Re-P-Tile

Recycling PVC into a façade Tile

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Exploration of the potential of recycled PVC waste streams from construction and demolition industry to engineer a façade sheet material as an architectural product

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“We all have a potential that far exceeds what our minds can imagine,

what we lack is the belief that we have it and desire to utilise it”

Special thanks to:

Mr. Jack Snijders

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Abstract

"Waste does not start as waste; instead, it is useful material in the wrong place" as explained by philosophy professor Michael Thompson in his book Rubbish Theory (Thompson, 1979). With the increasing population, industrialization, and rising human standards of living, waste generation is also increasing. The UNEP's Global Waste Management Outlook 2024 projects that by 2050, the world's waste generation will have increased from 2.1 billion tonnes in 2023 to 3.8 billion tonnes, emphasizing the need to transition from the garbage era to one where waste is transformed into resources. A breakdown of world's municipal solid waste composition in the report indicates that a large amount of waste comprises of food and garden waste, paper and cardboard waste, glass, metal, and plastics. While food and garden waste, paper and cardboard are biodegrade and ,glass and metal have infinite recyclability, the major issue arises with plastic, which is a growing global concern. Plastic has become essential in daily life due to its cost benefits, but the complexity of recycling lies in identifying its diverse compositions, contaminants, and fillers. The construction and demolition industry significantly contributes to Europe's plastic waste generation.

The thesis entitled **"Re-P-Tile"** focuses on the challenges that hinder the recycling process, specifically targeting the PVC waste stream in the construction and demolition industry. The aim of the thesis is to find alternative utilisation paths of this waste, by crating architectural products.

To fully understand the complexity of the plastic waste management problem, particularly in Europe, a literature review was conducted. This review involved examining online data and consulting with research experts, industry professionals, and fellow master thesis students. The study aimed to identify the challenges associated with recycling plastic and analsye plastic material flow. All types of resins were evaluated, with an analysis of material properties including the cost of virgin plastic, mechanical properties, flammability, and waste production percentage and PVC was chosen to study further.

Based on the identified plastic waste streams, PVC was found to generate greater amounts of waste than other resins, with particular concern regarding construction and demolition waste.PVC windows and pipes have material qualities that allow for their disassembly and segregation at the source, making them suitable for cascade recycling to manufacture other components instead of ending up in landfills. The idea of recycling PVC windows with UV-resistant chemicals and sewage pipes with calcium carbonate fillers is an example of transforming waste into a treasure.

Considering the high quality of PVC waste of windows and pipes, the second part of this thesis is dedicated to exploring the potential of recycling PVC for developing architectural components for cladding purpose. The thesis aimed to engineer a PVC sheet material as an architectural component. The composition, impurities, additive content, and thermal behavior of the waste samples were experimentally characterised, along with experimenting with different production tests to find a feasible production technique. A heat press was used to produce the tiles, and the influence of the production parameters was optimized. This included optimizing operational parameters such as temperature, pressure, and dwell time, as well as the effect of shred size and composition. The samples were evaluated for mechanical strength testing through the application of ASTM 970 standard procedures, microscopic visualization, and UV resistance testing.

The findings of these experiments indicate the material's potential to be used as a façade panel, offering an alternative to conventional cladding materials. The mapping of waste management hierarchy and the carbon footprint assessment of the material, benchmarked against conventional materials, show promising results for the application of this material as a façade panel. The design freedom of the panels could potentially be used for dual façade cladding, particularly for artistic expression. For instance, these panels can produce an expressive visual statement on facades that incorporate dynamic wind or movement and can function as a screen on a white surface. After all, a façade is a canvas for expression, much more than just the exterior of a structure.

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1

Research framework

Background | Methodology | Outline

1.1 Background

Waste management is a global problem that has significant environmental and public health implications. The waste streams contributing to the waste generation can be analyzed by looking into the materials that end up in the municipal waste. Figure 1 represents data from "Municipal waste statistics" retrieved from Eurostat, 2024 shows that the major waste streams from the materials aspect is the food, waste paper and plastic. Unlike food and waste paper, which have relatively lower environmental impacts, as well as glass and metals, which have unlimited recyclability and demand for recycling, plastic presents a huge and escalating global waste management issue.

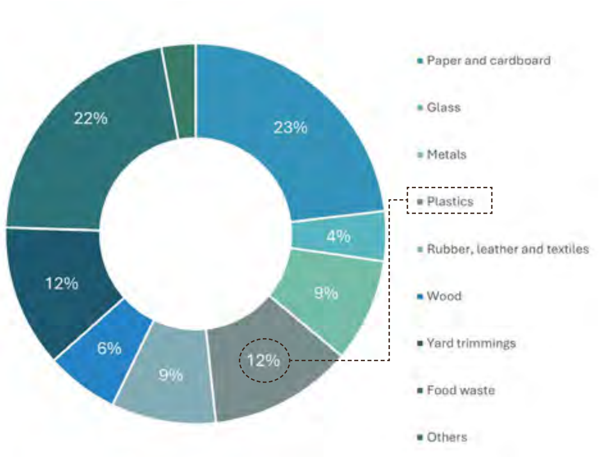

Figure 1: Graphical representation of materials contributing for solid municipal waste generation in EU, 2020 in percentage (Source : Eurostat)

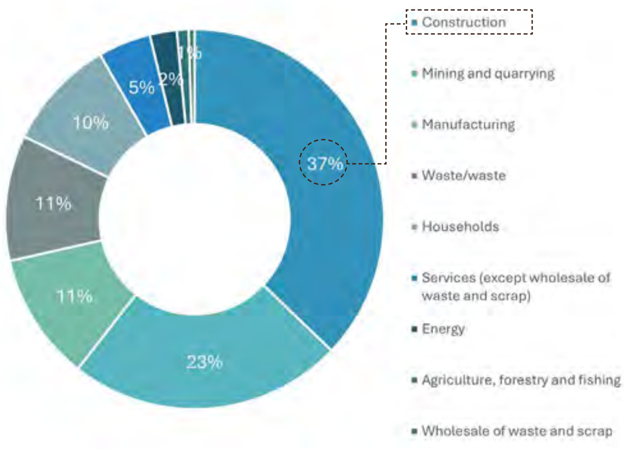

Figure 2: Graphical representation of economic activities and households contributing for waste generation in EU, 2020 in percentage (Source : Eurostat)

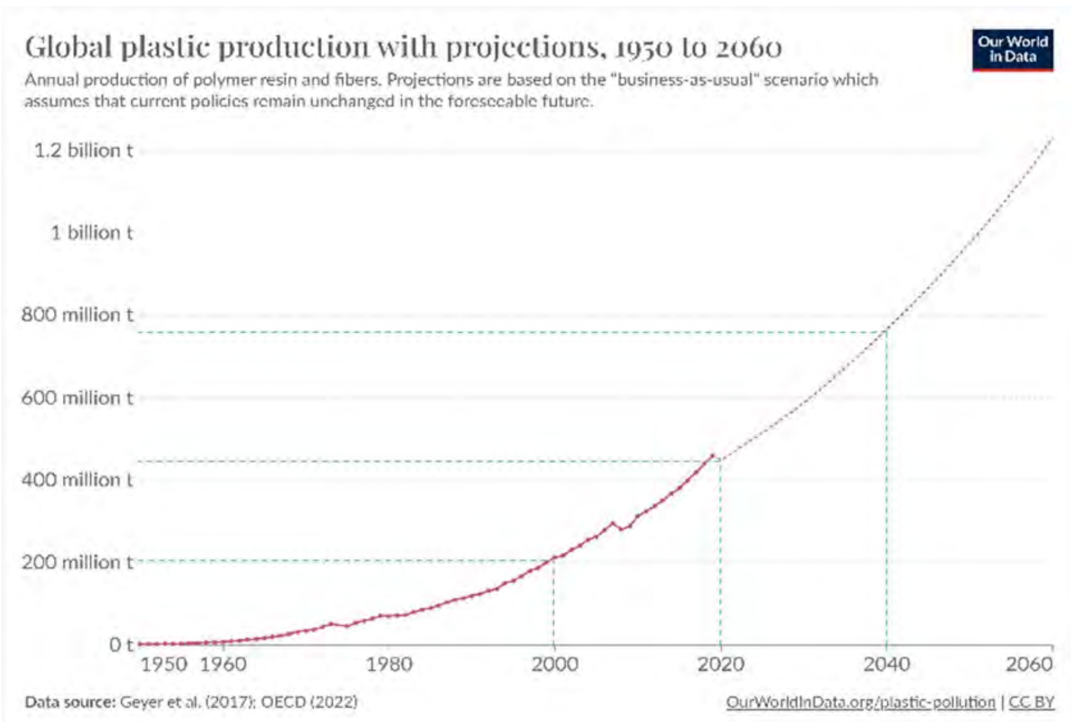

Figure 3: Graphical demand of the global plastic production (Source: Our world in Data)

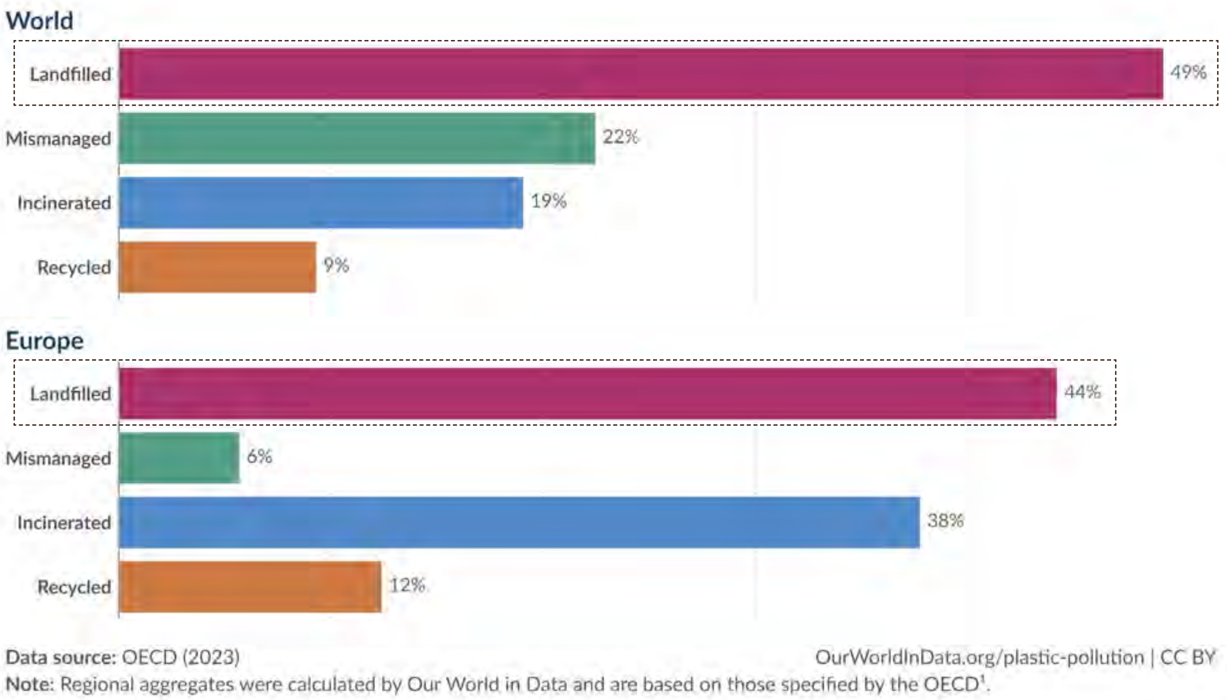

Figure 4: Graphical representation of share of plastic waste that is recycled, landfilled, incinerated and mismanaged in 2019 (Source : Eurostat)

The emergence of plastic in the late 1800s marked a transformative moment in human history. The very first plastic 'Bakelite' was introduced in 1907 according to the world in our data (Ritchie, Samborska, & Roser, 2023) and since the last 70 years there has been a steep demand for the material. According to data from our world in data (Geyer et al) , the demand of plastic doubles every two decade (see Figure 2). The material makes it to the forefront of modern manufacturing due to its versatility, affordability and durability and pervades the modern lives as it is used in everything from packaging to building materials. This alarming demand in global plastic consumption is a cause of concern for the waste management as most of the plastics used is discarded as waste at the end of the use.

While we believe that most of the plastic waste is recycled, data from the OECD (see Figure 4) reveals that only 9% of total plastic waste is recycled globally, a trend that holds true for Europe as well. The majority of plastic waste ends up in landfills or is mismanaged, leading to significant environmental and health hazards. This mismanagement underscores the critical need to rethink the plastic waste management strategies and focus on developing effective solutions to minimize the environmental footprint of plastic waste is imperative for sustainable living and the well-being of our planet.

In parallel with the challenges posed by plastic waste, the construction and demolition sector emerges as a substantial contributor to the global waste stream. The industry's resource-intensive nature generates various types of waste materials, including concrete, wood, metals, glass, and plastics, constituting approximately 37% of total solid waste globally (see Table 4). Within this spectrum, plastics in construction, utilized in pipes, insulation materials, and packaging, mirror the challenges associated with single-use plastics when it comes to disposal at a building's end-of-life. The durability of plastics, advantageous during a building's lifespan, becomes a concern when structures are demolished, contributing to long-term environmental impacts.

Efforts to address construction and demolition (C&D) waste in the EU have promoted sustainable practices through specific regulations. According to the European Commission retrieved on May 31, 2024, construction and demolition waste management is a crucial aspect of environmental policy. The main goals are to manage C&D waste in an environmentally sound manner and to harness its potential to support the circular economy transition.

- Under the Waste Framework Directive, C&D waste is a priority stream with set objectives:
- Increase the re-use, recycling, and material recovery of non-hazardous C&D waste to at least 70% by weight.
- Promote selective demolition to safely handle hazardous substances and enable high-quality recycling.
- Reduce overall waste generation.

