20 cm)

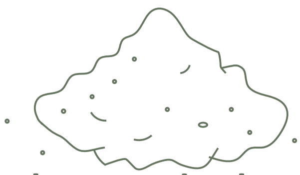
Filler types:

- ASF: Almond shell filler , which is currently used in the base recipe of NPSP.

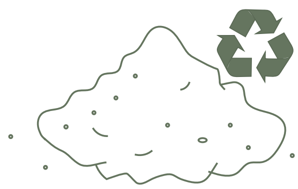
- RF_NEW: Recycled filler of sample plates that have been newly manufactured and recycled right away.

- RF_OUT: Recycled filler of façade panel that has been outside for 6 months.

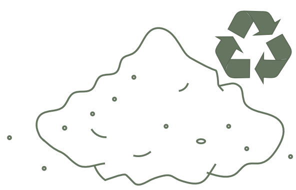
In this phase the following 3D samples were produced and tested:
- RF_ASF_45
- RF_NEW_50
- RF_OUT_55
- RF_OUT_50



Almond Shell



NEW



OUT

4.7.2 Procedure

Before pressing the recipes in the 3D tile mould, already pressed samples of this mould were weighed to ensure the right amount of dough needed for this mould. This was between 300 – 350 grams. 325 grams of dough was used for the pressing of the tiles.

The mould was cleaned and treated with a release agent, which would help the sample to release from the mould once pressed.

The different doughs were already made for the previous phases. Unfortunately there was not enough dough of the recycled filler from the QUV (RF_QUV), due to limited space available in QUV machine.

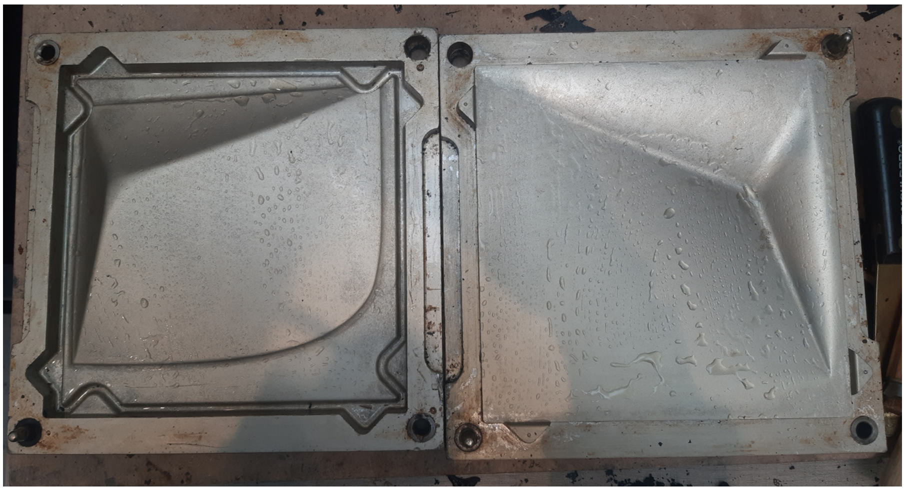


Figure 37. Mould before placing dough

To ensure that the whole 3D shape would be covered with the bio composite panel once the dough was pressed, the doughs were spread evenly over the mould. On the slopes of the 3D shape, more dough was added to ensure a good distribution.

Figure 38. Mould filled with dough

4.7.2 Procedure

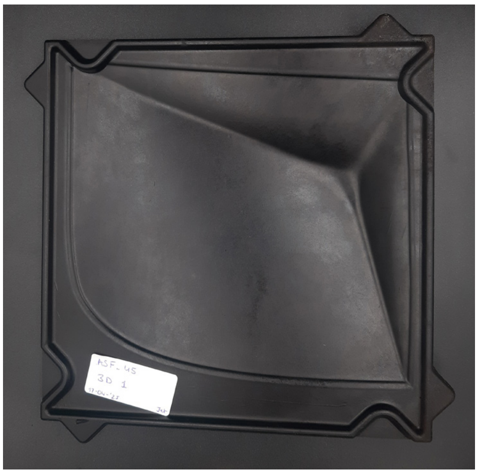
After the first tests with the 3D mould, another test was done with recycled filler samples. For this test the sample material: RF_OUT_50 was used. A new technique was tested at NPSP, where the dough was hammered into a flat sheet that has the dimensions of the 3D mould. The sheet would then be placed in the mould before pressing it. Since the sheet is one whole dough, it would be easier for the dough to spread everywhere over the mould, which would in the end result in a smoother finished surface and product.

Figure 39. Dough hammered into flat sheet

Figure 40. Sheet dough placed in mould

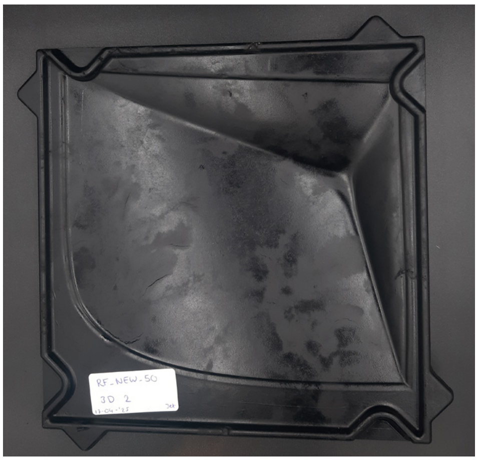
Figure 41. Pressing 3D mould

4.7.3 Analysis



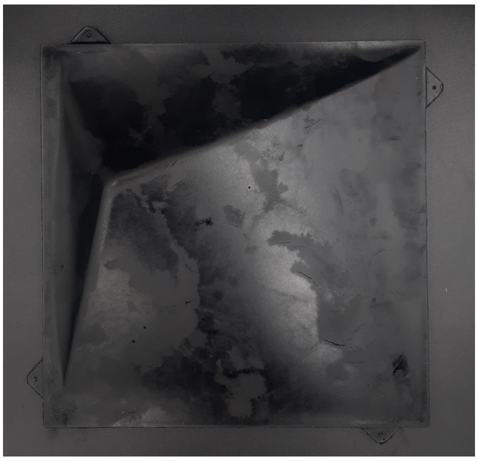
ASF_45

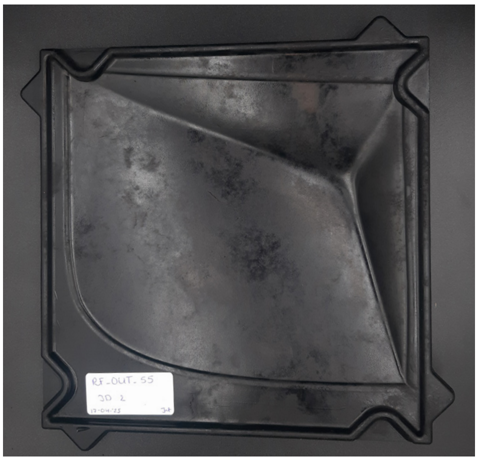
When analysing the almond shell filler in the 3D tile mould, the panel looks really smooth and uniform, especially compared to the other tiles. Not many defects can be detected. Only on the ridge on the top left a little inconsistency can be found.



RF_NEW_50

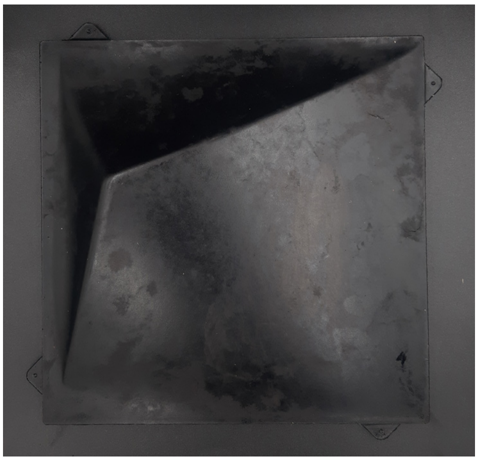
The 3D tile with the recycled filler NEW, shows some cracks and uneven distribution of the curing process. Different spots can be found that indicate that the flow of the resin is not good enough to spread over the whole tile. Some of the ridges are not completely filled.

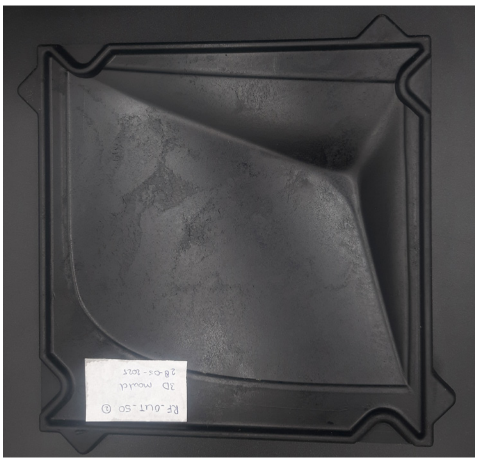




RF_OUT_55

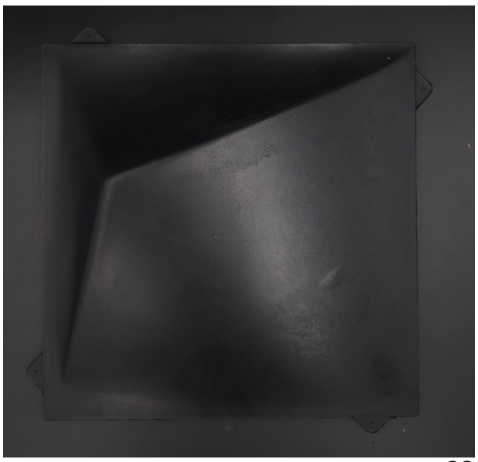
The tiles with recycled filler that had been outside for 6 months, has some uneven distribution of the resin, along with some cracks on the surface of the tiles.





RF_OUT_50

An extra test had been done with this filler load ratio, to test if a different placement of the doughs could help with a smoother surface. The dough was hammered flat to make a sheet of dough that could be placed in the mould before pressing.



4.7.4 Discussion & Conclusion

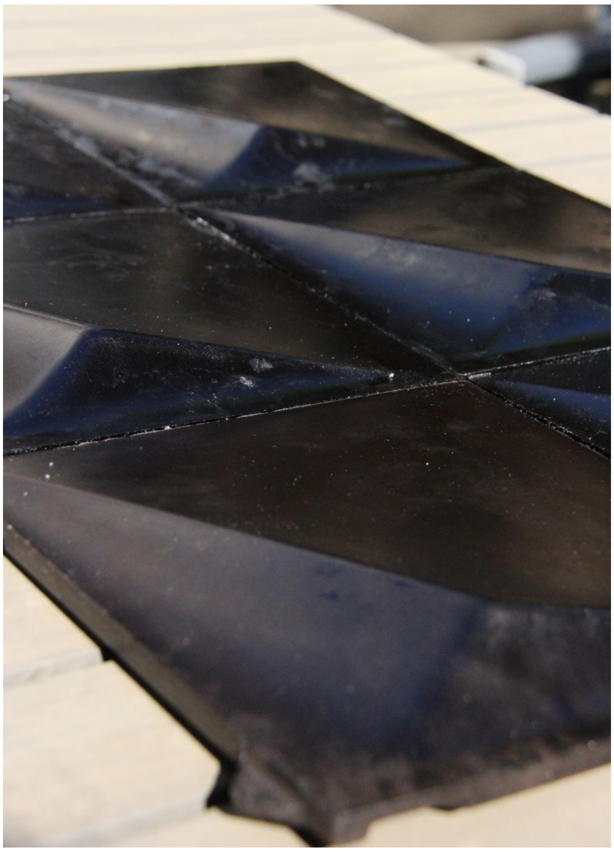
It is clear that the 'original' recipe with almond shell, is much more workable than the other recipes that have recycled fillers in the composite. The RF_NEW and RF_OUT show some cracks and uneven distribution of the resin. This can be explained by the lower amount of resin inside the doughs. The RF_NEW had 50wt% of filler, RF_OUT had 55wt% of filler compared to the ASF which had 45wt% of filler. The resin is the glue of the composite. Since the recycled filler composites have less of this resin, the dough flows less easily to all the parts of the 3D mould.

However the test performed with the RF_OUT_50, where the dough was hammered to a flat sheet, showed potential in the workability of these recycled fillers. The 3D tile did not have any cracks or uneven distribution visible on the surface. This could be a solution to still ensure a quality product from the recycled fillers, although this method is labour intensive to repeat for every tile, especially if the dough is still quite stiff. For the application of the recycled panels it could be considered to make a secondary function façade panel.