1.2 Problem statement

The demand for plastic consumption is a catalyst for material extraction. Plastics Europe's 2022 statistics reveal that approximately 82% of plastics utilized originate from fossil-based sources, while a mere 18.3% of plastics within the construction and demolition sector undergo recycling. Despite the sector's significant waste production and the effectiveness of its resin performance, there is an alarming lack of adaptation to circular economy strategies. This heavy reliance on fossil fuels stands in sharp contrast to sustainable development objectives. The European Union (EU) is committed to transitioning toward a circular economy, aiming for enhanced resource efficiency and waste minimization. However, fossil-based plastics, characterized by a linear "take-make-dispose" model, present a fundamental challenge to this ambition, creating a need to focus more on plastic recycling within the circular economy framework.

The principal challenge in plastic recycling lies in its inherent complexity, marked by diverse compositions, contaminants, and fillers across various plastic types. This complexity poses challenges to the recycling process, particularly in terms of maintaining the mechanical properties similar to that of original products. Another major reason is that for the plastics to be recycled, they have to be segregated by resin type. Consequently, manual labour-intensive processes are required, creating competitiveness within the recycling sector.Moreover, with each recycling iteration, material properties undergo noticeable deterioration, resulting in declination in structural integrity and performance.

To address these concerns, there is growing interest in designing products to last longer and be reused. However, economic challenges, especially the availability and lower cost of new virgin plastic, makes it difficult to widely adopt recycling initiatives.

Additionally, UV radiation is a critical concern, as it induces photodegradation resulting in material loss, thereby compromising structural stability. However, there is potential to upcycle plastic waste into architectural products by using existing UV retardants as contaminants in certain items without changing the chemical makeup. This creative approach can help reduce material degradation and support sustainability goals in a circular economy.

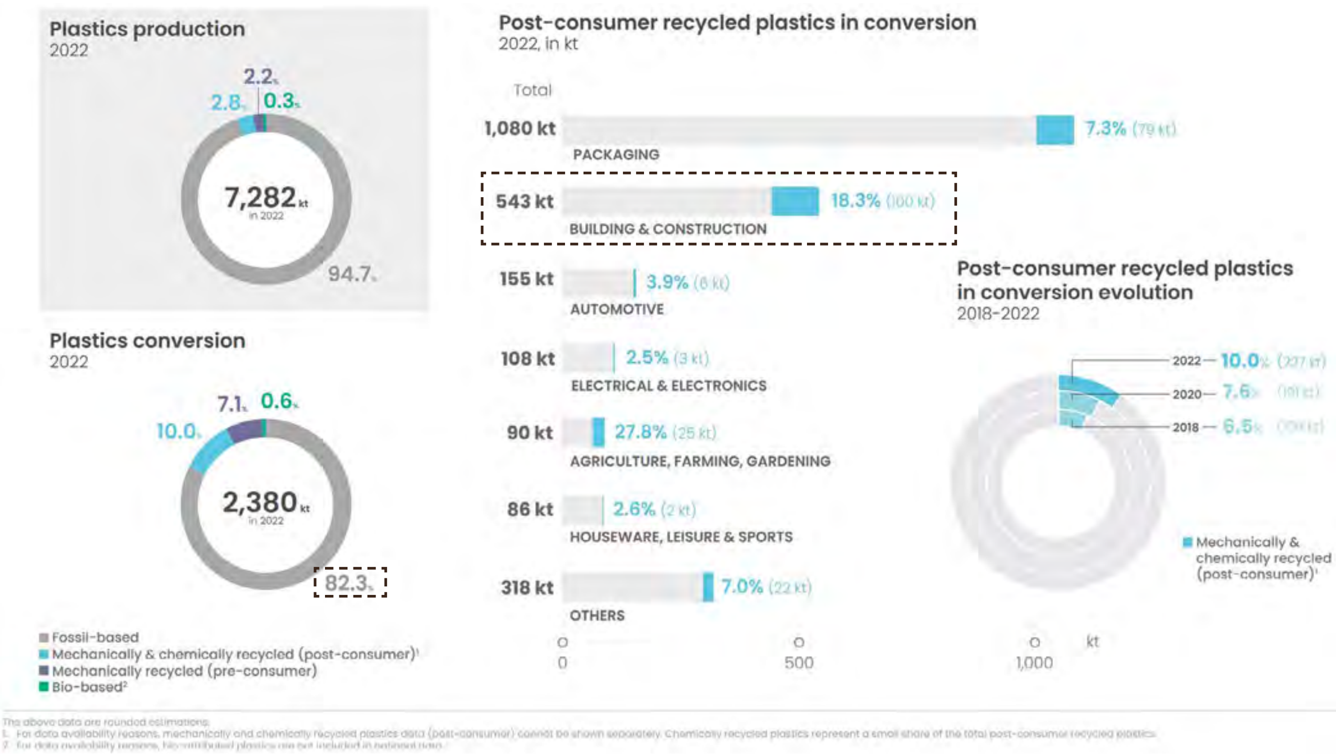

Figure 5: Graphical demand of the global plastic production and conversion in 2022 (Source: PlasticEurope)

“ We need to use fewer virgin materials, less plastic and no harmful chemicals. We need to ensure that we use, reuse, and recycle resources more efficiently. And dispose safely of what is left over.”

Inger Andersen , UNEP Executive Director

Image credits : © Claudio Schwarz on Unsplash
Quote from : UNEP Nairobhi | Source : https://x.com/UNEP/status/1724060089374413046

1.3 Objective

1.3.1 Limitations

The research is confined to utilizing PVC pure resin waste streams exclusively, without the incorporation of other plastic resins, which may limit the versatility of the production process and resulting architectural material. The thesis focuses on developing tiles for façade applications, keeping aside other potential uses or broader applications of recycled PVC materials due to the feasibility of testing facilities.

1.3.2 Primary objective

The primary objective of this study is to develop a component for architectural applications by engineering tiles from pure PVC resin waste streams, without any mixture of other plastic resins. This research aims to assess the feasibility of tile production and evaluate its material strength and UV degradation along with benchmarking the material into conventional material used in application location.

1.3.3 Secondary objective

- The first objective of the research is to explore the challenges faced in recycling plastics. This exploration is conducted by a literature review.
- Following the literature review, the material properties of different types of plastic resins are assessed, focusing on their application in the construction industry and the contribution of each resin type to waste generation. The aim is to select a waste stream to work with.
- The chosen resin, PVC, is studied with respect to current trends in recycling challenges and the necessity of recycling.
- The retrieved waste samples are scientifically analysed to understand their composition and to establish an operational range to work in the experimental phase.
- The experimental phase involves exploring feasible production techniques and operational parameters, producing various samples that are evaluated for mechanical strength and UV resistance.
- The developed material is assessed for circularity using mapping R-strategies, carbon footprint, design flexibility, and benchmarking against conventional materials.
- The research concludes with various findings and further recommendations.

1.3.4 Results

The expected outcome of the thesis is to have a tile as an end product, upcycled and engineered to withstand a certain amount of load and have potential design flexibility to be used in architectural applications. Ideally, this should yield a sheet material which has a necessary properties needed for the façade material inherently with the material property which can be produced in a very feasible production facility.

Given the limited recyclability of plastic, it is crucial to maintain the chemical structure without degradation across multiple recycling cycles.

We need a way to close the material loop and recycle plastic waste into new usable materials. Otherwise, there is limited use in convincing consumers to recycle, as merely exporting plastics to other countries is not sustainable.

1.4 Relevance

1.4.1 Environmental relevance

The construction industry significantly contributes to global plastic waste generation. This sector uses a large amount of plastic materials for various applications, such as insulation, piping, and fittings, and produces substantial plastic waste during construction, renovation, and demolition activities. Addressing this issue is crucial for achieving sustainability goals and minimizing environmental impact. Recycling and reusing materials from construction and demolition (C&D) waste reduce the demand for virgin materials, which are typically derived from non-renewable resources like fossil fuels.

Despite anticipated improvements in waste collection, sorting, and treatment, the increase in plastic waste generation is expected to result in higher volumes of mismanaged waste—waste not disposed of in an environmentally sound manner—compared to 2020 levels (see Figure 6 and Figure 7), and significantly increased plastic waste management costs. While the output of recycling is expected to increase, the increased generation of plastic waste will maintain a significant roles of landfilling and incineration in treating plastic waste at the end of its life. Therefore, it is crucial to upcycle waste streams to prevent them from being disposed of in landfills.

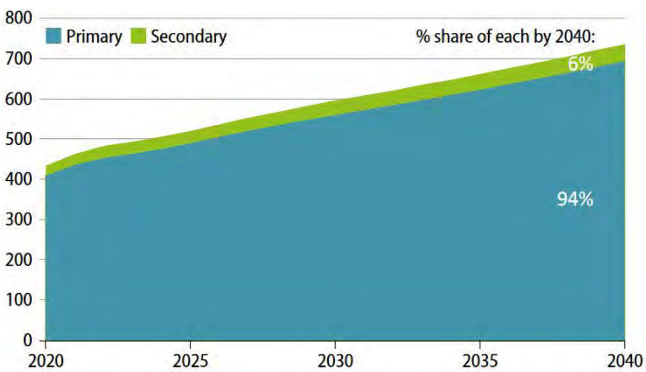

Figure 6: Projection of annual plastic use (Source: PlasticEurope)

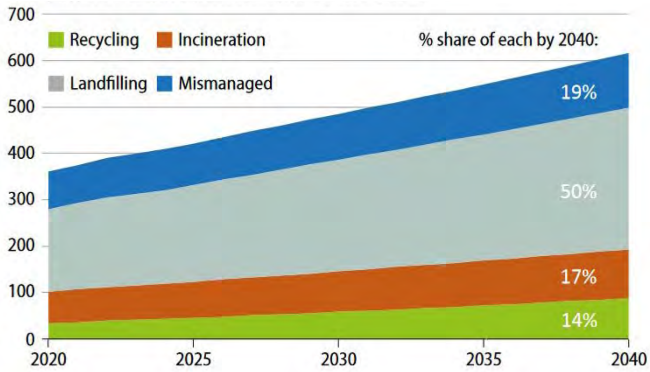

Figure 7: Projection of fate of waste and its end-of-life scenarios (Source: PlasticEurope)

1.4.2 Social relevance

With the rising global problem of waste management, the upcycling of plastic waste into architectural components emerges as an innovative and sustainable solution. Upcycling represents a paradigm shift in how we perceive waste. Instead of discarding plastic materials to landfills or incinerators, upcycling gives them with new purpose and value. Architectural components crafted from upcycled plastic waste offer a tangible positive outlook, transforming what was once considered trash into functional and aesthetically pleasing elements of built environments.

The social relevance of upcycling plastic waste into architectural components is multifaceted. Firstly, it addresses the pressing environmental crisis posed by plastic pollution. With landfills overflowing and under exhaustion, upcycling diverts plastic waste from these pathways, reducing its impact on ecosystems and mitigating the depletion of natural resources.It also fosters a culture of sustainability and resourcefulness within communities. By harnessing locally sourced plastic waste as raw material, upcycling initiatives empower individuals and communities to take ownership of their environmental footprint and reduce the dependency on the natural non-renewable resources.

Nzambi Matee from Kenya started Gjenge Makers, a company that turns plastic waste into building blocks to help with the global plastic pollution issue, especially in Kenya. Matee's initiative shows how using recycled plastic can be a big part of the solution. This initiative proves that creative ideas that care about the environment and society can make a big difference.

Incorporation of upcycled plastic components into architectural design promotes social equity and inclusivity. Conventional building materials often come with high production costs and environmental consequences. In contrast, upcycled plastic materials offer a more affordable and accessible alternative.

Figure 8: Images of Matee with the building blocks made from plastic waste (Source: Worldarchitecture.org)

1.4.3 Scientific relevance

Upcycling plastic waste streams into architectural components represents a pioneering approach in sustainable design and construction, bearing scientific relevance in the realms of material science, circularity designing, and product development. This innovative practice not only addresses the pressing issue of plastic pollution but also harnesses the potential of discarded materials to create functional and aesthetically appealing architectural elements.

Firstly, from a material science perspective, the upcycling of plastic waste into architectural components involves extensive testing to understand the properties of various types of plastic in a selected waste stream and experimentation to transform the waste into durable building materials. In this thesis, exploration with hot press is emphasised as it was a feasibilie method of production. This process required experimentation, analysis and validation to ensure quality and durability of the upcycled products, thereby advancing the knowledge base of material science.

The scientific relevance extends to circularity designing, as upcycling plastic waste mitigates the environmental impacts associated with conventional disposal methods such as landfilling and incineration and focuses on bringing the material back into use. By diverting plastic waste from landfills and reducing the demand for virgin materials, upcycling contributes to resource conservation and minimizes carbon emissions. Carbon footprint assessments and mapping R-strategies play an important role in quantifying the environmental benefits of upcycling initiatives, promoting circular economy principles.

Furthermore, upcycling plastic waste into architectural components challenges traditional notions of design and construction, fostering interdisciplinary collaborations between architects, engineers, scientists, and designers. This convergence of expertise fuels innovation and creativity, leading to the development of novel architectural solutions that integrate sustainable materials and techniques.

1.5 Research questions

The research focuses on engineering an architectural product from plastic waste streams by addressing challenges and transforming them into opportunities. The main research question is:

"How can PVC waste streams originating in windows and pipes be processed to develop sheet materials for facades cladding??"

The sub-questions are formulated to inform the broader research methodology and assist in organizing the research progress chronologically, using the results of previous sub-questions as a starting point for subsequent ones. The sub-questions are as follows:

- What are the key challenges in plastic recycling, specifically with PVC, and what strategies can be employed to address these challenges effectively?
- How do we determine the compositional differences and material behaviour in PVC waste from various sources, colors, and applications, which complicate the recycling process?
- How do the compositional differences in the waste streams and production parameters, such as temperature, pressure, and dwell time, influence the processing of PVC into flat tile materials?
- How do variations in shred size and composition affect the mechanical properties of the resulting tiles?
- How can we effectively evaluate the strength of recycled PVC tiles and analyse the causes of failure using morphological analysis and sample homogeneity?
- What role does compositional variation play in influencing the UV stability of these tiles?
- How do aesthetics and material application correlate with sustainability, considering factors like R-strategies to map the waste management hierarchy, carbon footprint, and benchmarking against conventional materials typically used in façade systems?

1.6 Research methodology

The thesis is structured around five integral phases, each contributing to the overarching goal of developing a sheet material for an architectural product from a recycled plastic waste stream:

Phase 1 - Literature review and interviews
In this initial phase, a comprehensive literature review is conducted to identify non-recyclable plastic waste streams. The primary objective is to analyse the material flow of plastic waste, mapping out the various types encountered. The research involves understanding the challenges associated with recycling, which include economic, logistical, technical, regulatory, and societal aspects.

Another important part of the literature is to engage with various research experts, companies operating in a similar domain, and fellow master's thesis students for gaining a comprehensive understanding of the challenges involved. Conversations with research experts provided insights into potential technical innovations. Interacting with other master's thesis students offers valuable leads and practical tips and companies shed light on business challenges and the complexities of transitioning from product development to large-scale production. These interactions collectively helped in a better understanding of the material and the reason behind the challenges encountered.

Phase 2 - Choice of plastic resin
The next phase involved the selection of the preferred resin. This choice was dependent on the inherent properties of virgin plastic and the intended location of the architectural product that is being crafted. Various factors, such as the cost of virgin plastic, mechanical properties, flammability, and waste production percentage, were considered during this selection process. This step is very important as it also affects the type of component that can be created, and the properties that can be dealt with.

After a comprehensive analysis of all the important properties of the material, PVC was chosen as the ideal plastic resin due to its significant waste generation volume, self-extinguishing material characteristics, and the array of material properties it offers. Following this, samples of the PVC were tested to understand their composition, as additives can influence material properties. This testing was conducted both at macro and micro levels, evaluating factors such as the purity of the shreds, the presence or absence of hazardous substances, and the glass transition temperature.
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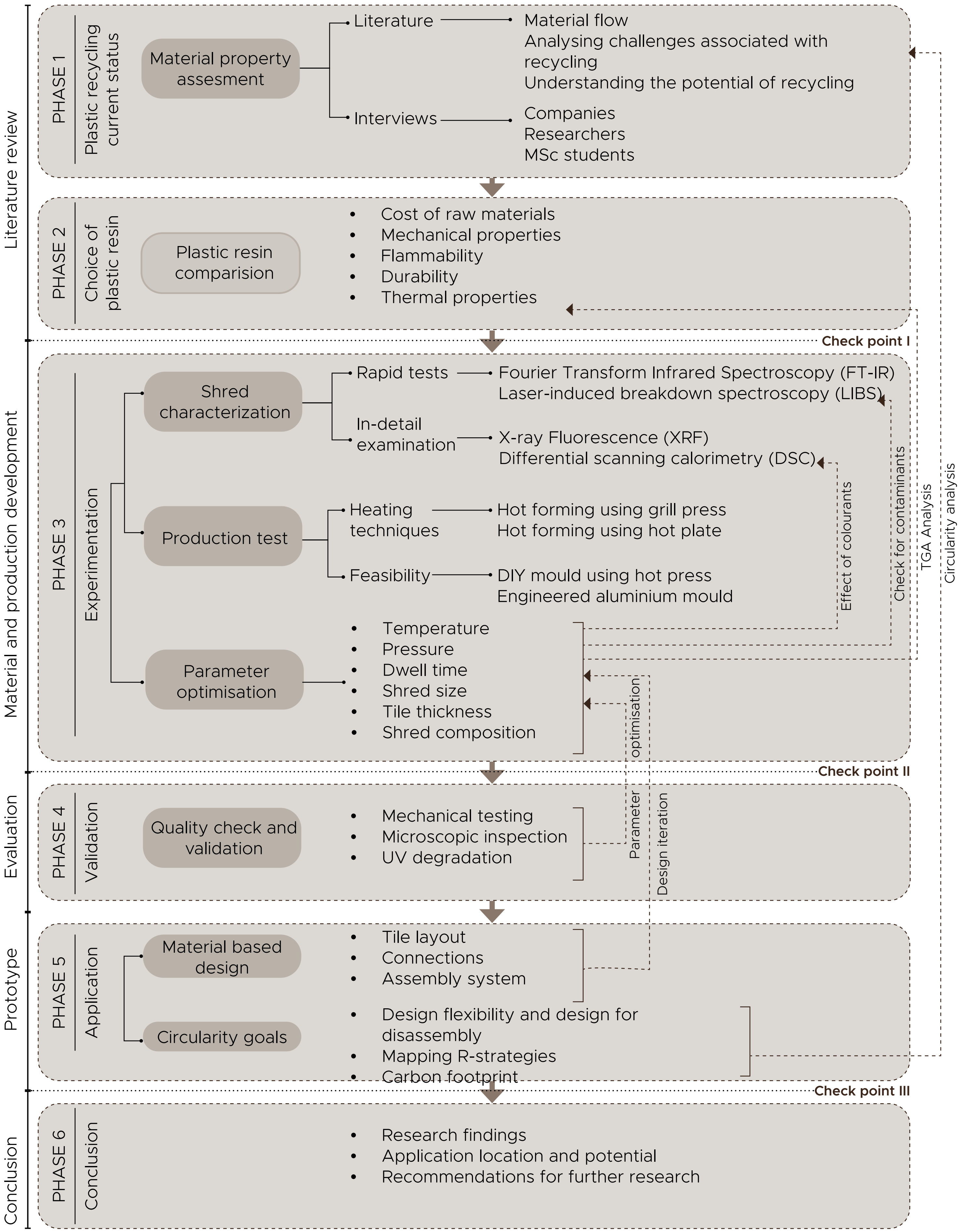
Phase 3 - Experimentation
Following the scientific analysis of sample composition, the rPVC shreds underwent various fabrication techniques that seemed suitable and had the potential to yield the desired outcomes. Initially, the sampling was conducted to ascertain temperature and pressure requirements, followed by using a mould for larger sample production. Due to limited literature on hot pressing PVC samples, extensive experimentation was carried out to determine the optimal pressure for sheet pressing. Initial experiments aimed at maintaining constant composition and thickness of the sheet material while adjusting pressure levels. Subsequently, temperature variations were introduced alongside composition adjustments to understand their interplay. The experimental phase aimed to produce a number of samples at the end of the experimentation phase with varying compositions and thicknesses for validation.

Phase 4 - Validation and analysis
The validation phase consists of a range of standard procedures aimed at assessing the viability of the designed material as a competitive alternative to conventional materials used in similar applications. These tests include conducting accelerated UV tests to gauge long-term effects of UV exposure, as well as flexural strength tests to evaluate its capacity to withstand loads. Additionally, the samples were inspected under the microscope to understand the reason of fracture. Furthermore, the conclusion aims to also address the avenues for further research and development.

Phase 5 - Application and circularity strategies
Based on the extensive study conducted on the material, the final phase includes designing of a component. Various criteria and building requirements are taken into account to choose the location of application. The phase further explores in mapping of R-strategies for waste managemnet hierarchy of the material and determining the carbon footprint with the results are benchmarked with some of the conventional materials used in the application. The application section also focuses on designing facade tile by two methods - (a) by using a mould designed by NPSP.B.V to produced a facade tile and (b) layering technique of the shreds. The section also provides few visualisations of the product in use.

1.7 Research outline



2

Plastic waste and recycling

Review | Challenges | Choice of resin

2.1 Plastic- as a material

Plastics, polymers composed of repeating monomers, are widely used in the modern economy due to their unique properties and cost-effectiveness. Their prevalence has soared over the past decades and is expected to double in the next 20 years (see Figure 2). In building construction, plastics offer diverse advantages, including lightweight, moldability, durability, low maintenance, and cost-effectiveness. This section explores the chemical composition, production processes, and applications of plastics in the built environment, focusing on their role in siding, insulation, and roofing systems.

2.1.1 Chemistry of plastics

Chemical structure of plastics

Plastics are man-made materials made up of long chains of molecules called polymers. Some of the most common plastics include polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyurethane (PU) (Shah et al., 2008). Table 1 shows the chemical structures of these polymers.

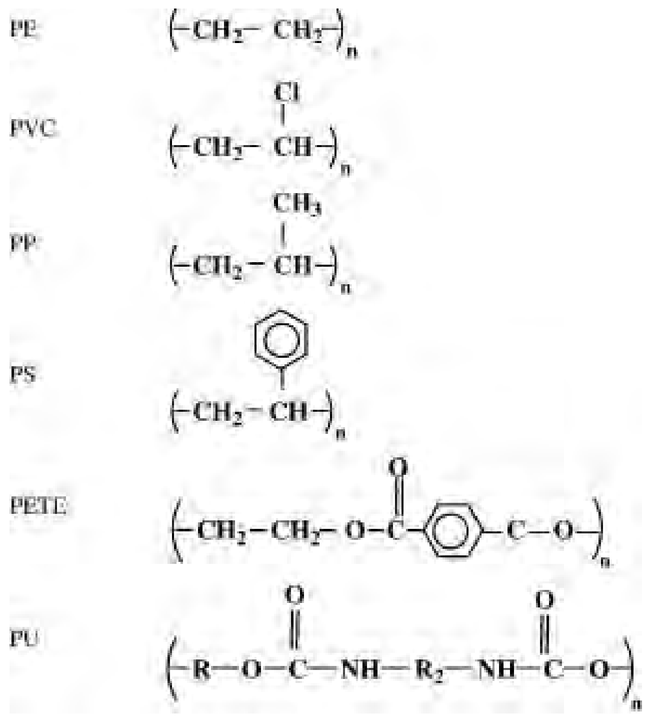


Figure 9: Chemical structures of plastics

(Source: Shah et al., 2008)

Plastic types based on processing

Plastics are categorized based on their behavior when exposed to heat. The two major catergories of plastics are - thermoplastics and thermosets. Thermoplastic polymers, are held together by weak secondary bonding forces. They soften when heated and can be molded into different shapes. When they cool down, they return to their original solid state without any change in their chemical structure. This heating and cooling process can be repeated multiple times, making thermoplastics recyclable and versatile for various applications. (Zijderveld, n.d.). Figure 2 lists the common commercial thermoplastics available with their recycling code and their chemical composition

On the other hand, thermoset polymers behave differently. When heated, they undergo a chemical reaction that causes them to solidify irreversibly. Once a thermoset polymer has hardened, it cannot be remelted or reshaped. This permanent setting provides thermosets with high thermal stability and structural integrity, making them suitable for applications requiring durable and heat-resistant materials. (Zijderveld, n.d.)

Plastic types

- Thermosets
- Thermoplastics

Plastic name	Short form	Recycling code	Chemical composition
Polyethylene	PE	2 HDPE, 4 LDPE	(-CH2-CH2-)n
Polypropylene	PP	5 PP	(CH2-CH(CH3))n
Polyvinyl Chloride	PVC	3 PVC	(CH2CHCl)n
Polyethylene Terephthalate	PET	1 PET	(CO-(C6H4)CO-O-(CH2)2-O)n
Polystyrene	PS	6 PS	(CH(C6H5)-CH2)n

Plastic name	Short form	Recycling code	Chemical composition
Polycarbonate	PC	7 Other	(O-(C6H4)-C(CH3)2-(C6H4)-CO)n
Polyamide	PA / Nylon	7 Other	(NH(CH2)5CO)n
Acrylonitrile Butadiene Styrene	ABS	7 Other	(C8H8)x·(C4H6)y·(C3H3N)z
Polyether Ether Ketone	PEEK	7 Other	(O-(C6H4)-O-(C6H4)-C(O)-(C6H4))n
Polytetrafluoroethylene	PTFE	7 Other	(CF2-CF2)n
Polymethyl Methacrylate	PMMA	7 Other	(CH2-C(CH3)COOCH3)n
Ethylene Tetrafluoroethylene	ETFE	7 Other	(-C2F4-)n

Figure 10: Plastic types and their identification

2.1.2 Application of the material

Plastics in our daily lives

Plastic materials are widely used because they are strong, lightweight, and water-resistant. Additionally, plastics are very stable and durable (Shah, Hasan, Hameed, & Ahmed, 2008). These characteristics set them apart from other materials, which is why they are used in so many everyday products. Because of their adaptability, affordability, and broad availability, they are widely used in products that need to do multiple tasks. To meet all of its varied requirements, a single object can need a combination of these qualities. Extreme temperature resistance, chemical and light resistance, strength, and flexibility are just a few of the qualities offered by plastics. Figure 67 and Figure 12 showcase varied application of plastics in daily lives.