Also, the recycled filler has mechanically grinded bio composites, which already have a high percentage of cured furan resin. This doesn't bind well with the new resin.

So with less resin and less binding parts inside the filler, the recycled filler bio composite has a less workable flow for 3D moulds.

Would this be a problem in the long term, when recycling bio composite panels that have been outside for a longer period than 6 months? Since the panel already started to discolour while being outside for 6 months, it could mean that the resin slowly starts to dissolve over time. This could be positive for the recycling potential. When more resin dissolves, less unbinding material stays behind when recycling. This would be a very interesting aspect to be tested in future research.

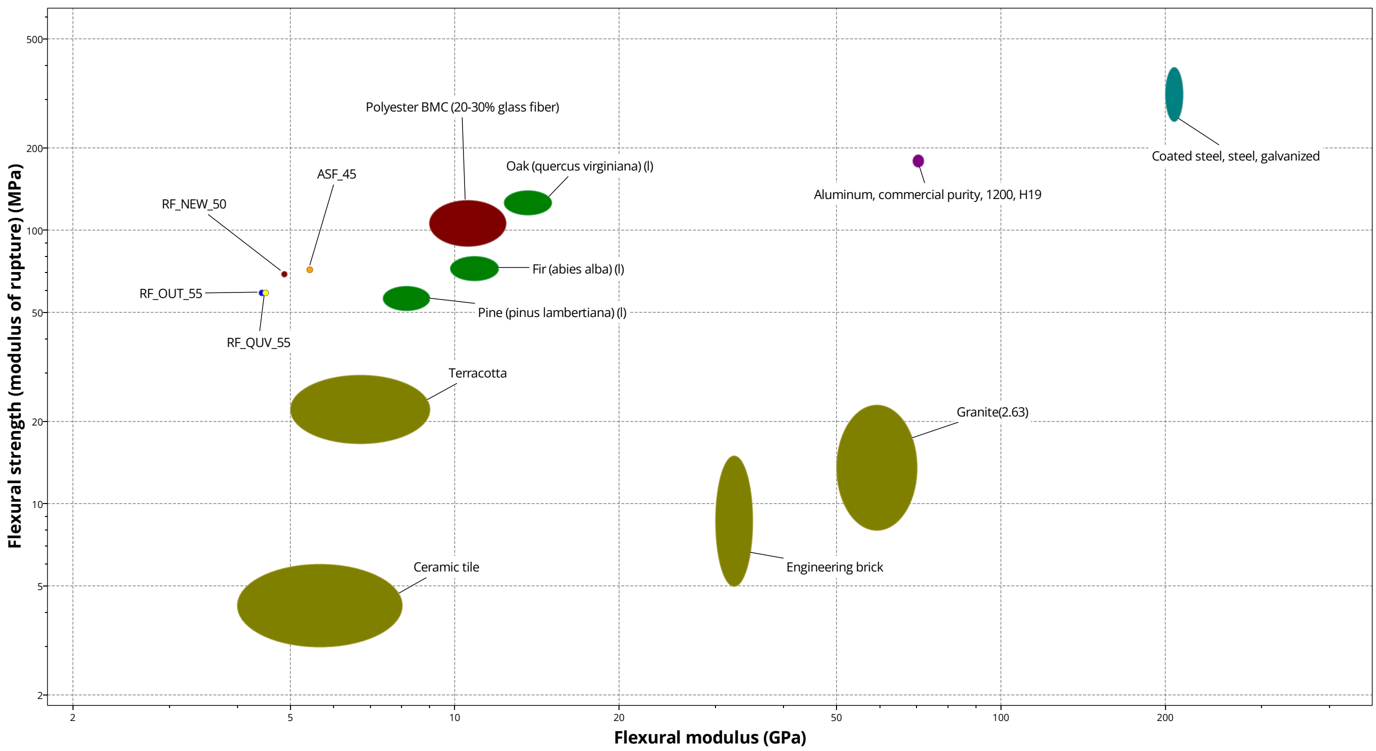


4.8 Material comparison

Comparing the recycled fillers and almond shell filler with conventional materials shows that the bio composite materials can be compared to soft woods based on flexural strength. The stiffness of the materials can be compared to terracotta and ceramic tiles, which are commonly used façade products. The flexural strength is higher than that of ceramics, terracotta and bricks.

Comparing them to non-bio based materials such as aluminium, steel and polyester composites, show that they are still being outperformed by these materials in both flexural strength and stiffness.

The bio composite façade materials are manufactured in a different way than the other materials, which has an influence on the properties. The comparison doesn't include the form freedom of the material. This is something that a bio composite can offer, where brick or aluminium panel have their limits.



Graph 8. Material comparison based on data from (Granta Edupack, 2024 R2)

4.8.1 Life cycle assesment

For the LCA the stages 1-3 are calculated. There is not enough data to consider the whole life cycle.

Base recipe bio composite:
- 45% Almond shell filler
- 45% Furan resin
- 10% Additives (Linseed oil and Catalyst)

The base recipe is compared to the recycled filler recipe

Recycled bio composite:
- 50% Recycled filler NEW
- 40% Furan resin
- 10% Additives (Linseed oil and Catalyst)

Almond Shell (embodied carbon):
The almond shell components are analysed to find the carbon content.

Table 14. Components inside Almond shell (Li et al., 2018)

Component	Weight percentage [%]	Carbon content [%]
Cellulose	38.47	44.4
Hemicellulose	28.82	45.5
Lignin	29.54	60-65
Extractives	3.14	-
Total		**49**

converting to CO2 weight:

44.01 g/mol (molecular weight CO2)/
12.01 g/mol (molecular weight Carbon) = 3.67
per kilogram shells:
0.49kg carbon ×3.67 = 1.8kg CO2
For each kilogram of almond shells we can therefore assume a carbon balance of about -1.8kg.

Almond shells (production):
The producing and processing of almond releases carbon, the embodied carbon is substracted from the carbon produced by the almond shell production.

Almond kernel: 4.3 kg CO_2e/kg
Almond shell without embodied carbon:
4.3 - 1.8 = 2.5 kg CO_2e/kg

4.8.1 Life cycle assesment

Furan:

Emissions in production:

4.7kg (assumed all fossil source)
Sequestration potential of organic matter:
0.7kg carbon per kg resin
per kilogram resin:
0.7kg carbon ×3.67 = 1.76kg CO2
Based on data from (Tumolva et al., 2011)

total balance:
4.7kg - 2.57kg = 2.1 kg CO2-eq

Release agent, Linseed oil: 3.3 kg CO_2e/kg
(bron: carboncloud)

Catalyst: 1.2 kg CO2-eq/kg
(Brentrup et al., 2016)

Table 15. CO2 in base recipe

Ingredient	**Content [%}**	**CO2-eq [kg/kg]**
Almond shell	45	2.5
Furan resin	45	2.1
Linseed oil	3	3.3
Catalyst	7	1.2
Total	**100**	**2.2**

Milling:
Machine 1: Cutting Mill SM 300
Energy: 3 kWh power consumption
Production rate: 2kg/h

Machine 2: Rotor Mill SR 300
Energy: 2.5 kWh power consumption
Production rate: 1 kg/h

Total energy per kg:
1.5 kW/kg + 2.5 kW/kg = 4 kW/kg powder

Carbon energy equivalent:
0.355 kg CO2-eq/kWh carbon emission for
electrical energy in the Netherlands (Ember, 2023)
= 4 * 0.355 = 1.42 kg CO2-eq/kg filler
= **0.426 kg CO2-eq/kg composite**

4.8.1 Life cycle assesment

Drying:
Oven energy consumption:
Duty Cycle = 20% (0.2) (estimate)
Energy Consumption = 3 kW × 1 hour × 0.2 = 0.6kWh
~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 ASF: 1.32 kg/l

1.3 kWh/ 10.56 kg * 0.5h (30 minutes processing time) = 0.0616 kWh/kg
= 0.022 kg CO2-eq/kg composite

Moulding:
An average production cycle is:
1 plate, 15min
~0.28 kWh/kg (Krishnan et al., 2010)

= 0.099 kg CO2-eq/kg composite

Result:
0.426 kg (milling) +0.426 kg (drying) + 0.022 kg (kneading) + 0.099 kg (moulding) = 0.973 kg CO2-eq/kg composite

Composite ASF: 2.20 + 0.973 kg =
3.2 kg CO2-eq/kg composite

4.8.1 Life cycle assesment

Recycled bio composite:
Using the CO2-eq from the base recipe for the recyclec filler.

Table 16. CO_2 in recycled recipe

Ingredient	Content	CO2-eq [kg/kg]
RF_NEW filler	50	3.2
Furan resin	40	2.1
Linseed oil	3	3.3
Catalyst	7	1.2
Total	**100**	**2.6**

Result:
0.426 kg (milling) +0.426 kg (drying) + 0.022 kg (kneading) + 0.099 kg (moulding) = 0.97 kg CO2-eq/kg composite

Composite RF_NEW: 2.6 + 0.97 kg =
3.6 kg CO2-eq/kg composite

This shows that the carbon produced during manufacturing and materials stages are a bit higher for the recycled filler, but this does not keep in mind the life span of both products. If an LCA would be made from the products is would possible give another result.

4.9 Chapter Conclusion

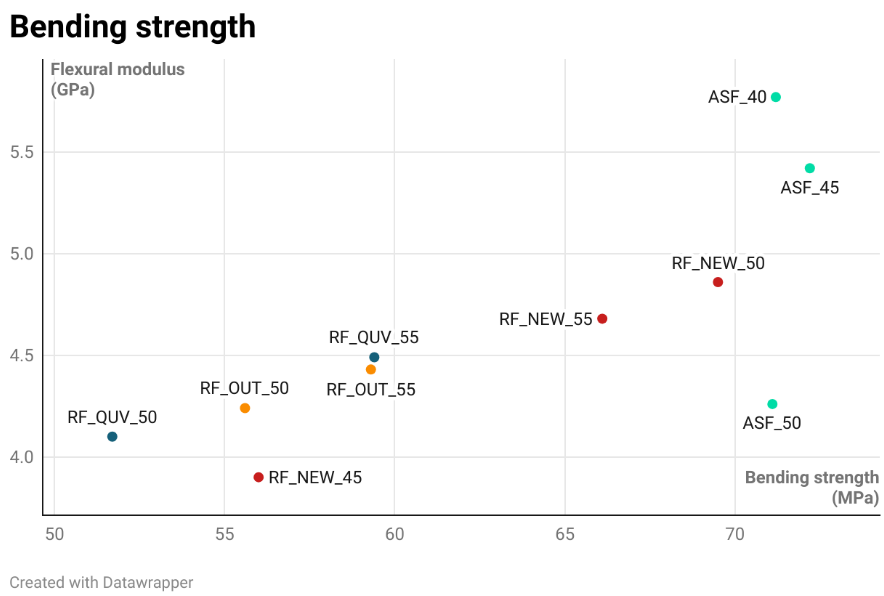
Phase 1:

Comparing the almond shell filler with the recycled fillers in different ratio's showed that the filler material properties had much influence on the filler load needed to achieve similar results in mechanical strength and consistency of the dough. This could be explained by the size and distribution of the filler particles.

Another reason why the recycled fillers samples need more filler to achieve the same consistency of the dough could be because of cured furan inside the filler material. This does not bind well with the furan resin.

Phase 2:

The recycled fillers were compared to each other and to the almond shell filler, regarding their performance in strength, impact, workability and durability. These factors all play an important role in a façade product. The recycled fillers have a bit lower flexural strength and impact resistance compared to the almond shell fillers, but the samples RF_NEW_50 & RF_OUT_55 still performed sufficient to be used as a bio composite material. All recycled fillers have a higher strain compared to almond shell filler bio composites.
So recycled fillers can be used in a bio composite façade panel.



Graph 9. Bending strength vs flexural strength all samples

4.9 Chapter Conclusion

Phase 3:

During the 3D mould testing only a few samples were used. These samples were pressed in a 3D mould to analyse the flow and potential critical points. It was interesting to see the difference between the almond shell filler and the recycled filler (NEW & OUT). The surface of the almond shell filler was smooth and did not have much defects, while both recycled fillers showed some texture issues and cracks on the surface. The reason why the flow is less compared to the almond shell filler is because of the lower amount of resin inside the recipe. This does not mean that the material is not usable for 3D moulding, but it needs to be placed carefully in the mould before pressing. The second testing showed that hammering the recycled filler dough did influence the finish of the surface after pressing. If the dough is just placed randomly, the pressed and cured product has a higher chance of defects. However, this alternative preparation is very labour intensive which, if unchanged wouldn't make it feasible for mass production purposes.