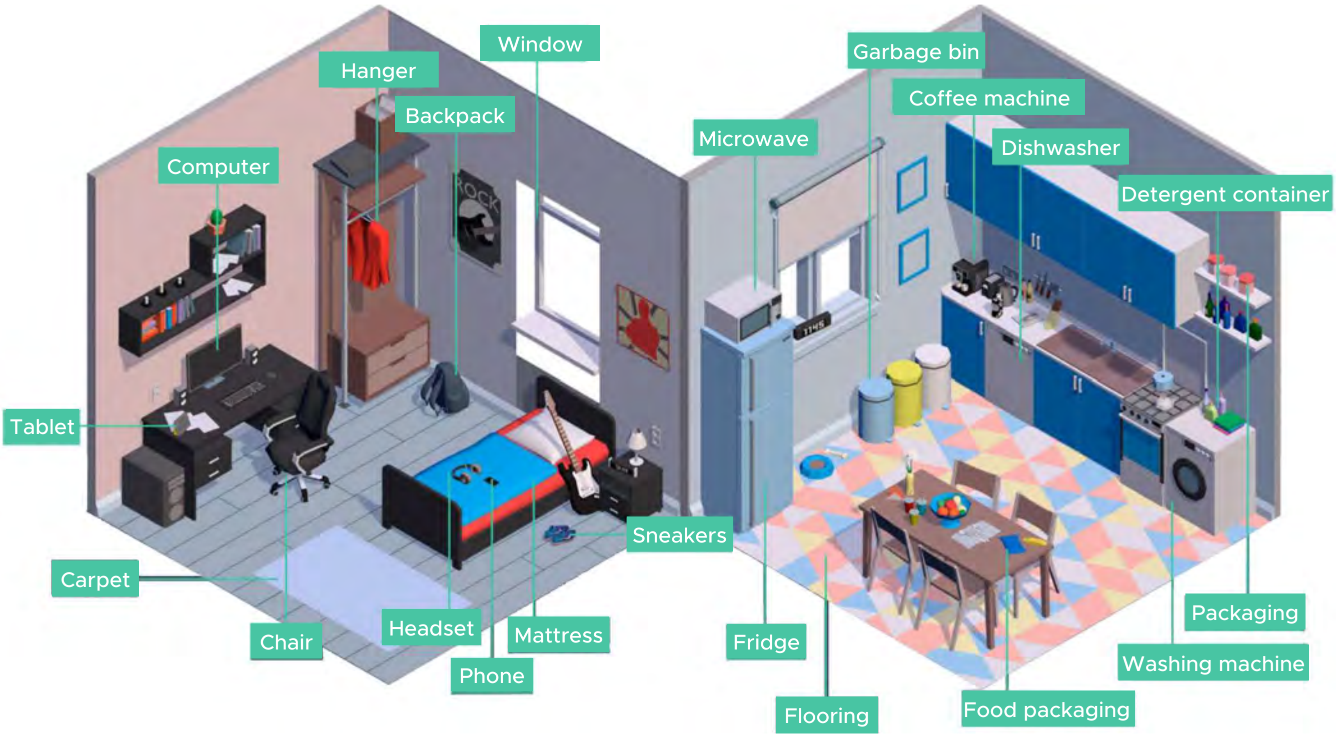


Figure 11: Applications of plastics in daily lives (Source: PlasticEurope, 2020)

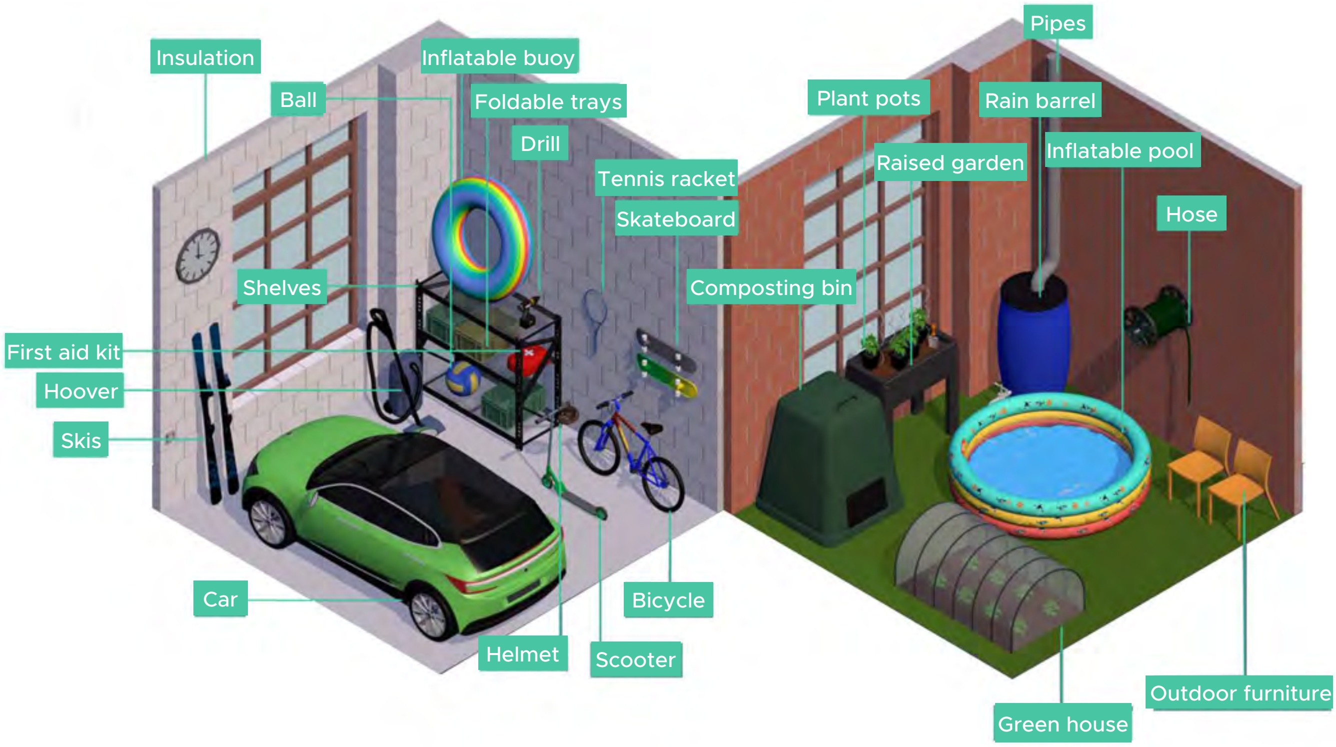


Figure 12: Applications of plastics in daily lives (Source: PlasticEurope)

Plastics in built environment

Plastics are in demand for numerous applications in the construction industry due to their unique properties for the cost paid. They are strong yet lightweight, making them easy to handle and transport. Their resistance to water and many chemicals enhances their durability and longevity. Plastics are also highly mouldable, allowing for versatile designs and shapes. Moreover, their low thermal conductivity and electrical insulating properties make them valuable in both thermal and electrical applications. The ease of mass production and cost-effectiveness further contribute to their widespread use in various industries.

Construction industry consumes plastics for various applications. Some of them are:

- Siding and Cladding: PVC sidings, popularly known as vinyl sidings, exemplify plastic's role in building construction. Their ease of installation, durability, low maintenance, and cost-effectiveness make them a preferred choice. Vinyl sidings provide protection against weather elements and enhance the aesthetic appeal of buildings.

- Insulation: Plastics, being poor conductors of heat and hydrophobic, are extensively used in insulation materials. Polyurethane, PIR, PS, and PVC find application in various forms such as batts, rolls, loose fill, sprayed foam, and foam boards. These materials serve as effective thermal and moisture barriers in walls, basements, attics, roofs, and heating/cooling systems.

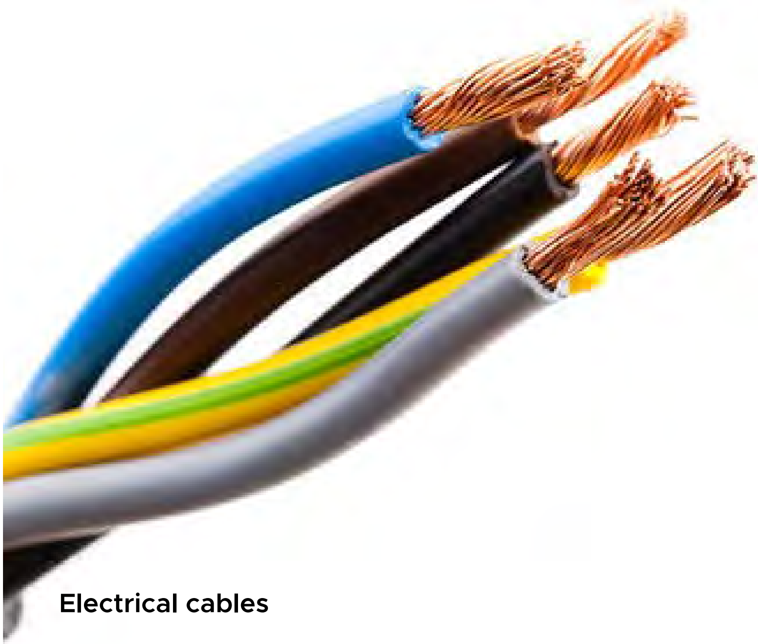
- Roofing Systems: Plastic plays a crucial role in roofing membranes, providing a durable layer that prevents water leakage. PVC, known for its flame-resistant properties, is a dominant polymer in wire insulation. However, concerns about toxic smoke generation during combustion have led to the incorporation of additives to mitigate this issue.


Insulati


Siding and cladding


Drain pipes


Doors and windows


Electrical cables

2.2 Plastic - from products to waste

Product lifespan

Plastic products entering the market have varied lifespans. Items like insulation boards, cables, cars, and electronic devices often remain in use for years, not becoming waste in short period of time. Some are exported for a second life, never becoming waste within the Europe (e.g., used cars). Others, such as furniture and toys, are resold and used second-hand, extending their lifespan. This is the reason behind the variability in the waste quatities are smaller that the total plastic consumed annually. Similarly, waste collected anuualy may include items introduced decades earlier, like old fridges or mattresses. Figure 13 provides an overview of the products life span that is a potential waste for next years.

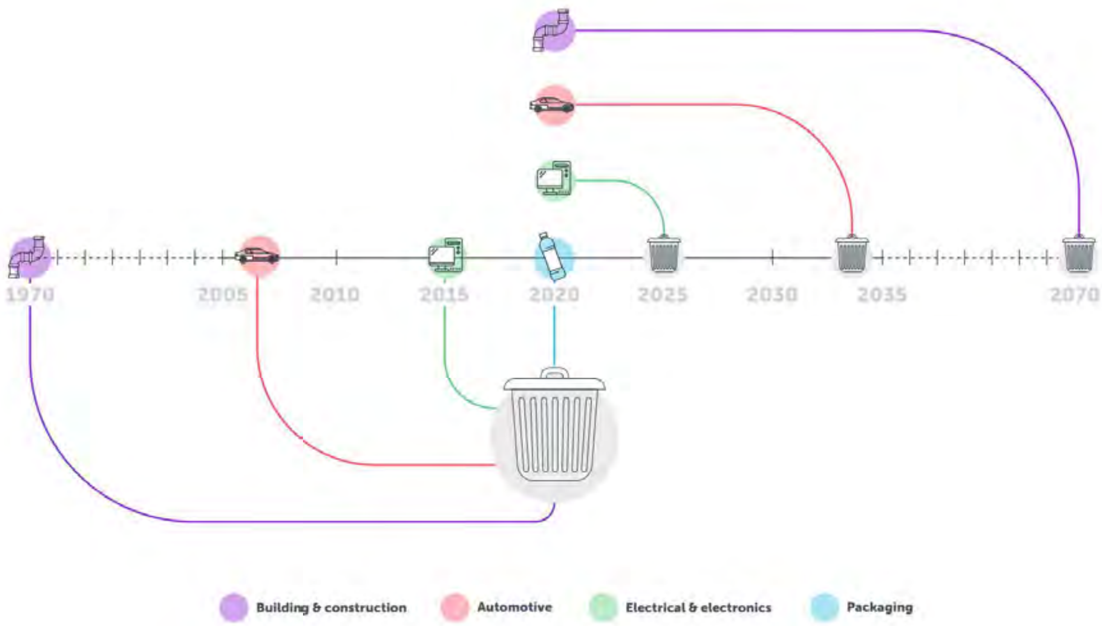


Figure 13: Plastic products average lifespan before entering into waste stream (Source: Plastic Europe report 2022)

Plastic products consumed today will become waste in the future according to their average life span

Plastic Europe report 2022

A key factor to consider when choosing a product's material is the duration the item will last. It significantly influences not only the sustainable use of the materials for the intended solution but also the methods of disposal. Solutions to address the challenges posed by plastic products and waste can be found in the guidelines of the Plastic Pact. These include strategies such as eliminating unnecessary plastics, replacing them with biodegradable materials to avoid contamination issues in compostable and dry recycling streams, and improving product design to extend their lifespan. Further, substantial expenditure is necessary to increase the scale of collection and sorting infrastructure.

It's important to design products for easier recycling by avoiding complex material combinations and rationalizing polymers. Furthermore, raising the amount of recycled material in new goods is essential for boosting the market for recycled plastics.

Enhancing recycling after use and extending durability and repairability are essential goals for long-term use products, such as building materials. This requires upgrading the machinery used for equipment separation and sorting, especially for electronic waste and auto parts. Building materials are used over an extended period of time, thus it is critical to enhance their labelling and tracking in order to make sure they can be identified and reclaimed later on.

2.3 Review of plastic recycling

2.3.1 Current status of plastic waste generation

Plastic waste streams pass through various aspects of our daily lives, ranging from durable goods to packaging components in personal care products. They exhibit resistance to natural degradation, resulting in extensive disposal on a global scale. The rapid generation of plastic waste has outpaced our ability to mitigate its impact on living organisms, leading to a prevailing consensus that plastics are an unsustainable material.

The existing challenge is compounded by the failure to address the linear economic model underlying the production and disposal of goods. This model is based on perpetual economic growth and does not consider the finite nature of the planet's resources. It operates under the assumption that natural resources are abundant, easily sourced, and inexpensive to dispose of. This oversight has contributed to the unsustainable trajectory of plastic waste accumulation.

The diagram below (Figure 6) depicts the demand for plastic recyclates among five major industries: Packaging, building and construction, automotive, electrical and electronic, household, leisure and sports, agriculture, and others, collectively contributing to almost 50.7 million tonnes. Notably, plastic resins such as PE, PP, and PET dominate the packaging industry, while PVC holds prominence in the building construction sector.

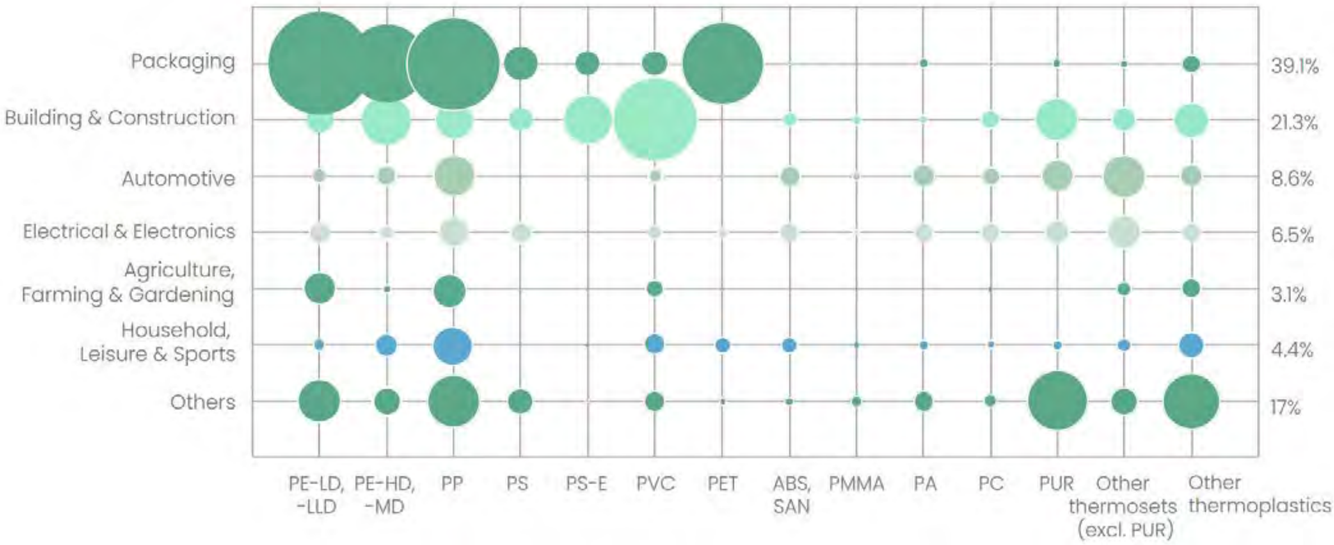


Figure 14: Plastic demand by industry (Source: PlasticEurope)

2.3.2 Post-consumer waste generation

High waste generation is a consequence of high demand. According to the datafrom plastic europe (see Figure 6), the construction and demolition industry is the second most plastic-consuming industry after the packaging industry. It's important to take into account that waste from short-lived products is primarily produced by the packaging sector, while waste from historically contaminated materials is typically dealt by the construction and demolitions waste.

An overview data of post-consumer plastic waste generation by resin type is shown in the Figure 15.

Type of plastic	Total waste generation	Total recovery	Total recovery	
			Mechanical Recycling (%)	Energy recovery (%)
LDPE	90	70	27	51
HDPE	225	164	24	49
PP	130	95	23	50
PS	30	21	7	64
EPS	140	95	9	59
PVC	910	683	34	41
Miscellaneous	235	172	7.5	65.5
Total	1,760	1,300	25	47.5

Figure 15: Data of waste generated by resin type from EuRIC report (Source: EuRIC AISBL 2020)

Type of Plastic	Total waste generation	Total recovery		Waste mishandled at waste generation stage		Total recovery				Losses at recovery stage	
						Mechanical recycling		Energy recovery			
Units	*Kilotonne (kt) (*)*	*Kilotonne (kt) (*)*	*Percentage (%)*	*Kilotonne (kt)*	*Percentage (%)*	*Kilotonne (kt)*	*Percentage (%) (*)(**)*	*Kilotonne (kt)*	*Percentage (%) (*)*	*Kilotonne (kt)*	*Percentage (%)*
LDPE	90	70	77.8	20	22.2	18.9	27	35.7	51	15.4	22.0
HDPE	225	164	72.9	61	27.1	39.4	24	80.4	49	44.3	27.0
PP	130	95	73.1	35	26.9	21.9	23	47.5	50	25.7	27.0
PS	30	21	70.0	9	30.0	1.5	7	13.4	64	6.1	29.0
EPS	140	95	67.9	45	32.1	8.6	9	56.1	59	30.4	32.0
PVC	910	683	75.1	227	24.9	232.2	34	280.0	41	170.8	25.0
Miscellaneous	235	172	73.2	63	26.8	12.9	7.5	112.7	65.5	46.4	27.0
Total	1760	1300	73.9	460	26.1	325.0	25	617.5	47.5	357.5	27.5

Table 1: Ellaborated data of waste generation

The data presented in Figure 70 is derived from a report by the European Recycling Industries' Confederation (EuRIC 2020) and illustrates the total waste generated and waste recovered by resin type for the year 2018. Table 8 serves as an elaboration and extension of the information provided in Figure 70.

- Approximately about 70% of all plastics are recovered for recycling, indicating a commendable recovery rate.
- The generation and recycling numbers of PVC is positive. However, 227 kilotonne of PVC was face mishandling during the waste generation stage. This figure almost surpasses the collective sum of mishandling of waste in all other types of plastics. This may be due to durability, extended lifespan and cost associated with segregating waste in construction and demolition (C&D) waste. The energy recovery rate to mechanical recycling rate stands at 1.2, underscoring the potential for reintegrating PVC into the material flow.
- HDPE follows PVC, boasting a relatively better performance. Its mechanical recycling rate is half that of its energy recovery rate. The energy recovery rate to mechanical recycling rate is 2.0, signifying the potential for HDPE to be reintroduced into the material flow.
- In the case of PS and EPS, a significant proportion of plastics are directed towards energy recovery than mechanical recycling. These materials, commonly employed in packaging, are often contaminated with food residues, dirt, and other substances. Additionally, they possess a high volume-to-mass ratio. The economic viability and demand for these materials make energy recovery a more favourable option.

2.4 Plastic waste management

2.4.1 Plastic recycling process

Recycling is the process of collecting and processing materials to create new goods out of materials that would otherwise go away as waste. This is a significant practice to encourage circularity. With a focus on reducing raw material consumption, extending the lifespan of products, and promoting high-quality material reuse, the Dutch government's circular plastic policy is essential to accelerating the shift. The primary approach is to replace fossil plastics with recycled materials made from recycled polymers.

There are 3 different types of recycling processes according to Plastic Europe:

Mechanical Recycling:
Mechanical recycling stands as the most widely adopted method for recycling plastic. This traditional approach, in practice for decades, constitutes the primary means of plastic recycling globally. It involves processes such as grinding, washing, sorting, and reprocessing to transform plastic material. The resulting plastic recyclates can be repurposed into alternative products, serving as substitutes for virgin plastics. This article primarily explores the collection, sorting, and reprocessing of plastic through the conventional mechanical recycling pathway.

Chemical Recycling:
Chemical recycling is a method of recycling plastics that involves inducing a chemical change in the polymer structure, creating a raw material suitable for manufacturing new products. Unlike mechanical recycling, chemical recycling can handle plastics that may not be conducive to the mechanical recycling process.

Thermal Recycling:
Thermal recycling is another method of recycling that involves the use of heat to break down and transform plastics. This process utilizes heat to convert plastic waste into raw materials or energy.

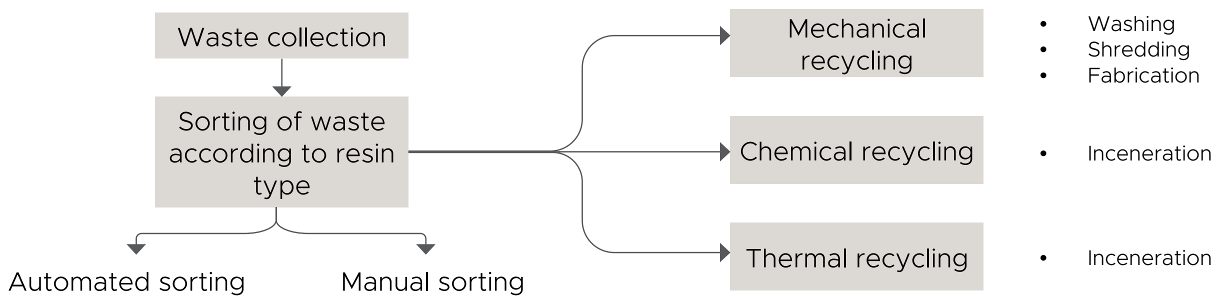


Figure 16: Overview of plastic recycling process

The process of mechanical recycling typically involves five distinct stages.

Collection:
The initial phase of the recycling process focuses on gathering recyclables from various sources. It is imperative to meticulously sort the items and have them prepared for collection and subsequent recycling. Municipalities usually oversee this stage, transporting the materials to material recovery facilities for sorting if necessary.

In the Netherlands, the municipality is responsible for collecting household waste. There is no standard sorting regulations at the collection point and every municipality has its defined rules to carry out the waste collection process. In some municipalities, e.g.: in Delft city center, the municipality separates waste into two bins namely organic and Plastic bottles, metal packaging and drink cartoons (PMD) whereas in Rotterdam they have 3 bin system – for organic, cardboard and recyclables separately.

Sorting:
The second stage entails the separation of mixed waste streams into distinct polymers, isolating different types of plastics. Plastics are conveyed on belts, and a series of techniques are employed to prepare the material for future processing. At this point, the separated plastic waste is referred to as monostreme polymers. The sorting process involves several techniques:

- Manual picking: Labor-intensive sorting by hand to remove large items, non-recyclables, and obvious contaminants.
- Trommels: Cylindrical drums with holes that allow finer materials to fall through as they rotate.
- OCC Screening: Separates old, corrugated cardboard (OCC) from mixed recyclables using a rotating disc system.
- Ballistic separator: Mechanically separates rigid waste items from flexible items, allowing glass and finer materials to fall through a mesh.
- Magnet separator: Removes any present metal as waste travels on conveyer belts under a magnet.
- Eddy currents (for non-ferrous metals): Separates non-ferrous materials like aluminum and copper from non-metallic material using rotating magnets and eddy currents.
- Optic sorting machine: Identifies plastics efficiently using near-infrared (NIR) measurements and separates waste through ejection methods.
- Sink-float separator: Utilizes water to separate high-density plastic sinking from low-density plastic floating.

Washing:
The washing stage involves employing various methods based on contamination levels and processing requirements. Common methods include friction washers, which use heat, kinetic energy, and pressure, and rotary washers, which use a caustic solution to remove oils and food residues.

Shredding:
Shredding or grinding plastic into smaller flakes is a crucial step in the recycling process. Washed and sorted plastic undergoes shredding in machines that grind it into smaller pieces. Methods of shredding include Hammer Mills, which use swivelling hammers in a rotary drum, and Shear Shredders, which use rotary cutters and guillotines to cut plastics to industry size requirements.

Fabrication:
The final stage involves melting down the shredded plastic and forcing it through an extruder. The extruded plastic is cut into pellets as it emerges, and these pellets are then sold to manufacturers.

The overall recycling process includes a combination of mechanical and chemical recycling followed by production processes. Figure 13 gives a brief overview of the available polymer recycling process.

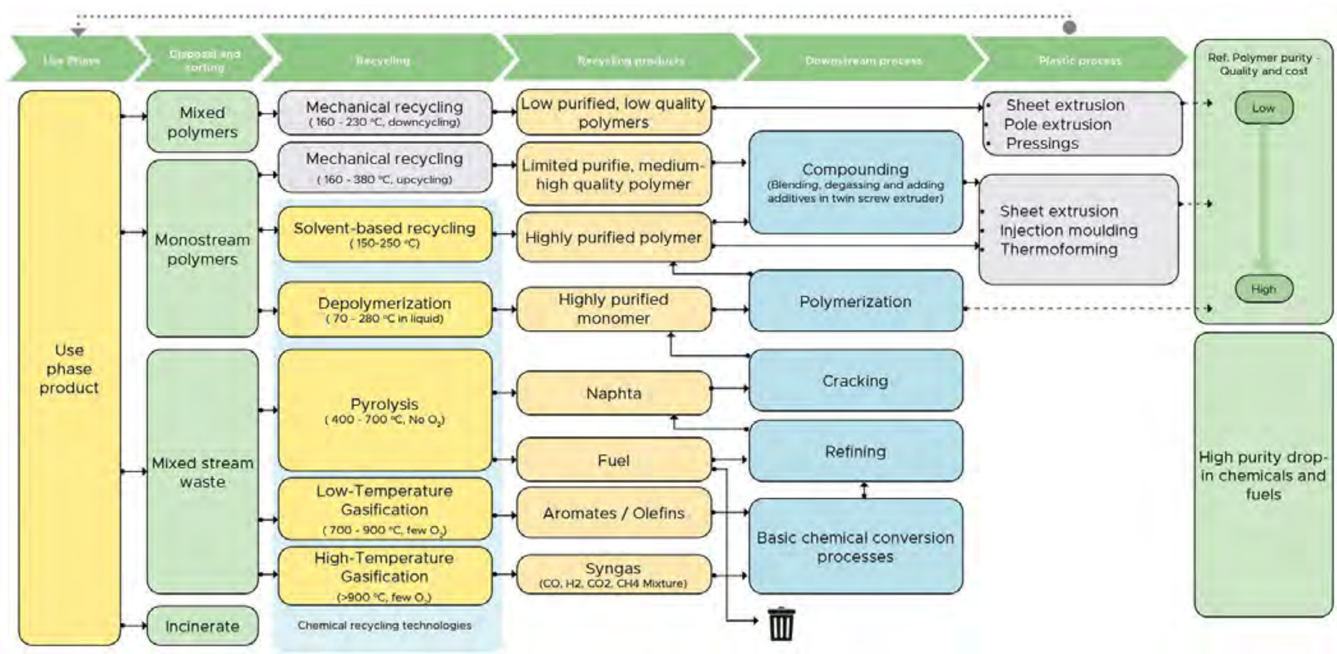


Figure 17: Overview of existing plastic recycling process

2.4.2 Challenges associated with plastic recycling

The advancements in plastic recycling technology have been significant.However, only 9% of plastics according to the data from OECD are recycled globally, raising questions about the challenges hindering recycling efforts.The challenges can be grouped under five categories - economical logistical, technical, regulatory and societal (see figure 8 for summary).

Economic challenges

- One primary obstacle lies in economics and logistics, with the cost-effectiveness of plastic being a major driver for its extensive use. High infrastructure costs render many solutions non-competitive, and the low price of virgin plastics, influenced by low oil and natural gas prices, contributes significantly to plastic pollution (Wagner, 2022).

- Additionally, a significant portion of expenditures is allocated to the manual sorting of plastics at recycling centres. This is also because of lack of standardised recycling process including the sorting techniques.