From the testing phases it can be concluded that recycled filler can be used in new bio composite façade products. Some factors however need to be taken into account, when designing or working with the material. For design a secondary façade panel function should be considered.

Due to the lower flow than the almond shell filler composites, it is important to spread the dough all around the mould so all the parts are covered. Visually the surface is not smooth, but has patterns. This can add an extra layer of depth to the aesthetics of the product. **The material is not suitable for small ridges, since the material will not fully fill them.**

Graph 10. Sample comparison

Design

In this chapter the design requirements / criteria will be set, which will lead the design process. The design requirements are informed by findings during the testing phases. Some boundaries are set to help the process. Different design variations are explored to find the most appropriate design for recycled bio composites.

5.1 Criteria

5.1.1 Application criteria

In the testing phases, the different filler materials for façade panels were tested on the following criteria :

- Mechanical strength, to withstand wind load and self-weight
- Impact resistance
- Weather resistance (water and frost)
- Flow (viscosity of dough)

If these criteria are not met, the material is not suitable for a façade product. The flow is an important factor in the design criteria.

5.1.2 Design criteria

Designing a façade panel that can be produced with a bulk compressing moulding method. Where the design can be mass produced, in a single mould. Since the material is not that easily pressed without any defects or smooth finished surfaces, a secondary façade element can also be considered.

Design criteria:
Keeping the **slopes minimal**, so the dough can easily flow. Depending on the viscosity of the dough is flows easier or more difficult.

Avoid small and steep ridges, these parts are difficult to reach for the dough.

Compatible with the already existing design, exploded view, which will create more design variations.

5.2 Design development

The design development happens in different steps, firstly some preliminary designs were made to see some organic forms that fit with the message of bio composites. Organics shapes such as sinus waves, line attractors. These design seemed to be a bit intense if implemented on a façade wall.

So a more simplified design was made that when playing around with a extrusion of corners and one diagonal.

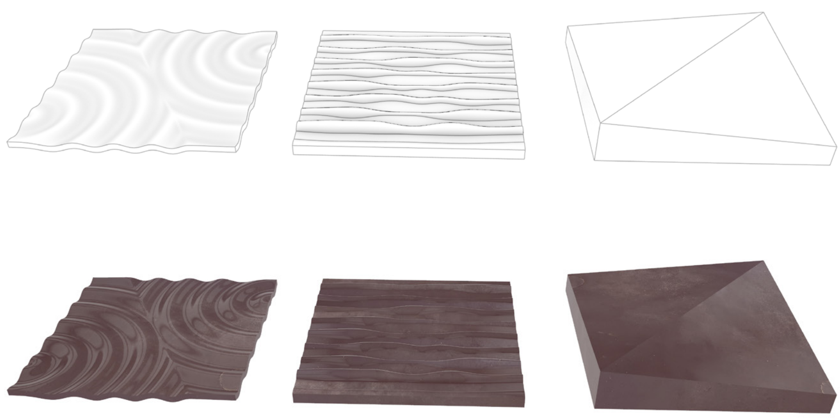


Figure 42. Design iterations

Figure 43. Exploded view design (NPSP)

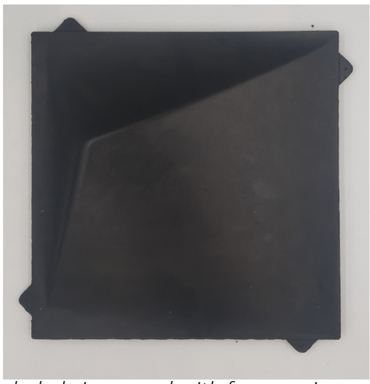


Figure 44. Exploded view panel with furan resin

Since the design needs to be inline the existing design and product. The more simplified design was fitting with the existing exploded view design. This design had one point on the surface that is extruded out the surface. This gives a simple, but interesting shape. To give some more design freedom and configuration options when making a façade design.

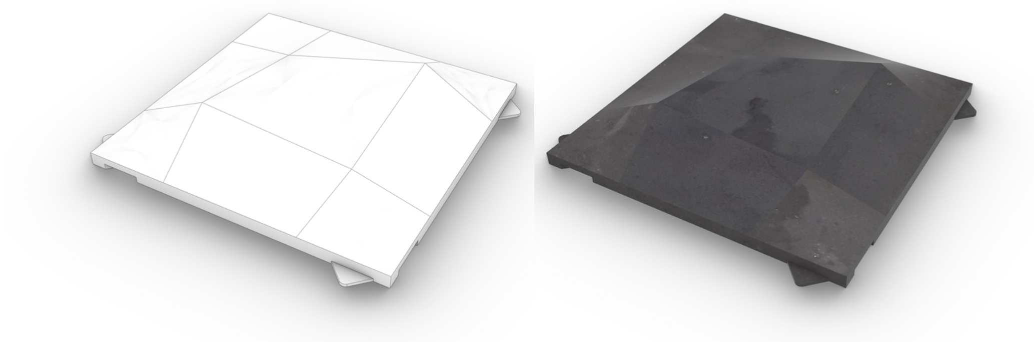


Figure 45. Design iternation 2

5.2.1 Functional façade element

Functional façade element, can be elements that cover the corners of a façade. Which will provide a clean finish. These corner elements can be connected to the main façade elements.

A corner element is often overlooked during the design process and can play a huge role in the appearance of a building. If the corners are visible it means it is not design well. Other than a visible function they also serve for other functions. It can protect the back structed again weather and fire spread, if the corners are not well designed of missing the risk of fire spread and water reaching the back structure is higher.

This corner element would need to be compatible with the existing façade panel designs of NPSP. These façade panels have a dimension of 600 x 600 mm.

Covering the corner of a 90 degree façade angle would be helpfully in completing the whole façade. To minimize the weight of this panel the dimensions are reduced compared to the façade panels.

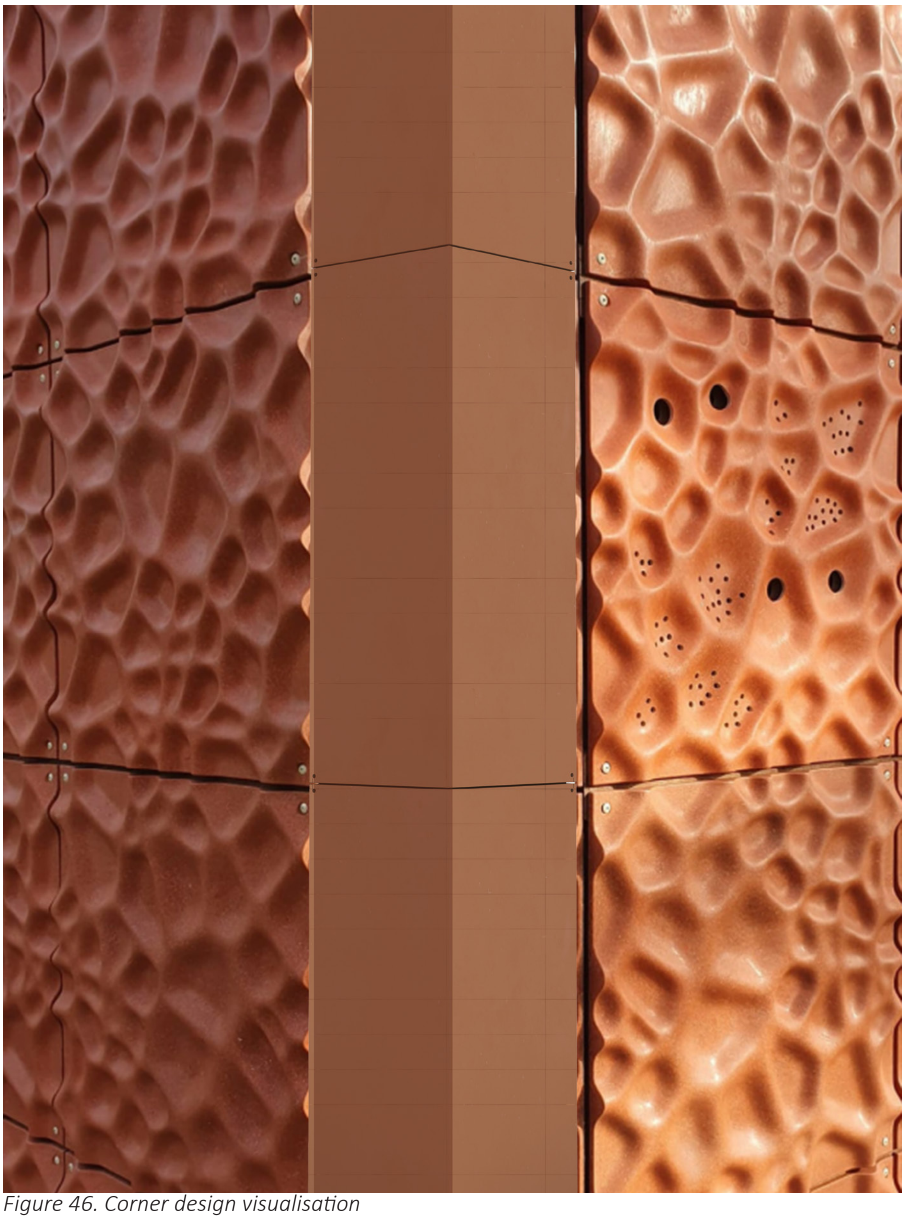
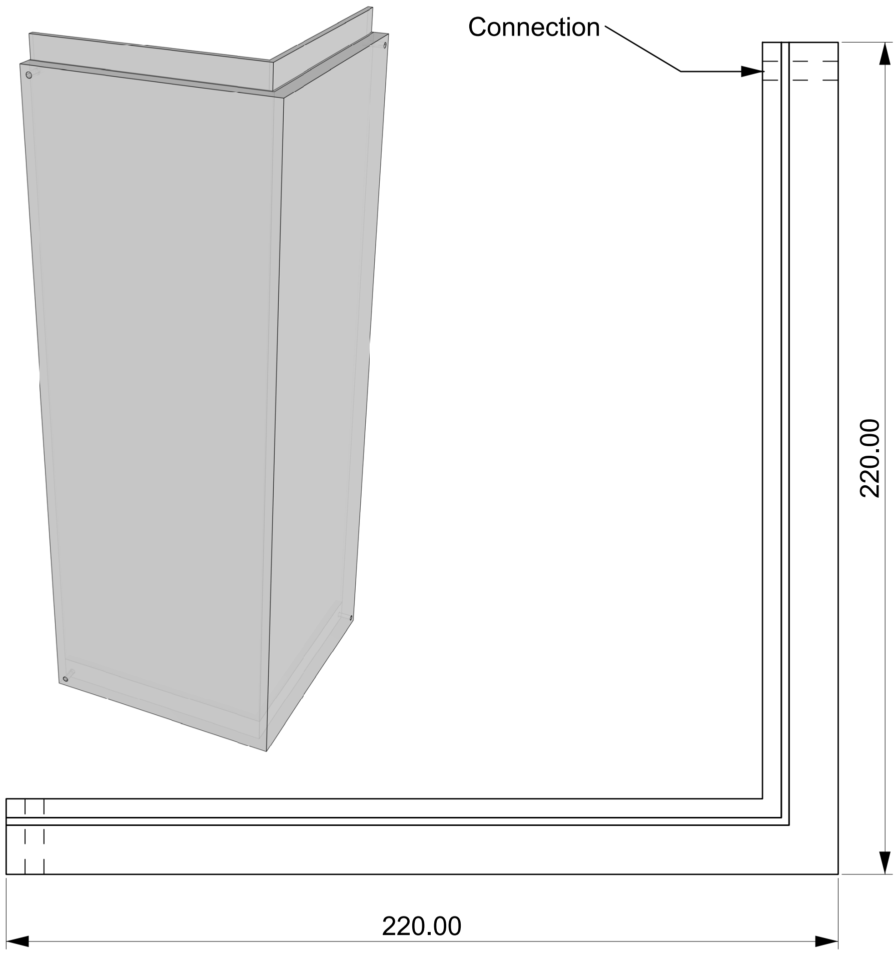


Figure 46. Corner design visualisation

5.3 Chapter Conclusion

Designing with a recycled bio composite material can be a challenge, since a lot of materials properties need to be keep in mind. Not every shape or function of the panel is optimal, some shapes can be difficult to achieve the same material properties or visual finish.