- Economic solutions aim to reduce plastic consumption through financial incentives or creating a level playing field for alternative materials, recycling, and circular business models (Wagner, 2022).

- Levies on single-use products, especially plastic bags, have been a widely adopted economic instrument, yet the global impact remains uncertain (Nielsen et al, 2019).

Logistical challenges

- One of the biggest bottlenecks in plastic recycling is that every resin i.e. PE, PP, PVC etc needs to be processed separately.

- Emerging market countries often lack the infrastructure for proper waste sorting. In Netherlands itself, the waste sorting process varies from one municipality to another.

- The waste generation-to-recycling ratio is minimal, therefore creating pressure on the recycling infrastructure (Bryan D. Vogt, 2021).

- Efforts focus on transitioning from typical down-cycling to circular recycling and up-cycling, promoting a shift in recycling paradigms (Bryan D. Vogt, 2021).

- Much research has focused on the difficulty in finding technological solutions, governance difficulties and economic considerations that it is almost forgotten to address the complexity of the plastic waste pollution and the diversity of plastic composition generated. (Wagner, 2022).

- A different way to deal with the waste issue is by making more compostable or biodegradable plastics. The hope is that these materials will break down quickly, either in places like factories and homes or in the environment (Crippa et al., 2019; Lambert and Wagner, 2017). Although there are various biodegradable plastics made from both fossil and renewable sources, they make up less than 0.5% of the world's plastic production. This is mostly because they are expensive compared to their limited benefits and there are challenges in increasing their production capacity (Crippa et al., 2019; Wagner, 2022).

Technical challenges

- The difficulties in technology involve the complex formulas used in plastics, which include various additives like plasticizers, pigments, and fillers for specific industrial applications. When developing new plastic recycling technologies, it's crucial to consider the different contaminants added, as they affect the properties of the recycled plastic material.

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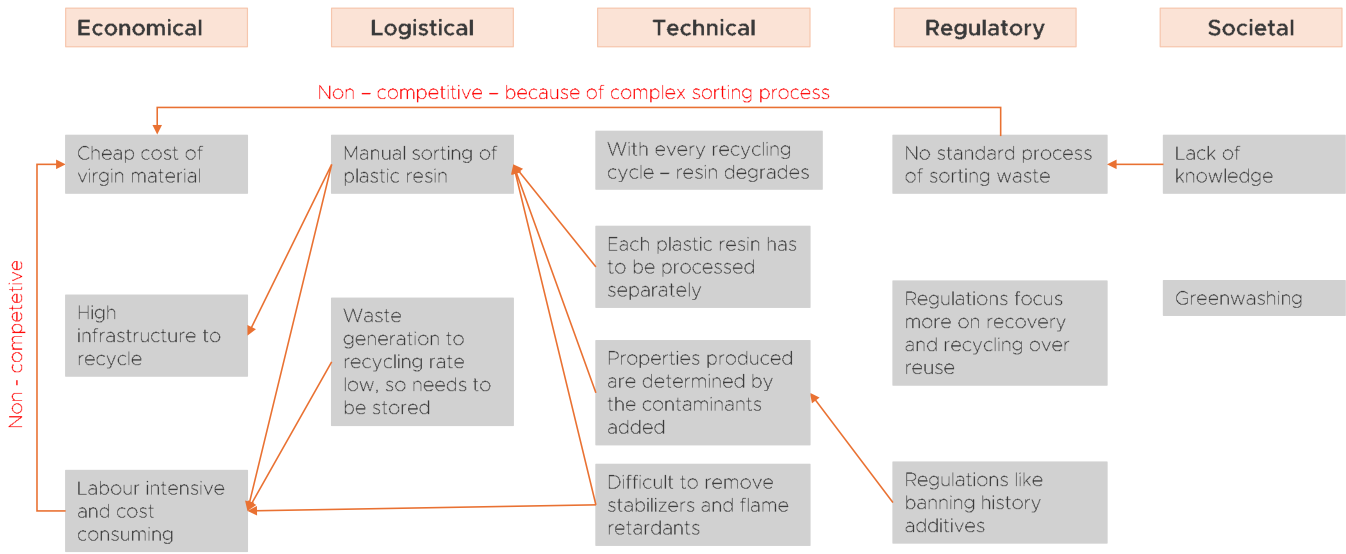


Figure 18: Pictoral representation of challenges associated with plastic recycling (Source: Worldarchitecture.org)

- Additionally, the properties of recycled plastics vary, restricting their potential uses. Enhancing the consistency of properties from a highly variable source of recycled materials would open up new applications for recycled plastics. The chemical recycling approach, proposing polymer recycling into monomers, faces technical and economic challenges (Bryan D. Vogt, 2021). A potential solution lies in redesigning plastics for intrinsic chemical recycling, offering a simpler approach to address these technological challenges.

- Technological challenges include the complex formulations of plastics, with various additives impacting their properties. Variability in recycled plastics' properties limits their applications, emphasizing the need for improved uniformity from variable feedstocks.

- Eliminating outdated additives from end-of-life PVC introduces complexities to the recycling process. The inclusion of chemicals like metal-based stabilizers and flame retardants raises concerns about the cost-effectiveness of recycling, often making the use of virgin plastic more economically favourable.

Regulatory challenges

- Promotion of recycling takes precedence over emphasizing reuse and the individual accountable or the stakeholder for ensuring material circularity remains unclear.

- Current solutions to address the plastic waste issue focus on less favourable alternatives, particularly recovery and recycling. For instance, in the European Strategy for Plastics in a Circular Economy (European Commission 2018), the terms "prevention" and "reuse" are mentioned only 8 times each, while "recycling" is cited 76 times. This preference may stem from the fact that technological approaches to recycling, recovery, and disposal are well-established within the waste sector. Conversely, strategies to diminish plastic use and encourage reuse necessitate the involvement of diverse stakeholders, including social scientists and designers (Wagner, 2022).

- Characterizing plastic pollution as a resource problem centers on the concept that valuable materials are squandered when plastics are employed in short-lived products, such as packaging and single-use items.

Societal challenges

- In contrast to the other challenges discussed, an alternative perspective attributes the issue of plastic pollution to a more deeply rooted cause, namely, the influences of consumerism and capitalism. (Wagner, 2022)

- On the business front, the marketing of "ethical" plastic products, such as those made from ocean plastics, employs similar mechanisms, albeit occasionally criticized as greenwashing. Notably, all these approaches are rooted in the concept of ethical consumerism, emphasizing individual responsibility, all while operating within the confines of the capitalist framework.

Conclusion

A promising solution for addressing the issue of plastic waste involves designing products that enables the utilization of recycled materials, fostering development of a market of recycled plastics. This approach aligns with the principles of a circular economy, where materials are in closed-loop system to minimise waste and promote sustainability.

However, the challenges associated with plastic recycling often boils down to a cost-benefit analysis. The economic considerations involved in the recycling process, including collection, sorting, and processing, can be substantial. To navigate these challenges effectively, it is crucial to rethink traditional approaches to material recycling.

2.5 Material flow

The surge in plastic waste generation is a result for the demand of the material, thereby worsening the global challenge of plastic pollution. The assessment from McKinsey of global polymer flows in 2016 reveals that only 16% of polymer waste is directed toward recycling, 19% is mismanaged, 25% is incinerated, and a 40% finds its way into landfills. This highlights a considerable portion of polymers produced are being lost indefinitely, despite their inherent potential for reuse and recycling. In developing countries, the most common method of getting rid of municipal solid waste remains dumping plastic waste in landfills. Waste management operations are facing a crisis due to the quick exhaustion of available space for waste disposal and public opposition against the development of new waste disposal sites.

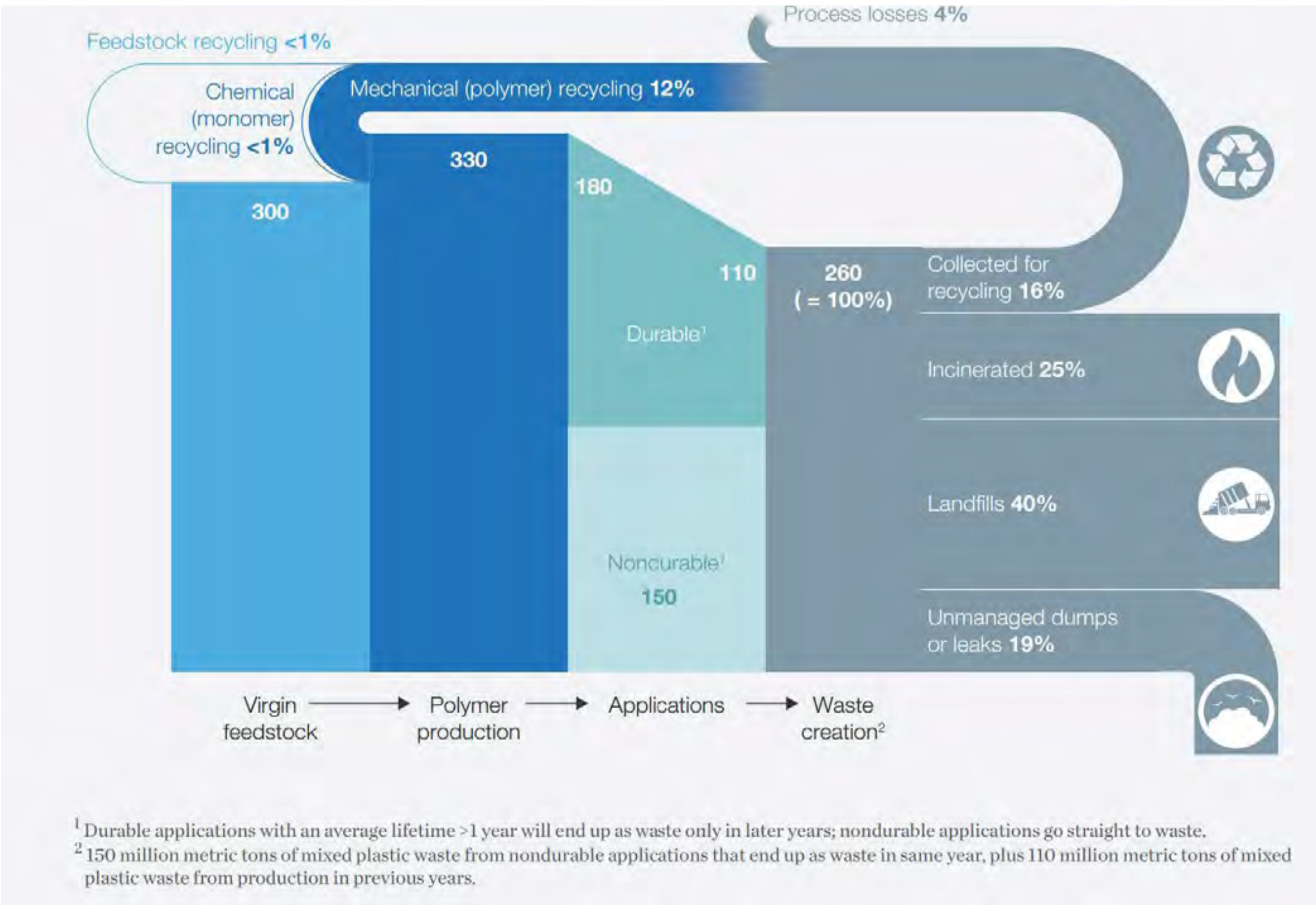


Figure 19: Global polymer flows, millions of metric tons per annum, 2016 (Source: McKinsey and company)

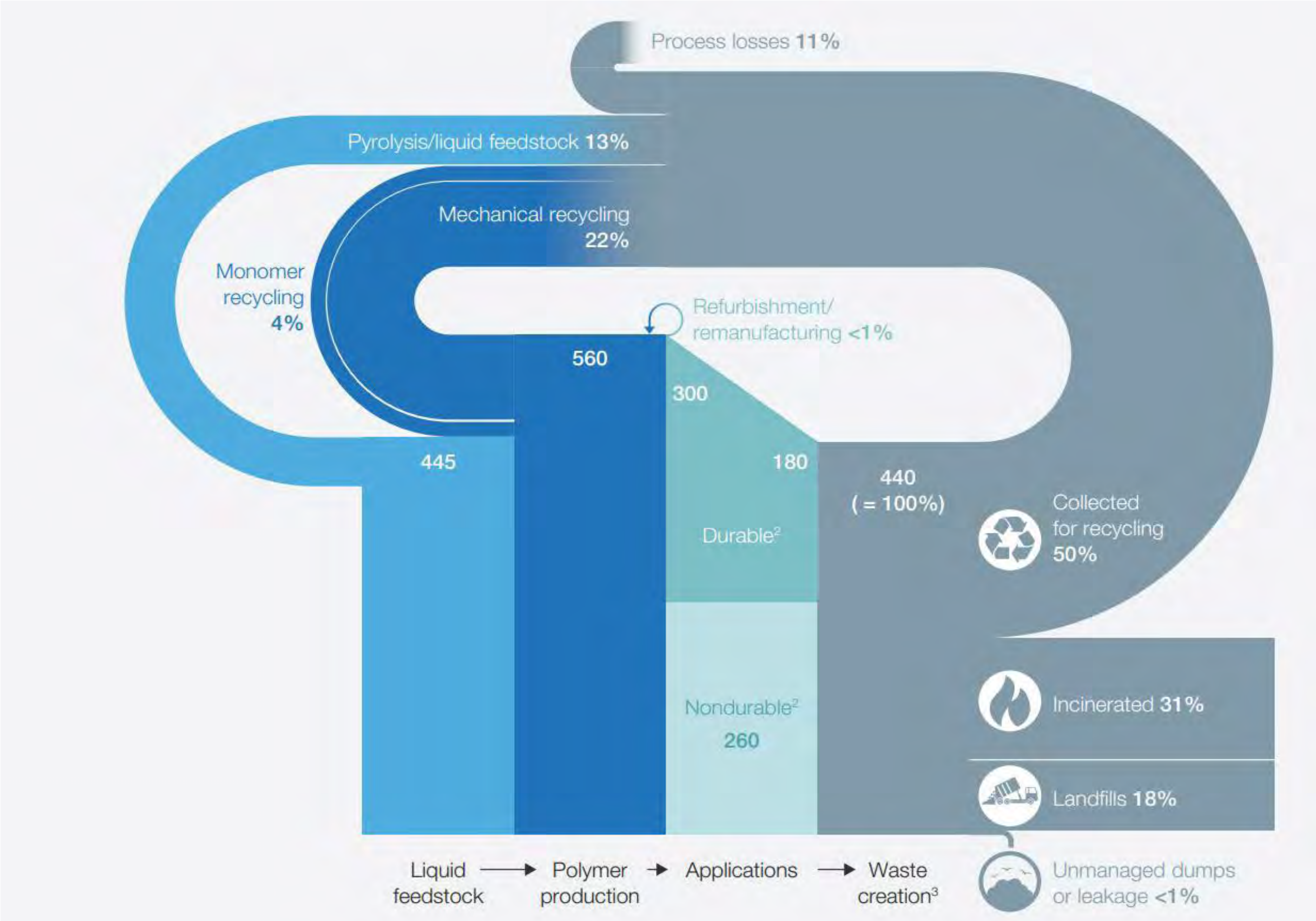


Figure 20: Global polymer flow projections 2030, millions of metric tons per annum (Source: McKinsey and company)

McKinsey's trajectory polymer flow analysis extends to predicting the future global waste flow, potential recycling strategies, and the economic returns associated with such initiatives. The scenario envisions a transformative shift for the plastics industry, to achieve an increase in global plastic reuse or recycling by 2030 compared to 2016 by prioritizing recycling profitability, employing low-cost measures to minimize waste leakage. Another scenario envisions to incorporate advancements in collection, sorting, and recycling technologies. The third scenario is to increase reuse and recycling through a multi-stakeholder approach, supported by an array of regulatory measures.