While the designing some different direction were tested to see the possibilities of the materials design. In the end the design was based on a function parts of the façade, a corner panel. This panel has a lot of influence on the water tightness and fire spread of a façade. Also on an aesthetic level it can make huge differences, by ensuring a clean finished corner the building's façade will look more put together.



6 Discussion

In this chapter the results and methodology used are discussed and analysed to see what could have been optimized or done differently.

6.1 Discussion of Results

6.1.1 Filler properties

The analysis of the filler properties based on density and microscopic analysis. The bulk density tests showed that the almond shell filler had a higher density than the recycled fillers, this is correlated with a higher surface area. However when looking at the particle size, the recycled fillers has a smaller particle size which would mean a higher surface area. The two different test contradict each other. The results of the density test are not that precise due to the testing method, however since this procedure was performed in the same way for each sample the differences can be analysed.

6.1.2 Sample properties

Testing the different samples and its properties, had some difficulties. The filler load of the almond shell and recycled filler was different, to get the same workability of the dough. Also when looking at the mechanical properties, the best performing ratios were not all of the same filler load. This made comparing based on filler load more difficult. However all tests were performed with a filler load of 50wt%. Only for the RF_NEW was this the optimal ratio, considering all the criteria.

Since there was a limited amount of recycled filler available, especially from the RF_QUV filler. It was decided to only continue with two different ratios instead of three, which were expected to perform the best in all criteria's. These samples could not be tested on the durability of the materials, this means that the assessment of this material is incomplete. However it could be possible that some valuable information was missed because of this decision.

Although considering that in a real life scenario, these panels placed inside the QUV would not be recycled into filler material. These tested were performed to get a bit more understanding on the effect of weathering of material samples and their recyclability.

It would also be interesting to see what would happen to the properties of the bio composite, when mixing two different filler together. Such as the almond shell filler and the recycled filler. In both samples different key performance properties are found, which could when put together even enhance the overall properties of the bio composite.

6.1.3 3D product properties

For the product testing a 3D tile mould was used, only three of four the different fillers were tested in this way. This was again due to the limited amount of RF_QUV filler. Also only the best performing ratios from each filler type was tested in this test.

The results of the recycled filler (NEW_50 & OUT_55) showed that there were some cracks or non-homogeneous surface. However since this test was only performed once for the ASF and two times for both recycled filler (NEW_50 & OUT_55), these crack or uneven distribution could be a minor issue. In production of 3D panel with this technique, some manufacturing errors occur.

After some adjustments in the manufacturing method, the pressing of RF_OUT_50 showed promise that the recycled filler can also have a smooth finished surface without any cracks or defects.

6.2 Discussion of Methodology

6.2.1 Filler recycling

The testing framework defined at the beginning of the thesis, was deemed not realistic. This was mainly because of the different testing phases that changed. First different ratios would have been tested along with different grain sizes of the fillers. However after starting to grind and mill the recycled filler, it became clear that the filler particle size would only fit into one size bracket < 50 µm. This meant that the whole testing structure had to change, looking back the used methodology has a more interesting scope of research and outcomes.

6.2.2 Mechnical testing

The mechanical testing methods were according to standards for plastics composites. Some deviations in the mechanical strength happened, this could have been excluded by remaking the sample plates. For an even more accurate baseline of results more mechanical testing would be advised to ensure the quality control of the product.

The sample preparation that was done with the CNC milling machine could have an influence on the results of the mechanical testing. If the edge of the material was not cut properly or could have a dent it could influence the results. Ensuring that all the sample plates have the same thickness could minimize the errors made by the CNC milling machine.

6.2.3 Durability testing

The testing method for durability are not all that reliable. For the water submersion test a scale was used that measures grams. For more acuate results on how much water absorption takes place a more precise scale would be needed. The results will now be used as an indication and a visual sign of the weathering effect of water on the panel.

6.2.4 3D product properties

The method for placing the dough in the 3D mould before pressing, could have been more optimized. During the second round of testing an experiment was conducted which tested if the 3D tile would have a smoother finish. In this experiment the dough was hammered into a flat sheet, which would fit in the dimensions of the mould. Due to the dough that was still one component is remained intact and one smooth surface after being pressed. This method however is more labour intensive and time consuming than the original method. If this method is unscalable is questionable, it should be easily repeatable and manageable.

7 Conclusion

In this chapter the research results are concluded and the research questions are answered. The limitations of the research are discussed and the future research possibilities are highlighted. Recommendations are made based on the results of this research.

7.1 Results

After gathering the results of all the different tests and finding the overall performance of the samples, the following conclusions can be made.
Looking at the individual results of the tests, it is clear that the recycled fillers perform less mechanically on flexural strength compared to the almond shell filler, while on impact resistance the RF_NEW performs better than all the other sample materials.

Workability wise the almond shell filler samples are performing the best, but the recycled filler with a higher filler content and less furan resin also have a good workability.

The durability test was split into three sub tests: frost resistance, water absorption and QUV. The average of these results have been used to determine the durability of the sample materials. These rankings on the scale are based on a visual change compared to reference samples that have not been weathered in any way.

The results are ranked by a ranking system. For each test another evaluation scale is made. In table 16 the evaluation scales are explained.

Since not all the samples that have been tested for mechanical properties have also been tested on durability properties. Only the samples that were tested in all four categories of the evaluation scale are concluded in the final results.

The higher the points on the scale the higher the performance of the sample material. Looking at the average of the samples, it shows that the RF_NEW_50 is performing the best, however the ASF_45 is a very close second. This difference is really minimal, so in overall it can be concluded that the recycled filler can perform similar to the almond shell filler on the chosen mechanical and durability properties.

Looking at the 3D shaping of these samples, the ASF_45 does have a better finish. For the recycled filler more preparation needs to be done before pressing to get the same results.

Table 17. Evaluation scale

Evaluation scale	1. Flexural Strength (MPa)	Resistance (kJ/m²)	3. Workability	4. Durability
	Scale 0-80	Scale 1-6	Scale 0-5	Scale 0-5
	0 = 0-16	0 = 1-2	0 = liquid not workable	0 = total destruction
	1 = 17-32	1 = 2-3	1 = thick liquid	1= cracks and all of above
	2 = 33-48	2 = 3-4	2 = super sticky	2= deformation
	3 = 49-64	3 = 4-5	3 = sticky	3= visual change (coloration)
	4 = 65-80	4 = 5-6	4 = thick crumble (a bit sticky)	4= minimal visual change
	5= 80	5= 6	5 = crumble	5= no visual change

Table 18. Sample rating

Samples	1. Flexural Strength	2. Impact Resistance	3. Workability	4. Durability	Average
ASF_45	4.5	1.5	5	3	3.5
RF_NEW_50	4.5	2.5	3	4.5	3.6
RF_OUT_50	3.5	1.5	3	4.5	3.1
RF_OUT_55	3.5	1.5	4	3	3.0

7.2 Answering the research questions

The **main research** question:

“How can bio composite façade panels at their end of life be recycled into new bio composite façade panels while maintaining or increasing their high performance properties and freedom of design?”

With mechanical recycling, bio composite façade panels can be recycled into filler material which can be used in new bio composite façade panels or other applications. Looking at the performance of this new panel made from recycled filler it shows that the mechanical performance is a bit lower than the original not recycled bio composite panel. However other performances like durability, tested with the QUV, are better than of the original panel. Comparing all the properties of this application of a façade panel show that the new panel made from RF_NEW even performs better. This shows a lot of promise for the durability and sustainability of the products life.

The **sub questions** are:

“What are the key performance properties of recycled bio composite façade panels?”

The key properties that are important for a façade panel are; mechanical strength, impact resistance, durability, visual aspects and fire safety. These properties have been discussed in chapter 3.5. In the testing phases all these properties have been tested except for the fire safety of the product. Looking at the tested properties it shows that recycled fillers in bio composite façade panels have a potential. Especially durability wise the recycled bio composites have a strong performance.

Looking at the filler material level, it is clear that the particle size is much smaller for the recycled filler, which would mean a higher surface area that can bond with the resin. The preliminary density tests show that the density of the recycled fillers are lower than the almond shell filler. This correlates with the amount of filler load that needs to be added to the resin to get the same dough texture. Besides, the texture that is workable for pressing into a bio composite is a crumbly non sticking texture. The recycled filler materials are a lot darker compared to the almond shell filler.

“How do recycled filler materials compare to virgin raw filler materials used in current bio composite panels?”

Looking at the filler material level, it is clear that the particle size is much smaller for the recycled filler. Which would mean a higher surface area that can bond with the resin. The preliminary density tests show that the density of the recycled fillers are lower than the almond shell filler. This correlates with the amount of filler load that needs to be added to the resin to get the same dough texture. The texture that is workable for pressing into a bio composite is a crumbly non sticking texture. The recycled filler materials is a lot darker compared to the almond shell filler.

7.2 Answering the research questions

"How does the weathering of the pre-recycled panel influence the performance of the recycled bio composite façade panel?"

The weathering of a façade panel after six months already showed signs of decreasing mechanical properties compared to the newly recycled façade panels. It is interesting to see that adding more filler to the resin, increases mechanical strength with the weathered recycled filler. However it reduced the durability of the panel. Results from the QUV tests show that 5% more filler content in the composite resulted in much more discoloration while being exposed to the same accelerated weathering conditions. Overall the two filler performed quite similar on durability and workability with 50wt% of filler, only the mechanical properties of the weathered filler (RF_OUT) is lower than the newly recycled filler (RF_NEW).

"How does using a recycled filler affect the design of a bio composite facade panel?"

The recycled fillers don't necessarily create more design freedom. The flow of the recycled filler are less compared to the almond shell filler composites. However with the right distribution and placement of the dough inside the mould, still many 3D designs could be realized. Just like the already existing material the slopes and ridges are difficult to fill.

7.3 Recommented future researh

Further research on optimizing mechanical performance, fire safety and second end-of-life scenarios needs to be conducted to understand all aspects of the design, manufacturing and usage of recycled bio composites for façade panels. This could take the recycled bio composite product to the next level, were it can actually be implemented on a larger scale.

Optimizing mechanical performance
For future research it would be interesting to look into the mixing of the recycled filler with the almond shell. Since the almond shell has a higher mechanical performance, it could help increase the properties of the end material, while still keeping recycled filler in the product. Some things here could be learned from other industries. In the concrete industry for example the mixing of different sizes, shapes and textures of aggregates contributes to the mechanical performance of the concrete (Dehghan et al., 2023).

Second end of life
This thesis focused on the end of life of bio composite façade panels, recycling them one time and adding them as a filler in a new panel. If this life cycle then continues at the end of the new products service life, recycling the material (for another time) could again be an option. It would be interesting to examine what would happen with the performance of that newly recycled panel. Since there is already recycled filler in the bio composite, the (cured) resin content is already higher than in the 'original' panel.

This research would be beneficial to keeping still functional materials from ending up in landfill or being incinerated.

Fire safety
In the timeframe of this research and the available resources, it was not possible to test the sample materials on fire safety properties. This is an important property of a façade panel, since the product needs to be up to code according to the regulations on fire safety. So next research preferably also considers this aspect.

Optimizing manufacturing process
The process of recycling the bio composite panels is quite time consuming, right now many different steps need to be performed to achieve the required result. To get filler material from bio composite panel, they need to be hammered, shredded and milling until fine particles. This method would not be feasible for large scale projects. A bigger and more industrial machine would be necessary to implement recycled filler into the production process. Next to the manufacturing of the filler, the preparation of the dough for inside the mould is also a time consuming process. To achieve a smooth finished product the dough needs to be hammered into a flat sheet, this is not the most efficient process.

Reflection

In this chapter The thesis project is reflected upon, stating its relevance in the building sector. The graduation process is reflected on. As well as my personal development during the thesis.

8.1 Project reflection

8.1.1 Graduation process

This thesis aims to research the possibility of recycling bio composites for façade panels and using them into new bio composite materials, where the design is integrated into the recycling process.

The materials used in the bio composites that are being recycled are furan resin, almond shell filler and additives to help the process. Furan panels are a brittle material. Recycling furan elements can be an intensive process. Other materials could be more workable to recycle. This doesn't mean it is impossible to recycle, it takes a few more steps to get from (façade) panels to powder that can be used as a filler inside a new bio composite material.

The method used for testing was altered a few times. These changes were influenced by different factors. Before starting with the testing and designing, I wrote an approach for the test sequence. This approach was not feasible after discussing it with NPSP. I rewrote the approach to fit better with the available resources and already existing data and knowledge, which also lead to a more interesting approach which I thought wasn't possible in the beginning! Since recycling of bio composites doesn't happen after a panel is just made, in reality a façade panel would have been outside for a couple of years before coming to the end of its life. In the new approach different panels could be tested that have been outside and/or in the QUV for a period of time. By recycling these panels and comparing them to the original panels and newly recycled panels a better prediction can be made on the feasibility of recycling bio composite panels. This is important to understand if the weathering of the panels have an effect on the recyclability of the bio composites.

The method showed promising results for recycling bio composites made from furan resin. The way of mechanically recycling these panels into filler for new bio composites works to receive at least mechanical strong enough materials to be used in façade cladding.

To test a more realistic recycled filler, the recycled panels that have been outside for 6 months. This will give insight into a more realistic estimation of the possibilities of recycling the bio composites. The results of the recycled fillers showed some more decrease in mechanical properties, but the other properties show promise.

In hindsight it would have been valuable to start earlier with the weathering testing, since these tests take longer to perform. This would have given a more complete overview of all the samples' durability properties. However availability of resources and equipment were not always aligned with the planning.

Each recycled filler type had a limited amount of filler left at some point in the testing phases. This could have been prevented by preparing more bio composite panels that could be recycled in advance to ensure enough filler would be available for all the intended tests. That is a reason why not all fillers are tested in the 3D moulding phase.

The three different recycled recipes were tested in 3D moulds to see the flow of the material. These showed that recycled fillers were bonding less than the almond shell filler. However, this happens more often in production processes, so this can be optimized.

8.1.1 Graduation process

The design criteria were set based on the results from the testing phases. A framework will illustrate the boundaries of the design, size, amount of panels, pattern and function. The design process could have started earlier in the research, the material properties were a leading part in the design requirements and guidelines. At the end of the research it was decided to design a more functional façade element, a corner panel, because of the results from testing phase 3. This is an important part of the façade that can increase the aesthetic appearance, ensure water tightness and avoid fire spread.

8.1.2 Relevance

Recycling bio composites could make a difference for bio based building products. These products are now not always the most attractive option to choose for. Proving that recycling is an option and keeps the same properties increases the circularity and sustainability of the product. Besides mechanical properties, design with bio composite can give more flexibility to design a product which can be compared to 3D printing. So also more freedom of design.

8.1.3 Socio-cultural Reflection

The thesis research was done in collaborating with NPSP, the material testing and results are applicable on their products. In this thesis I proofed that recycling this material is possible and can help to also start and continue recycling bio based materials in the built environment.

Impact can be made with this thesis project, be promoting to keep innovating even for already bio based materials. This can inspire to keep developing circular building products.

Looking at the Sustainable Development Goals, my thesis is in line with three key goals. It contributes to goal 11, Sustainable Cities and Communities, by researching and developing sustainable building materials. The second goal is Responsible Consumption and Production, goal 12, by phasing out fossil fuel building products and working with a sustainable industry. Lastly, taking action to battle against global warming, by recycling materials in line with goal 13, Climate Action.

The ethical impact of my thesis project is reduced waste at the end of life of a façade product and giving it a new life by recycling it into a new product.

8.2 Personal reflection

8.2.1 Process Reflection

By digging into the literature and writing the literature review, I gained a deeper understanding of bio composites and how the manufacturing process is structured. This helped me to design a research framework and testing phases, where the methodology was the road to the results. I learned how to overcome obstacles during my thesis, if things did not go my way I could adapt.
I listened to the feedback from my mentors and company supervisors, but also made my own choices that I thought were logical in the course of this thesis. If I was a bit lost during the thesis process I always received some helpful feedback or questions to go further.
In the process of recycling bio composite façade panels, a lot of challenges arose, from the way of recycling to the processing method and scheduling of testing times. This meant that I had to adapt and reschedule plans. This was not always nice, but is an important skill to have, since things don't always go according to plan.

While testing, one of the main limitations was the planning and availability of the machines and equipment at NPSP. This equipment was not always available, so I had to adapt and improvise a lot comparing to the planning I made in the beginning of the testing phases. I first had to wait for a while for a grinding machine that would help with the recycling process of the bio composite panels.

Some of the feedback I got was regarding details within the presentation and written report, where explanation of certain parts could be improved to make it more easy to understand. Also the feedback to keep writing during the testing and designing phases was an important learning. And of course make the a realistic planning, not pushing everything to the end.

Other feedback was on the different testing phases, what tests are interesting to perform and how these tests can influence the design choices. I implemented it during the process and learned a lot from it.

8.2.2 Reflection questions

1. What is the relation between your graduation project topic, your master track (A, U, BT, LA, MBE), and your master programme (MSc AUBS)?

This graduation project focuses on circular product design and with a focus on recycling and reducing environmental impact. This fits very well within the Building Technology masters scope of research and education. The architecture faculty also has a big focus on circularity and aims to have a circular building environment.

2. How did your research influence your design/recommendations?

In my research the functional properties of the different materials shaped the design criteria. The flow of the materials appeared to be is an important factor in the manufacturing process, which is essential for recycled building products to be used.

3. How do you assess the value of your way of working (your approach, your used methods, used methodology)?

I think my way of working was really structured. I kept a sort of dairy were I would write down everything I did during the testing phases. This really helped to keep track of my own progress and results. Of course there is always room for improvement, some methods could have been researched or prepared more before starting them. This would have saved some time in the end or ensured more accurate results. The methodology of the tests was overall very well structured and lead to the results that could answer the research questions.

4. How do you assess the academic and societal value, scope and implication of your graduation project, including ethical aspects?

The recycling of bio composite materials in general, and used in façade panels in specific, have not been widely researched yet. The gained knowledge is valuable for both academic and company based research, as well as for the society. People might find it difficult to choose for a bio based product if that product has a shorter life span than for instance aluminium. However, if the bio based product has an extra advantage of being recycled in again a high value product that would enhance this overall value. In the end how circular is a bio based façade panel if at the end of life it ends up incinerated or in landfill, because there is no other destination seen for it. I think this thesis project shows the potential for recycling of bio composite materials and hopefully can contribute to less waste, less carbon emissions and exhaustion of raw materials in the building industry and by that, in the world.

5. How did you deal with unexpected changes and delay during the testing phases?

During my thesis I had to adapt a lot. The planning I had made in the beginning of the testing phases totally changed. Because I was working with a company (NPSP), I had to adapt to their scheduling and availability of machines and equipment, which did not always align with my expectations. I learned how to deal with these moments and continue with another part of my research. Some delays did have a big impact on the tests I could and could not do, however I think overall I handled everything pretty well and made the best out of difficult situations. if a machine broke down I helped to get it fixed, so that everyone could continue as fast as possible. I learned that the road to success is never a straight line!

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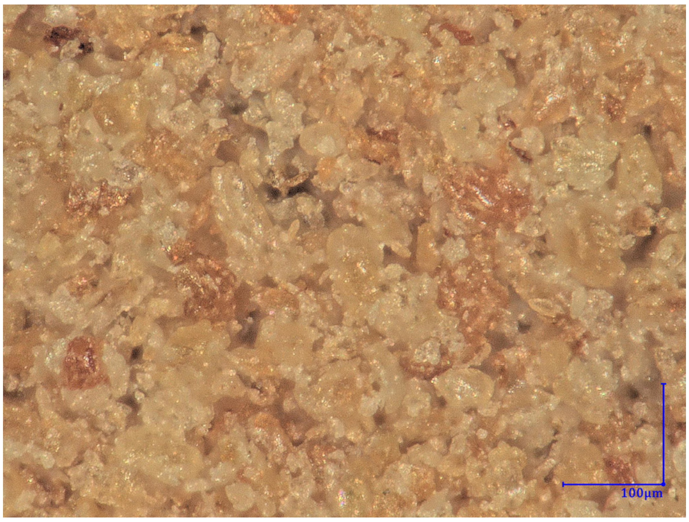
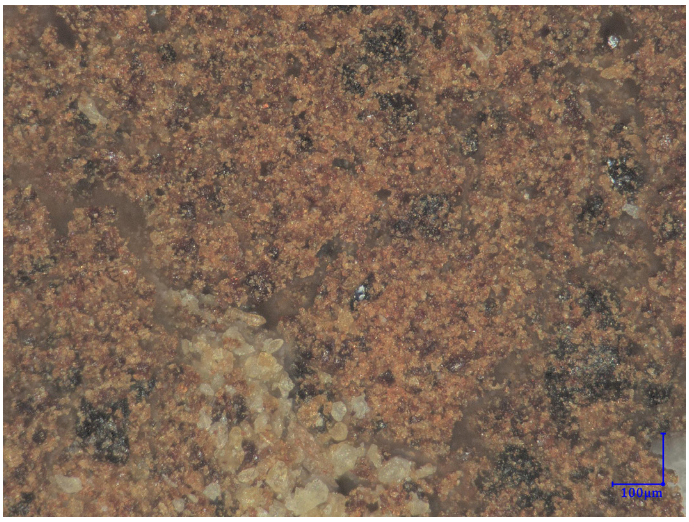
C Test results Phase 1