This is because of its fundamentally different starting point from traditional plastics manufacture: mechanical recycling can generate new polymer without having to invest billions of dollars in steam crackers and other units to create petrochemical building blocks.

McKinsey & Company

Technological interventions are is necessary to address the plastic pollution crisis. The technologies that exist or recognised as technologically feasible could make plastic reuse more possible. These include the extensive expansion of mechanical recycling—a sector capable of generating new polymer without any investment.

Monomer recycling and pyrolysis are additional technologies with the potential for expansion. The projections indicate that plastic reuse could potentially rise to 50% of total production by 2030, which can be achieved through strategic technological implementation.The material flow and the projection emphasise that effective waste management is essential for minimizing the environmental consequences of plastic pollution and to create economic opportunities through recycling, and utilizing the technological innovations for sustainability.

2.6 Conclusion

The post-consumer waste stream poses several layers of complexities due to the composition of commercial plastics, which incorporate diverse additives and increasingly sophisticated engineering, such as multilayer and composite materials (Vogt, 2021). Addressing resource challenges from a waste perspective primarily involves strategies aligned with the upper echelons of the waste hierarchy, namely recycling and reuse (Wagner, 2022). The ultimate goal is to preserve both the material and functional value of plastics, thereby extending the lifespan of materials or products.

Projections indicate that plastic upcycling is key to unlocking a sustainable future. By transforming waste plastics into higher-value products, upcycling not only reduces environmental impact but also creates economic opportunities. This innovative approach goes beyond traditional recycling, offering a solution that can significantly decrease plastic pollution and conserve resources. The benefits of upcycling make recycling more cost-effective, presenting a viable path towards sustainability.

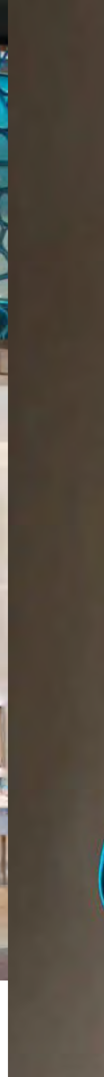
Pretty plastic - Facade tile
Resin : PVC

MVRDV - 3D printed facade
Resin : Ocean mixed plastic

Better future factory - Wall tile
Resin : PET

Plastic Upcycling

creative transformation of plastic waste into new reusable materials



Iris van Herpe
- Sculptural chlothes
Resin : Ocean mixed plastic

Polygood - light fittings
Resin : Not mentioned

Gomi- Speakers and powerbank
Resin : Mixed plastic

Ecoalf + Nagami - 3D printed interiors
Resin : Mixed plastic

Ecobirdy - Furniture
Resin : PP

2.7 Field study

2.7.1 Coolrec - Factory visit

Renewi Specialities' subsidiary Coolrec is an established company in the European circular economy space, particularly with regard to the recycling of electrical and electronic devices that have been disposed. Coolrec is an expert in the recycling of plastics and ferrous and non-ferrous metals from WEEE (Waste Electrical and Electronic Equipment), turning them into valuable secondary raw materials. The company has facilities in the Netherlands, Belgium, and France.

Millions of electronic and electrical goods are used and eventually disposed out by homes and companies across Europe every year. These electronic devices are made of materials that are highly recyclable as long as they are responsibly and sustainably separated, separated cleaned, and processed to meet market and environmental requirements.

Coolrec is the market leader in the EU for recycling refrigerators and WEEE plastics, with a focus on mechanically treating WEEE. Coolrec processes over 120,000 tonnes of cooling and freezing appliances, small domestic appliances (SDA), large household appliances (LHA), information and communications technology (ICT) equipment, air conditioning units, and heat pumps annually through the operation of four treatment plants spread across three European countries.

The factory visit at Waalwijk, The Netherlands offered the following insights:

- **Specialized Recycling Plants:** Coolrec operates different recycling facilities designed to handle different types of appliances. This specialization ensures that the most appropriate and efficient processes are used to process each type of material.
- **Food-Contact Plastics Recycling:** Recycled plastic from ovens and refrigerators—which are usually in contact with food—is used to make new items like toys. About 50–60% of the recycled material in these plastics is composed of up mostly of Acrylonitrile Butadiene Styrene (ABS), Polystyrene (PS), and Polyvinyl Chloride (PVC). These plastics are effectively separated using density separation technology, ensuring high-quality output.
- **Density Separation Technology:** There are two density separation plants in the factory. By effectively sorting polymers according to their densities, this technology plays a vital part in the recycling process. This is important for maintaining the purity and quality of the recycled material.
- **Challenges with Flame Retardant Plastics:** Flame-retardant-containing plastics are extremely hard to recycle. Because to the challenges associated with their processing, these materials are usually disposed of by burning them or using them as fuel in cement industry kilns.
- **Material Degradation in Chemical Recycling:** Degradation of materials continues despite advances in chemical recycling. The quality of recycled material may decrease over time when using chemical procedures, highlighting the significance of ongoing innovation and development in recycling technology.

Figure 21: The waste mixture before density separation (Source: Author)

2.7.2 Van Waren BV, recycling facility in the Netherlands - interview

Van waren is specialised service provider that deal with infrastructure waste in the Netherlands.

- **Conversation with the company representative gave the following insights:**
- Currently, recycled PVC is utilized in the interlayer of PVC pipes produced by our company.
- The recycling practice involves mixing new PVC with old, which effectively reduces lead contamination to levels between 1.1% and 1.5%.
- The existing recycling norms were not originally designed to accommodate the properties of regrind material, as the quality of recycled PVC is highly dependent on the additives used during its previous life cycle.
- To enhance the quality and safety of our recycled PVC, the company employs X-ray machines to detect and recognize the presence of metals within the material. Additionally, they also implement color sorting processes to ensure the purity and consistency of the recycled PVC used in our products.

2.7.3 Conversation with Dr. Francesco Di Maio, Research director of the recyling lab at CiTG, TU Delft.

Francesco is the Research Director of the Recycling Laboratory at Delft University of Technology. Francesco is currently working along the lines of circular economy, resource efficiency, waste separation, and recycling.

The insights from the conversation is a s below:

- Polyvinyl Chloride (PVC) is typically detected by Near-Infrared Spectroscopy (NIR). By using water flotation methods, PVC can be easily removed from mixed plastic waste due to its density.
- One of the simplest and most effective techniques for processing PVC is injection molding, which involves applying significant pressure to shape the material.
- In the production of PVC pipes, calcium carbonate is commonly used as a filler. However, this additive can reduces the flowability of the plastic, making the processing more challenging.
- For handling pure PVC waste streams, a method involving shredding, melting, and compounding the material is often used.
- Before their qualities deteriorate to the point where they are no longer useful, PVC and other polymers can usually be recycled two or three times. The breakdown of the polymer chains during recycling is the result of mechanical and thermal stresses, which leads to this degradation. The material frequently requires to be burned after it has been recycled a few times since it can no longer meet quality standards for recycling. It takes a lot of energy to recycle plastics with the least amount of stress possible.\
- It might be difficult to determine whether plastic has undergone second or third recycling. Analyzing the material's mechanical characteristics, such as tensile strength and elongation at break, or utilizing spectroscopic techniques to spot changes in the polymer's chemical structure are two ways to determine the recycling stage. These techniques may help in figuring out how much the material has degraded and how many recycling cycles it has gone through.
- Overall, the feasibility of recycling plastic, including PVC, is largely dependent on economic factors. Market demand for recycled materials, the cost of recycling processes, and the price of virgin plastic all play critical roles in determining the viability of recycling efforts.

2.7.4 Polygood® by the good plastic company- review

Polygood® is a sustainable and high-quality surface material developed by The Good Plastic Company. It is madefrom 100% recycled and recyclable plastics sourced from certified recycled plastic stocks. The company also has a free-take-back program through which use panels and cuttings can be returned and recycled into newpanels, ensuring minimal waste. Each pattern is developed based on the design preferences. The material'sGlobal Warming Potential (GWP) of only 487 kg per ton further highlights its eco-friendliness, making it a superiorchoice compared to virgin polystyrene and other solid surface materials

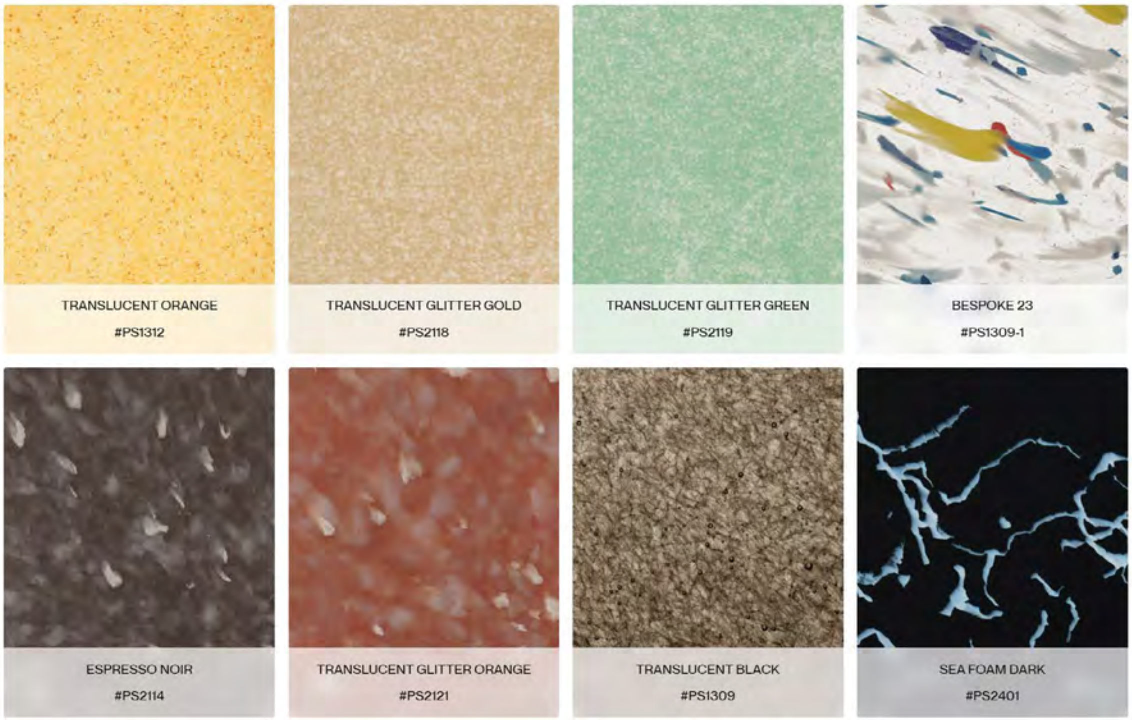


Figure 22: Samples of Polygood tiles (Source: Author)

2.7.5 Conversation with Casper van der Meer from Better future factory

Better Future Factory is a design and engineering firm dedicated to creating sustainable products. Collaborating closely with companies like IKEA and Unilever, they are creating products that operate within a circular economy model.

Casper van der Meer, the CEO and Co-founder of the firm gave a few insights regarding the process of manufacture and production techniques.

- Plastic, in general, melts and can be formed into various shapes through processes like injection molding. Injection molding, which involves shaping plastic by injecting it into a mold under high pressure, the easiest method for producing plastic parts from recycled waste.
- But this process requires high precision molds, and the choice of mold material impacts the quality of the final product. The cost of creating these precise molds contributes to the overall expense of injection molding.
- Polyvinyl chloride (PVC), is heat-sensitive and can burn rapidly, releasing chlorine gas, which poses health and environmental hazards.
- When recycling PVC, controlling the melting temperature is key factor to prevent burning.
- Production of large PVC tiles are prone to warping during the cooling process, which can affect their structural integrity and appearance.