Microscopic filler analysis

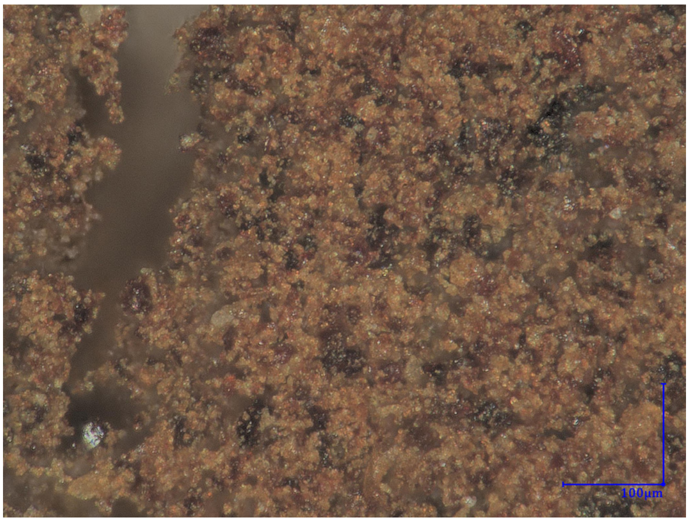
Almond shell filler 250x



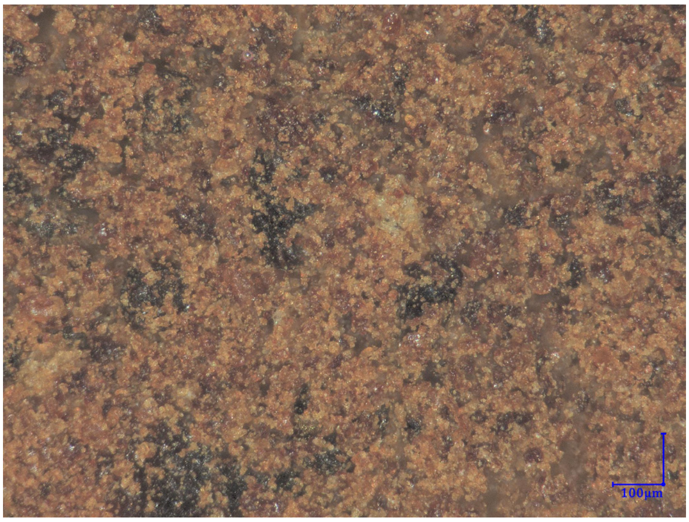
Almond shell filler 500x



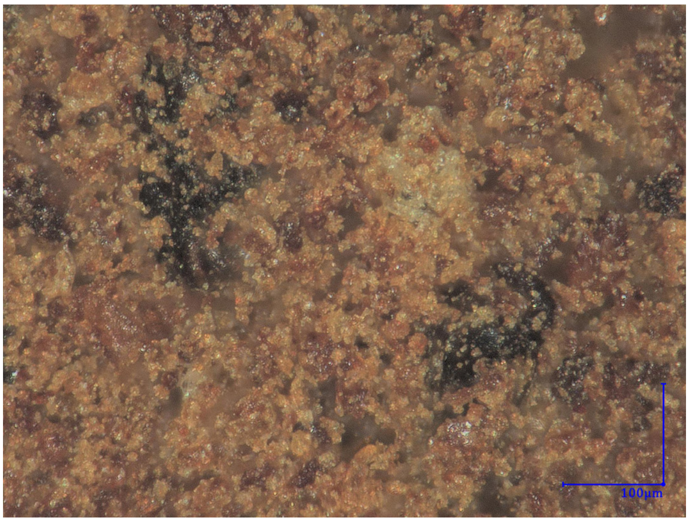
Recycled filler NEW 250x



Recycled filler NEW 500x



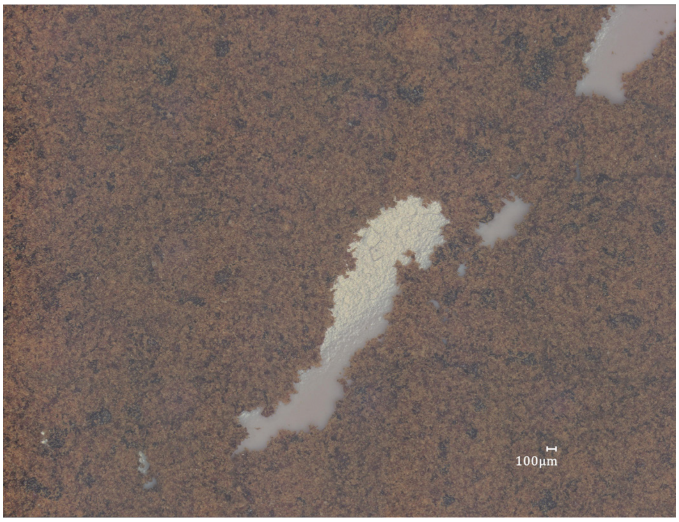
Recycled filler OUT 250x



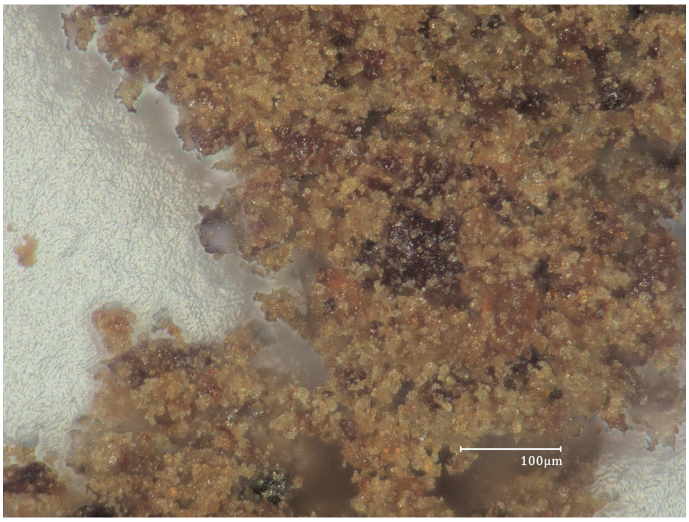
Recycled filler OUT 500x

C Test results Phase 1

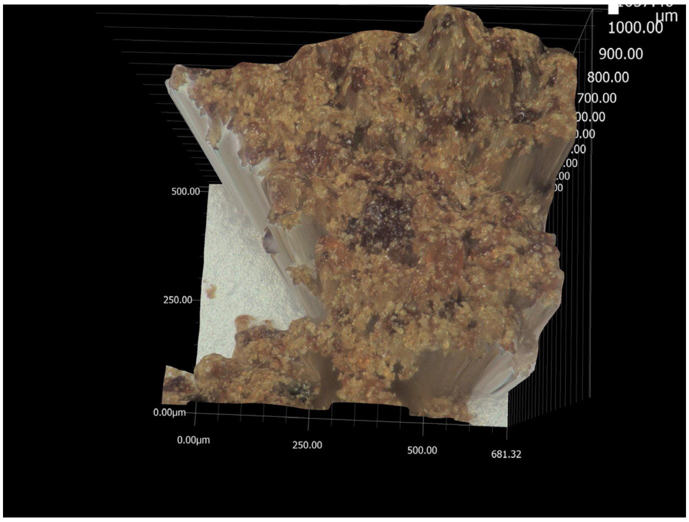
Microscopic filler analysis



Recycled filler QUV 50x



Recycled filler QUV 500x



Recycled filler QUV 3D

D Test results Phase 2A

Almond shell filler 40 (ASF_40)
Date: 14-3-2025 Mould: Sample mould (BMC) Note: 1 plate

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.25	4.72
2	0.17	3.26
3	0.14	2.73
4	0.16	3.15
5	0.17	3.41
6	0.18	3.49
7	0.17	3.38
8	0.20	3.85
9	0.15	2.98
10	0.15	2.96
11	0.15	3.01
12	0.23	4.69
Average	0.18	3.47
Standard deviation	0.03	0.65

Flexual Testing ISO 14125A

ASF_40	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
1	69.1	1.3	5.47	255.04
2	71.5	1.2	5.94	243.72
3	81.5	1.5	5.82	298.34
4	72.3	1.4	5.63	270.27
5	75.4	1.4	5.75	267.96
6	65.2	1.2	5.98	240.49
7	66.4	1.2	5.56	235.06
8	68.1	1.2	5.97	251.26
Mean	71.2	1.3	5.77	257.77
S.D.	5.33	0.12	0.2	20.59

Almond shell filler 45 (ASF_45)
Date: 14-3-2025 Mould: Sample mould (BMC) Note: 2 plates

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.13	2.92
2	0.16	3.48
3	0.13	2.85
4	0.11	2.52
5	0.13	2.84
6	0.13	2.93
7	0.12	2.63
8	0.11	2.55
9	0.10	2.32
10	0.13	2.82
11	0.13	2.78
12	0.13	2.80
Average	0.13	2.79
Standard deviation	0.01	0.29

Flexual Testing ISO 14125A

ASF_45	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
1	75.8	1.4	5.23	467.37
2	83.1	1.5	5.6	492.82
3	62.9	1.1	5.61	374.14
4	63.3	1.2	5.34	390.2
5	68.2	1.2	5.47	420.48
6	72	1.3	5.38	426.84
7	69.5	1.3	5.37	428.38
8	79.7	1.4	5.51	492.89
9	75	1.4	5.29	444.7
Mean	72.2	1.3	5.42	437.53
S.D.	6.94	0.12	0.13	41.55

D Test results Phase 2A

Almond shell filler 50 (ASF_50)
Date: 14-3-2025 Mould: Sample mould (BMC) Note: 1 plate

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.26	3.40
2	0.26	3.43
3	0.21	2.72
4	0.27	3.56
5	0.29	3.74
6	0.31	4.14
7	0.26	3.43
8	0.27	3.53
9	0.28	3.65
10	0.33	4.38
11	0.22	2.92
12	0.22	2.84
Average	0.27	3.48
Standard deviation	0.04	0.49

Flexual Testing ISO 14125A

ASF_50	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
1	76.4	1.3	5.73	596.36
2	74.3	1.2	6.08	576.97
3	69.9	1.2	5.6	519.95
4	68.3	1.2	5.66	527.05
5	64	1.1	5.75	466.42
6	71	1.2	5.71	551.02
7	76	1.3	5.71	586.86
9	68.9	1.2	5.57	533.47
Mean	71.1	1.2	5.73	544.76
S.D.	4.26	0.05	0.16	42.6

Recycled filler new 45 (RF_NEW_45)
Date: 6-2-2025 Mould: Sample mould (BMC) Note: 1 plate

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.24	3.63
2	0.24	3.53
3	0.17	2.58
4	0.19	2.92
5	0.28	4.35
6	0.17	2.76
7	0.26	3.96
8	0.19	2.95
9	0.08	1.25
10	0.19	2.93
11	0.18	2.78
12	0.19	2.85
Average	0.20	3.04
Standard deviation	0.05	0.78

Flexual Testing ISO 14125A

RF_NEW_45	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
1	62.2	1.7	4.03	361.64
2	52	1.4	4	295.34
4	48.5	1.3	3.96	283.65
5	56.9	1.5	4.01	318.06
6	59.2	1.6	3.8	349.6
7	51.6	1.5	3.63	305.07
8	59.8	1.6	3.88	345.54
9	57.6	1.6	3.88	340.44
Mean	56	1.5	3.9	324.92
S.D.	4.8	0.22	0.1	47.21

D Test results Phase 2A

Recycled filler new 50 (RF_NEW_50)
Date: 6-2-2025 Mould: Sample mould (BMC) Note: 1 plate

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.135416667	3.298758286
2	0.173611111	4.134582308
3	0.135416667	3.295771677
4	0.121527778	2.879354835
5	1	0
6	1	0
7	1	0
8	1	0
9	1	0
10	1	0
Average	0.14	3.40
Standard deviation	0.02	0.53

Flexual Testing ISO 14125A

RF_NEW_50	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
1	72	1.5	4.98	153.97
2	69.5	1.5	4.95	147.94
3	74.5	1.6	4.69	164.58
4	62.1	1.3	4.82	137.24
Mean	69.5	1.5	4.86	150.93
S.D.	5.34	0.11	0.13	11.43

Recycled filler new 55 (RF_NEW_55)
Date: 6-2-2025 Mould: Sample mould (BMC) Note: 1 plate

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.18	2.64
2	0.17	2.41
3	0.17	2.42
4	0.15	2.08
5	0.16	2.35
6	0.18	2.59
7	0.14	2.15
8	0.18	2.61
9	0.15	2.24
10	0.18	2.72
11	0.17	2.48
12	1.00	0.00
Average	0.23	2.43
Standard deviation	0.24	0.21

Flexual Testing ISO 14125A

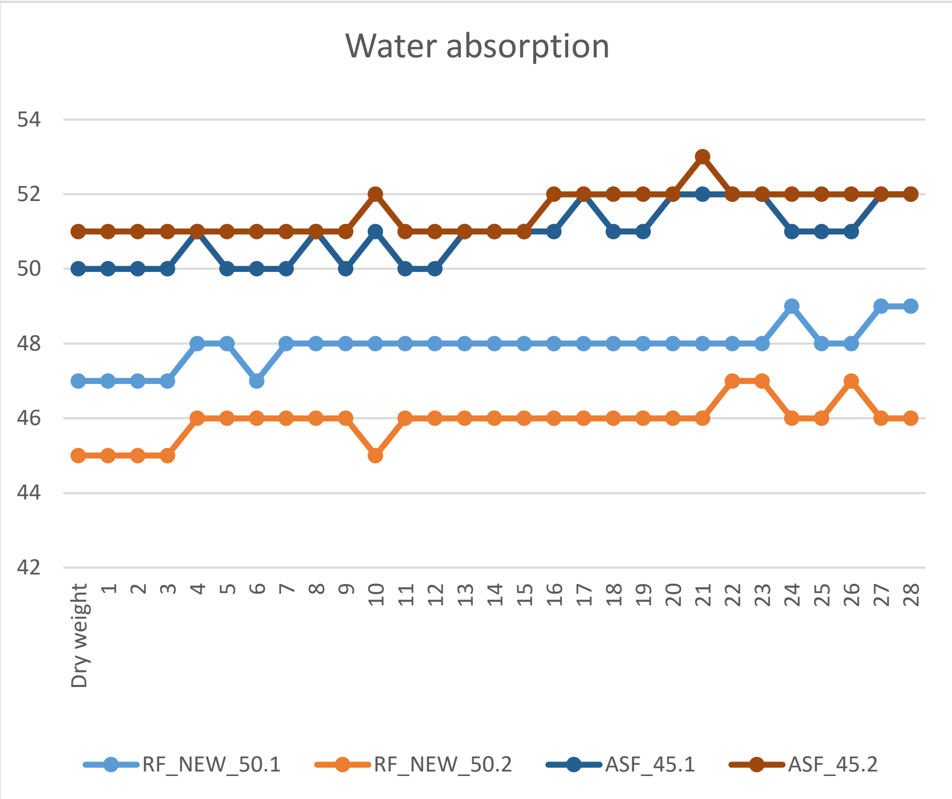
RF_NEW_55	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
1	70.3	1.4	5.11	381.1
2	74.9	1.6	4.78	428.37
3	60.8	1.3	4.66	347.94
4	66.2	1.5	4.53	393.65
5	61.8	1.3	4.68	352.55
6	60.3	1.3	4.42	339.12
8	68	1.5	4.57	396.8
Mean	66.1	1.4	4.68	377.07
S.D.	5.45	0.12	0.22	32.15

D Test results Phase 2A

Waterabsorption ASF_45 & RF_NEW_50

Name sample	Sample	dry [g]	14d [g]	14d-Av [%]	28d [g]	28d-Av [%]	Increase [%]	Average increase [%]
ASF_45								**4.0**
	1	50	51	2.0	52	4.0	4.0	
	2	51	51	0.0	52	2.0	3.9	
RF_NEW_50								**4.3**
	1	47	48	2.1	49	4.3	4.3	
	2	45	46	2.2	46	2.2	4.4	

Weight per day



Waterabsorption data per day - ASF_45 & RF_NEW_50

Day	ASF_45.1	ASF_45.2	RF_NEW_50.1	RF_NEW_50.2
Dry weight	50	51	47	45
1	50	51	47	45
2	50	51	47	45
3	50	51	47	45
4	51	51	48	46
5	50	51	48	46
6	50	51	47	46
7	50	51	48	46
8	51	51	48	46
9	50	51	48	46
10	51	52	48	45
11	50	51	48	46
12	50	51	48	46
13	51	51	48	46
14	51	51	48	46
15	51	51	48	46
16	51	52	48	46
17	52	52	48	46
18	51	52	48	46
19	51	52	48	46
20	52	52	48	46
21	52	53	48	46
22	52	52	48	47
23	52	52	48	47
24	51	52	49	46
25	51	52	48	46
26	51	52	48	47
27	52	52	49	46
28	52	52	49	46

E Test results Phase 2B

Recycled filler outside 50 (RF_OUT_50)
Date: 8-4-2025 Mould: Sample mould (BMC) Note: 2 plates

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.14	1.97
2	0.21	2.60
3	0.18	2.26
4	0.13	1.63
5	0.18	2.32
6	0.18	2.19
7	0.21	2.73
8	0.18	2.29
9	0.18	2.28
10	0.22	2.77
11	0.21	2.72
12	0.21	2.65
Average	0.18	2.37
Standard deviation	0.03	0.35

Flexual Testing ISO 14125A

RF_OUT_50	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
1	47.1	1.1	4.21	416.15
2	67.7	1.6	4.3	579.28
3	55.4	1.3	4.26	494.52
4	49.6	1.2	4.23	420.54
5	54.9	1.4	4.07	488.1
6	57.6	1.4	4.2	512.89
7	64.7	1.6	4.19	562.62
8	55.5	1.3	4.22	472.04
9	48.1	1.1	4.5	394.95
Mean	55.6	1.3	4.24	482.34
S.D.	7.06	0.17	0.11	64.13

Recycled filler outside 55 (RF_OUT_55)
Date: 8-4-2025 Mould: Sample mould (BMC) Note: 2 plates

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.18	3.11
2	0.17	2.97
3	0.13	2.32
4	0.13	2.24
5	0.18	3.15
6	0.12	2.03
7	0.13	2.36
8	0.17	2.90
9	0.16	2.71
10	0.11	1.85
11	0.11	1.85
12	0.16	2.86
Average	0.15	2.53
Standard deviation	0.03	0.48

Flexual Testing ISO 14125A

RF_OUT_55	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
2	65.3	1.5	4.47	340.94
3	60.5	1.4	4.51	314.68
4	57	1.3	4.36	270.6
5	55.6	1.3	4.4	263.93
6	62.4	1.4	4.43	301.47
7	60	1.4	4.42	311.01
8	54.4	1.2	4.4	278.94
Mean	59.3	1.4	4.43	297.37
S.D.	3.89	0.08	0.05	27.62

E Test results Phase 2B

Recycled filler QUV 50 (RF_QUV_50)
Date: 22-4-2025 Mould: Sample mould (BMC) Note: 1 plate

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.12	2.39
2	0.14	2.91
3	0.10	2.01
4	0.15	2.99
5	0.14	2.89
6	0.15	2.95
7	0.13	2.73
8	0.13	2.69
9	0.13	2.69
10	0.13	2.69
11	0.13	2.61
12	0.13	2.63
Average	0.13	2.68
Standard deviation	0.01	0.27

Flexual Testing ISO 14125A

RF_QUV_50	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
1	46.3	1.2	4.21	155.81
3	49.2	1.3	4.14	163.32
4	51.3	1.4	4.06	179.35
5	55.4	1.5	4.08	196.78
6	53.7	1.4	4.12	179.19
7	53.2	1.4	4.14	182.67
8	53.1	1.4	4.06	181.58
Mean	51.7	1.4	4.1	176.96
S.D.	2.3	0.21	0.05	11.68

Recycled filler QUV 55 (RF_QUV_55)
Date: 22-4-2025 Mould: Sample mould (BMC) Note: 1 plate

Impact Testing ISO 179

Number	Energy (J)	Charpy impact (kJ/m^2):
1	0.16	3.28
2	0.13	2.55
3	0.15	3.19
4	0.15	3.07
5	0.15	3.04
6	0.12	2.30
7	0.14	2.78
8	0.12	2.49
9	0.14	2.89
10	0.11	2.30
11	0.12	2.33
12	0.09	1.81
Average	0.13	2.67
Standard deviation	0.02	0.44

Flexual Testing ISO 14125A

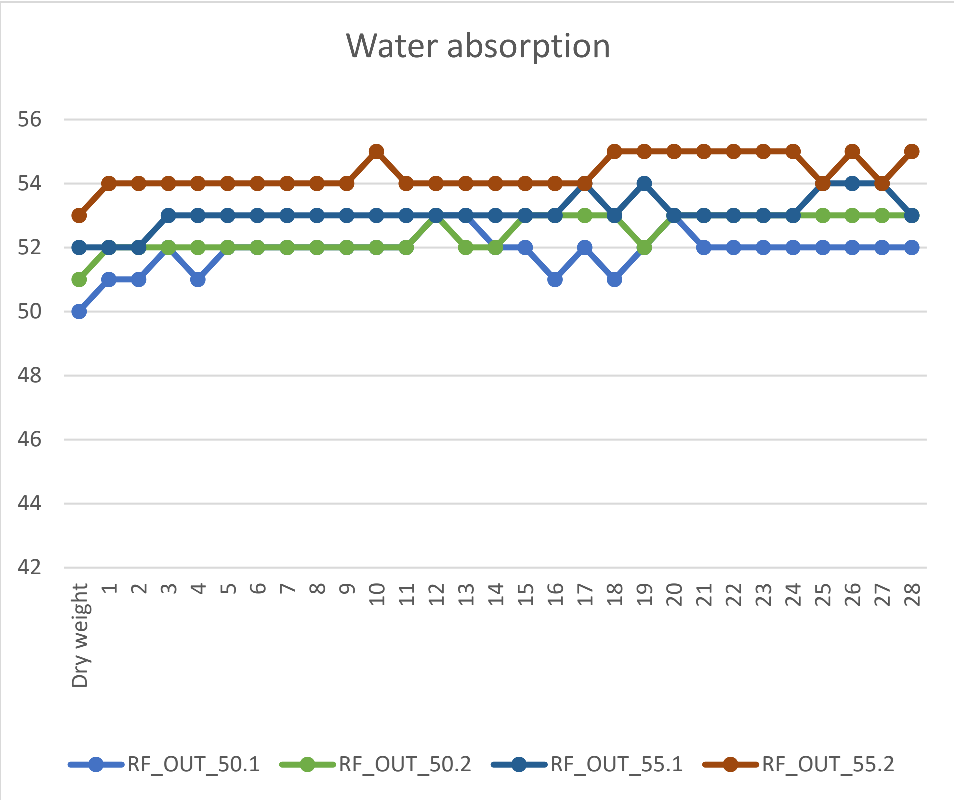
RF_QUV_55	Flexural Strength [MPa]	Flexural Strain [%]	Flexural Modulus [GPa]	Force at Maximum Flexure load [N]
1	60.6	1.3	4.75	203.14
2	58	1.4	4.24	192.47
4	62.8	1.4	4.69	212.13
5	56.1	1.3	4.4	187.77
6	61.8	1.5	4.55	211.35
7	58.6	1.4	4.42	193.01
8	57.7	1.4	4.36	194.18
Mean	59.4	1.4	4.5	199.2
S.D.	2.24	0.06	0.17	9.02

E Test results Phase 2B

Waterabsorption RF_OUT_50 & RF_OUT_55

Name sample	Sample	dry [g]	14d [g]	14d-Av [%]	28d [g]	28d-Av [%]	Increase [%]	Average increase [%]
RF_OUT_50								**5.0**
	1	50	52	4.0	52	4.0	6.0	
	2	51	52	2.0	53	3.9	3.9	
RF_OUT_55								**3.8**
	1	52	53	1.9	53	1.9	3.8	
	2	53	54	1.9	55	3.8	3.8	

Weight per day



Waterabsorption data per day - RF_OUT_50 & RF_OUT_55

Day	RF_OUT_50.1	RF_OUT_50.2	RF_OUT_55.1	RF_OUT_55.2
Dry weight	50	51	52	53
1	51	52	52	54
2	51	52	52	54
3	52	52	53	54
4	51	52	53	54
5	52	52	53	54
6	52	52	53	54
7	52	52	53	54
8	52	52	53	54
9	52	52	53	54
10	52	52	53	55
11	52	52	53	54
12	53	53	53	54
13	53	52	53	54
14	52	52	53	54
15	52	53	53	54
16	51	53	53	54
17	52	53	54	54
18	51	53	53	55
19	52	52	54	55
20	53	53	53	55
21	52	53	53	55
22	52	53	53	55
23	52	53	53	55
24	52	53	53	55
25	52	53	54	54
26	52	53	54	55
27	52	53	54	54
28	52	53	53	55

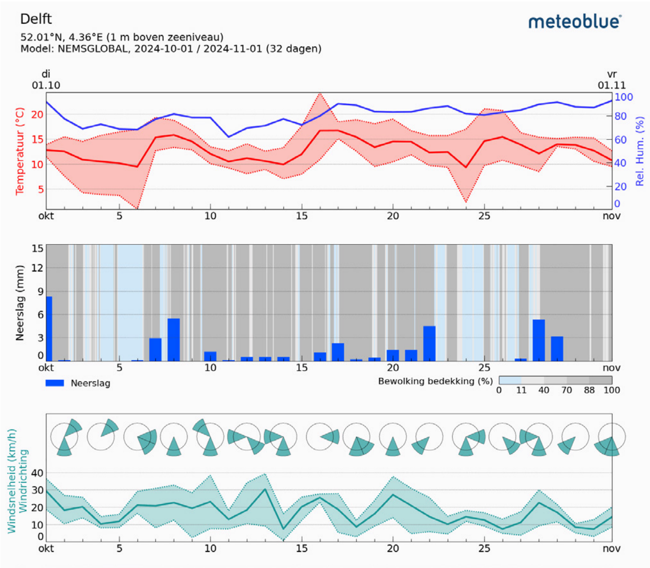
F Comparison samples

Samples	1. Flexural Strength	2. Impact Resistance	3. Workability	4. Durability	Average	.	4.1 Frost	4.2 Water absorption	4.3 QUV Results
ASF_40	4.5	2.5	4	x	**3.7**		x	x	x
ASF_45	4.5	1.5	5	3	**3.5**		3		
ASF_50	4.5	2.5	5	x	**4.0**		x	x	x
RF_NEW_45	3	2.0	2	x	**2.3**		x	x	x
RF_NEW_50	4.5	2.5	3	4.5	**3.6**		5		4
RF_NEW_55	4	1.5	4	x	**3.2**		x	x	x
RF_OUT_50	3.5	1.5	3	4.5	**3.1**		5		4
RF_OUT_55	3.5	1.5	4	3	**3.0**		3		3
RF_QUV_50	3	1.5	3	x	**2.5**		x	x	x
RF_QUV_55	3.5	2.5	4	x	**3.3**		x	x	x
Average	**3.85**	**2.0**	**3.7**		**3.225**		**4**	**#DIV/0!**	**3.66666667**

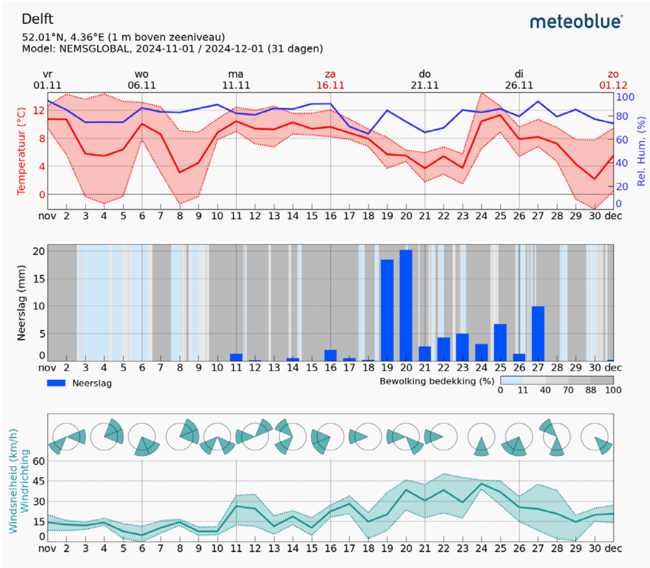
Evaluation scale	1. Flexural Strength (MPa)	Resistance (kJ/m²)	3. Workability	4. Durability
	Scale 0-80	Scale 1-6	Scale 0-5	Scale 0-5
	0 = 0-16	0 = 1-2	0 = liquid not workable	0 = total destruction
	1 = 17-32	1 = 2-3	1 = thick liquid	1= cracks and all of above
	2 = 33-48	2 = 3-4	2 = super sticky	2= deformation
	3 = 49-64	3 = 4-5	3 = sticky	3= visual change (coloration)
	4 = 65-80	4 = 5-6	4 = thick crumble (a bit sticky)	4= minimal visual change
	5= 80	5= 6	5 = crumble	5= no visual change

G Weather data

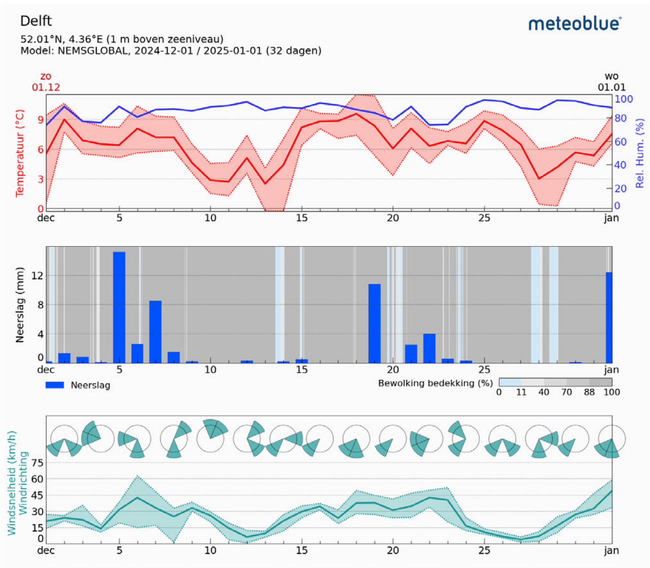
Weather data October 2024 - Delft



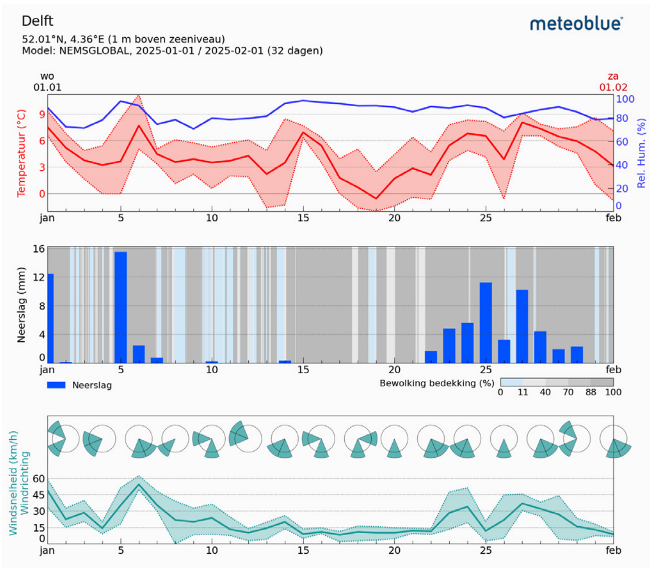
Weather data November 2024 - Delft



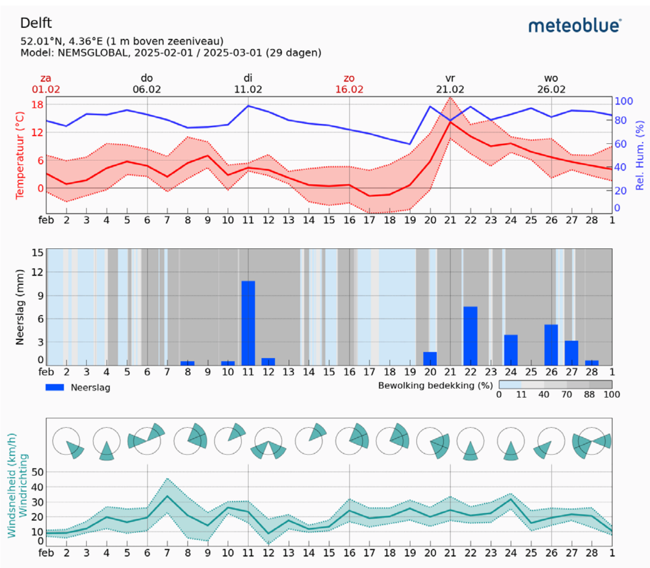
Weather data December 2024 - Delft



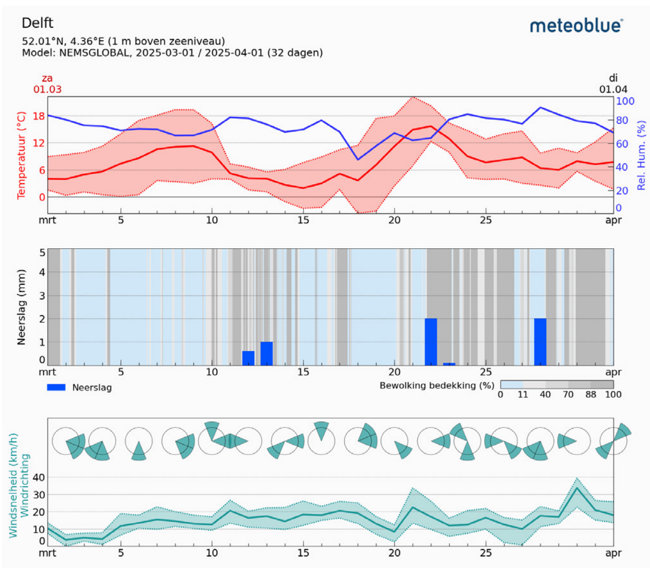
Weather data January 2025 - Delft



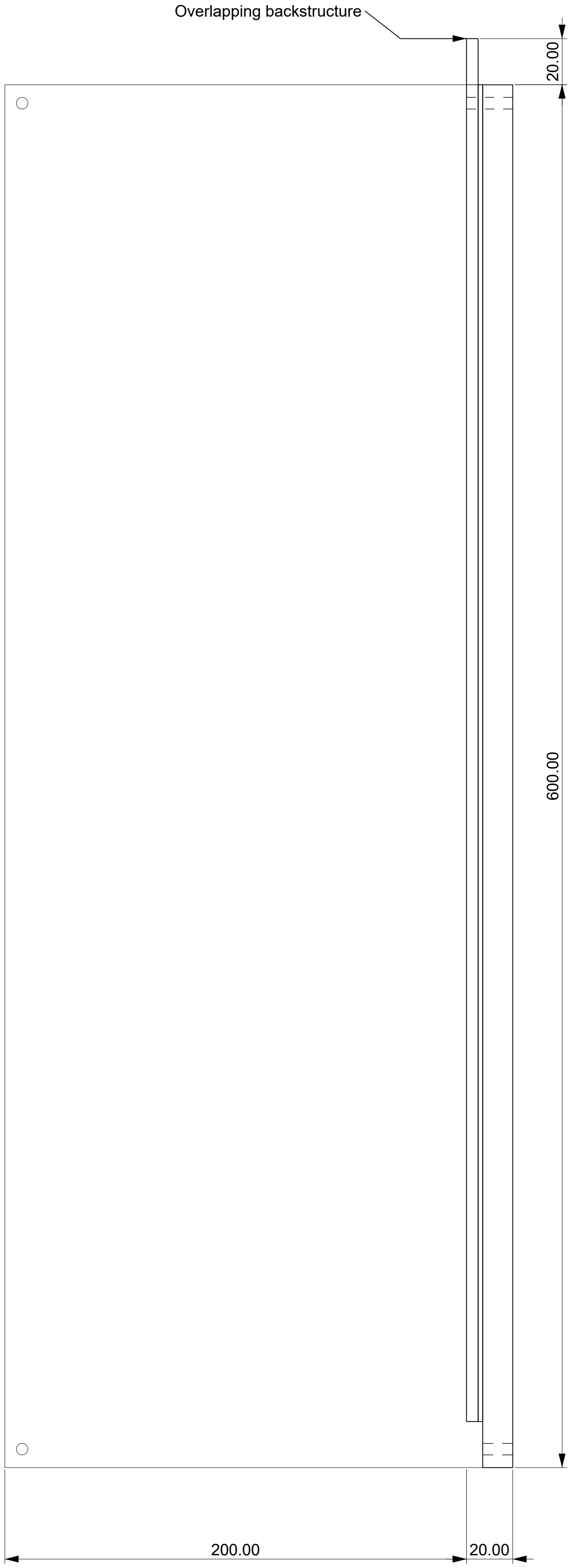
Weather data February 2025 - Delft

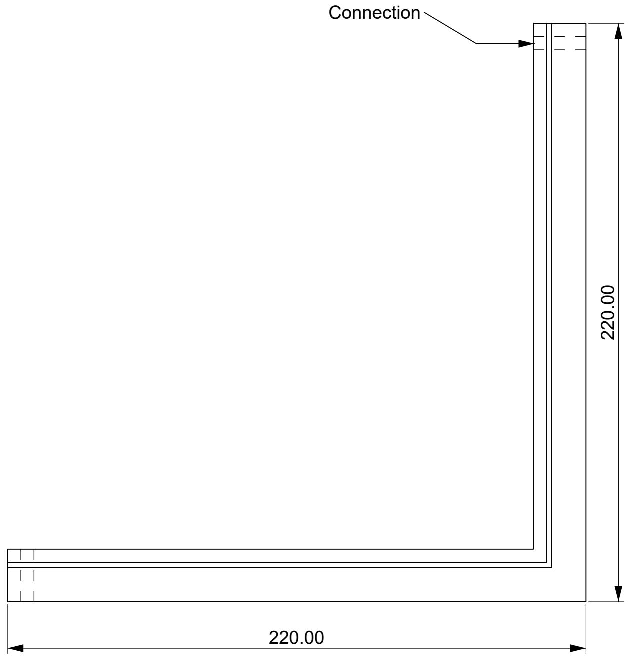


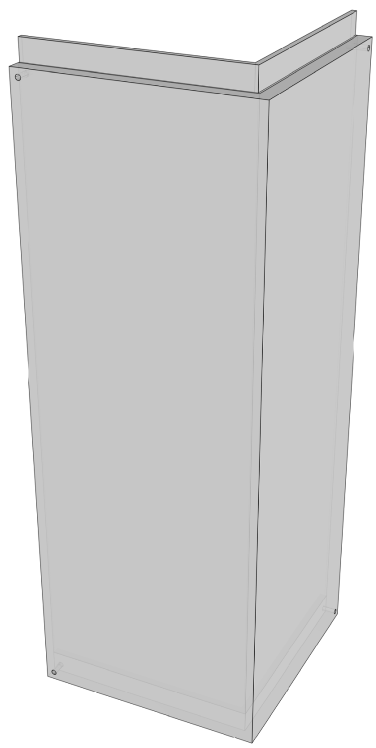
Weather data March 2025 - Delft



H Design details







TU Delft