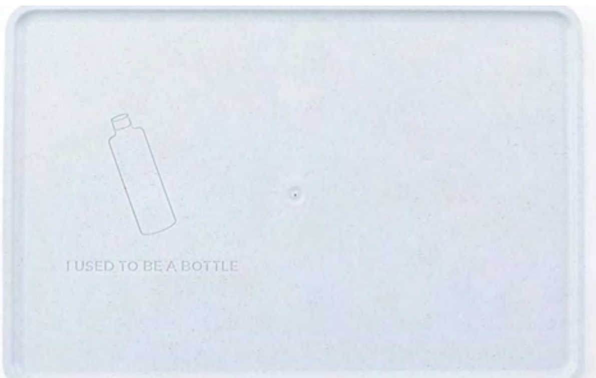


Figure 23: SProducts from better future factory (Source: Better future factory)

2.8 Plastic material properties data sheet

Plastic classification and properties *(Properties represent material data without any contamination)*			Price	Physical properties	Mechanical properties			Thermal and combustion properties			Durability		Optical properties	Usage in constr
				Density	Tensile strength	Compressive strength	Bending strength	Thermal resistivity	Melting point	Glass temperature	UV radiation	Flammability	Transparency	Superstructure
			Euro/kg	kg/m^3	MPa	MPa	MPa	m.°C/W	°C	°C				
Source of information			[1]											
Engineering plastics	Polyethylene (PE)	LDPE	1.6 - 1.78	917 - 932	13.3 - 26.4	10.8 - 17.4	*10.0 -20.0 (*)*	*0.3 - 0.4 (*)*	97.85 - 114.85	105 - 115 (*)	Poor	Highly fammable	Translucent	Vapour barrier and moisture protector
		HDPE	1.23 - 1.27	952 - 965	26 - 31	18.6 - 24.8	*20.0-37.0 (*)*	*0.4 - 0.5 (*)*	129.85 - 136.85	120 - 130 (*)	Fair	Highly fammable	Translucent	beams, columns , truss
	Polypropylene (PP)		1.51 - 1.73	895 - 909	26 - 50	23.8 - 25	21.7 - 39.1	5.02 - 5.22	139.85 - 149.85	160 - 170 (*)	Poor	Highly fammable	Translucent	-
	Polyvinyl Chloride (PVC)		2.14 - 2.26	1.29e3 - 1.46e3	38 - 46	37 - 44.3	37.2 - 54.7	4.78 - 6.8	59.85 - 149.85	79.85 - 87.85	Fair	Self - extinguishing	Transparent	Beams and columns
	Polyethylene Terephthalate (PET)		1.26 - 1.82	1.29e3 - 1.39e3	55 - 60	50 - 60	59.3 - 65.4	4.17 - 7.25	260.05	59.85 - 83.85	Fair	Highly flammable	Translucent	-
	Polystyrene (PS)		1.96 - 2.67	1.04e3 - 1.05e3	35.9 - 51.7	82.7 - 89.6	30.2 - 59	7.14 - 8.33	170 - 280	89.85 - 99.85	Fair	Highly flammable	Opaque	-
	ABS		2.44 - 2.56	1.03e3 - 1.06e3	37.9 - 51.7	39.2 - 86.2	19.4 - 53.6	3.8 - 3.95	190 - 270	101.85 - 114.85	Poor	Highly flammable	Opaque	Shear walls - High strength ABS
	Polycarbonate (PC)		3.11 - 3.38	1.19e3 - 1.21e3	62.7 - 72.4	69 - 86.2	62 - 73.5	4.59 - 5.18	280 - 320	141.85 -157.85	Fair	Slow burning	Optical quality	Panels - shear walls
	Polyamide (Nylon/PA)		4.08 - 6.02	1.12e3 - 1.15e3	42 - 72	46 - 82	52.5 - 99.5	3.95 - 4.29	219.85 - 259.85	43.85 - 65.85	Fair	Slow burning	Translucent	Beams and columns
	Polyetheretherketone (PEEK)		75 - 83.1	1.03e3 - 1,32e3	97 - 117	111 - 141	68.3 - 99.8	3.85 - 4.17	321.85 - 345.85	142.85 - 156.85	Excellent	Self - extinguishing	Opaque	-
	Polytetrafluroethylene (PTFE)		11.2 - 14	2.14e3 - 2.2e3	20.7 - 34.5	11.2 - 12.3	15.8 - 26.3	3.83 - 4.13	314.85 - 338.85	116.85 - 129.85	Good	Non-flammable	Translucent	-
	Polymethylmethacrylate (PMMA)		2.21 - 2.97	1.17e3 - 1.2e3	54 - 72	72.4 - 124	72.4 - 131	*0.15 - 0.2 (*)*	*205 - 230 (*)*	99.85 - 109.85	Good	Highly flammable	Optical quality	-
	Ethylene tetrafluroetylene (ETFE)		33.9 - 40.8	1.68e3 - 1.72e3	42.7 - 47.1	46.6 - 51.4	36.1 - 39.8	4.03 - 4.37	258.85 - 280.85	77.85 - 92.85	Good	Self-extinguishing	Translucent	-

Source : [1 Ansys Granta Edupack [2] - Resin identification codes defined by the european commission (https://en.wikipedia.org/wiki/Recycling_codes) [3 } Google search engine

truction industry - examples of projects / products			Typical products	Design guidelines	End of life
Enclosure	Interiors	Services			Recycle mark
[1]					[2]
-	Wall finish sheets	-	Buildig enclosure air and vapour barriers, exterior molding, milk bottles, toys, beer crates, food packaging, disposable clothing, plastic bags, paper coatings, cable insulation, artificial joints, low cost ropes and packing tape reinforcement.	PE is commonly produced as film, sheet, rod, foam and fiber.Drawn PE has exceptional mechanical stiffness and strength, exploited in geo-textile and structural uses.PE is good electrical insulator with low dielectric loss, suitable for containers for microwave cooking. Has poor resistance to aromatics and chlorine. Slow burning in fire, is cheap, easy to foam, biologically inert and cycleable	04 PE-LD
-	Wall finish sheets	Water pipes			02 PE-HD
PP foam insulation	-	-	Ropes, automobile air ducting, parcel shelving and air cleaners, garden furniture, washing machienece tank, pipe and pipe fittings, beer bottle crates, cable insulation, shatter proof glasses.	PP is inexpensive, light and ductile but has low strength.Stiffness and strength can be imporived further by reinforcing with glass, chalk or talc. When drawn to fiber PP has exceptional strength and resilience, water resistant. Can be easily molded than PE, has good transparency. Commoly produced as sheet.	05 PP
Exterior cladding-composite panels, Roofing material, window frames, doors	Flooring tiles (Vinyl flooring), wall panels - composite panels	Water pipes, drainage pipes, electrical boxes, electrical conduits, ductwork, cable trays	Pipes, fitting, profiles, road signs, cosmetic packaging, vinyl flooring, windows and cladding, vinyl records, wire insulation, film, sheet, fabric, car upholstery.	In its pure form, PVS is heavy, stiff and brittle. Plasticizers can transform it from a rigid material to one that is almost as elastic and soft as rubber. Less transparent than PMMA or pC, but also cost muc less. Widely used for transparent, disposable containers. PVC is available as film, sheet or tube. Can be joined with polyester, epoxy or polyurethene adhesives. excellent resistance to acids and bases. Good barrier properties to atmospheric gasses, but poor resistance to some solvents.	03 PVC
Exterior cladding-composite panels	-	PET Ducts	Electrical fittings and connectors, blow molded bottles, packaging film, industrical scrapping, carbonated drink containers, oven-proof cookware	4 gardes of thermoplastic polyesters - 1) Unmodified - have high elongation, 2) Flame retardants - are self extinguishing, 3) glass-fiber reinforced grades - toghest polymers but have problems with dimentional stability, 4) mineral filled grades - used to counter wrapping and shrinkage although some strength is lost. PET used in carbonated drink containers is able to withstand pressure from within, it is recycable and lighter than glass.	01 PET
Wall and roof insulation, interior doors	-	-	Toys, light diffusers, cutlery, general house appliances, refrigerator liners	PS comes in 3 guises. 1) General purpose PS - high impact varient, easy to mold, FDA approved - hence used in food containers and packaging, extreme clarity, ability to be coloured and high RI gives it glass like sparkle, is brittle and cracks easily, used where optical actractivness and low cost. 2) Midium impact PS - translecet, appears in electrical switch gears and circuit breakers, coat hangers and combs. 3) High impact PS - blend of PPO and PS, is opaque and copes better with low temperatures than most plastics. Found in interiors of refridgerators ad freezers.	06 PS
Window frames	-	Drainage pipes	Safety helmets, automotive instrument panels and other interior components , pipe fittings, plumbing hardware, wheel cobvers, weather seals, glass beading, conduit.	ABS has highest impact resistnace of all polymers, takes colour well, UV resistant for outdoor application if stabilizers are added, has high gloss, natural colour is off white, has good temperature and chemical resistance, high impact resistance at low temperature.	ABS
Roofing sheet	-	Electrical boxes	Safety shields and googles, glazing panels and lighting fittings, safety helmets, laminated sheet for bullet-proof glazing, twin walled sheets for glazing, kitchenware and tableware, microwave cookware, medicle sterilizable components.	The optical transparency and high impact resistance of PC makes it suitable for bullet-resistant or shatter-resistant glass applications. Usually processed by etrusion or thermoforming, injection molding is possible.	07 O
-	Carpets	Cable trays	lences, containers, tanks, book bindings, cables, ropes, protective clothing, air filteration bags and electrical insulation.	Nylons are tough, strong and low co-efficent of friction, easy to injection mold, machine and finish, have resistance to strong acids , oxidising agents and solvents, particularly in transparaent grades.	PA
-	Bearings, connectors	High performance seals, conectors	Electrical connectors, hot water meters, valve and bearing components, wire and cable coatings, pump wear rings, electrical housing, bushings, bearings.	PEEK can be used up to temperatures of 300 C for a short time and 250 C for a long time. It offers high hardness and therfore abrasion resistance, has excellent fatigue properties and good creep resistance. It has low co-efficient of friction, low flammability. Chemical resistance is good. Unreinforced PEEK offers highest elongation and toughness of all PEEK grades. Glass reinforcements significantly reduces the expansion rate and increases the flexural modulus. Carbon reinforced PEEK has high compressive strength and stiffness and low expansion coefficient.	
Coating	-	chemical-resistant linings for pipes and fittings	Wire and cable covers, high quality insulating tape, corrosion resistant lining for pipes and valves, protective coatings, seals and gaskets, low friction bearings and skis, transparent roofing and weather protection for other polymers (eg : ABS) , non-stick cooking products, water repellent fabrics.	PTFE is 2.7 times denser that PE and 2 times more expensive. But is more reitant to chemical attack, it can safely be used from -270 C to +250C. It has low friction, exceptional ability resist wetting. All fluroplastics are white, and to some degree, translucent. They are soft, waxy feel, Read GoreTex fabrics.	
Skylights, daylighting panels	Decorative room dividers	Transparent service panels	Used to cast sinks and basins, bullet proof sreens (not as resistnat as PC/Glass laminate) , skylights, outdoor fittings, motorcycle windscreen.	-	
Inflatable cushions for lightweight structures	Atrium coverings	-	Linings, chemical apparatus , wire coatings, components for pumps, valves, tower packings, filled grades, beaings in aggressive environments, pump impellors, gears and bodies.	-	

Additves			Where can we source for experimentation
Additives used	Ease of removal	Removal method	
[3]			
Antioxidants (Hindered Phenols), UV stabilizers (HALS - Hindered Amine Processing aids, Fatty acids esters	Easy as LDPE are not strongly bonded	Melting LDPE, and some additives may volatilize or be separated during this process	Shopping bags
Antioxidants (Hindered Phenols), UV stabilizers (HALS - Hindered Amine Processing aids, Fatty acids esters	Easy as HDPE are not strongly bonded	Melting HDPE, and some additives may volatilize or be separated during this process	Bottles, milk jogs, recycling bins
Antioxidant (Hindered phenols, Phosphites) Stabilizers (Slip agents, anti-blocking agents)	Moderate, generally feasible	Washing, melt filtration, and solvent extraction.	Flower pots, carry out beverage cups, microwavable food containers
Plasticizers (e.g., phthalates, DEHP, Non-phthalates) Stabilizers (e.g., lead-based, calcium-based, metal based) Flame retardants (Antimony trioxide, brominated flame retardants)	Challenging due to complex additives; challenges in separating PVC from other plastics.	Combination of mechanical separation, solvent extraction, and advanced recycling technologies.	Bottles for chemicles, plumbing pipes, window frames
Stabilizers (Phosphites), Colorants	Easy	Melt filtration, washing, and chemical processes like hydrolysis.	Soft drinks bottle, food containers
Stabilizers (hindered phenols), Flame retardants (Hexabromocyclododecane (HBCD)) Colorants - pigments	Challenging due to additives, especially flame retardants.	Depolymerization through chemical processes.	Toys, beer cups, styrofoam
Stabilizers (Hindered phenols), Flame retardants (Brominated flame retardants)	Moderate to challenging removal, especially for flame retardants.	Chemical and mechanical processes, such as solvent extraction and melt filtration.	Cell phones, lego bricks
Flame retardants (phosphorus - based flame retardants) Stabilizers (phosphites)	Moderate to challenging removal, particularly for flame retardants.	Solvent-based depolymerization and advanced recycling technologies.	Dome lights, flat or curved glazing, rooofing sheets, sound walls
Stabilizers (Phosphites) Flame retardants	Moderate	Hydrolysis and melt filtration.	Toothbrush bristles, socks, stockings
Stabilizers (hindered phenols), flame retardants	Depends on the formulation	High temperatures used usually	Aerospace components, medical implants, electrical connectors, and high-performance machinery parts.
Stabilizers (hindered phenols)	Moderate	removal of additives is generally achievable through melt processing methods.	Non-sticking cookware, seals and gaskets
Stabilizers (hindered phenols)	Moderate	removal of additives is generally achievable through melt processing methods.	Used in eyeglass lense, amera lense, signage and displays
Stabilizers (hindered phenols)	Moderate	removal of additives is generally achievable through melt processing methods.	Greenhouse film, transparent roofing and façade materials

2.9 Plastic resin selection

2.9.1 Assessment of material properties of different plastic resin

***** Refer material properties summary table on previous page***

Cost of the raw material

A diminished expenditure on the raw materials means that there is a large allocation for technological advancements, thereby supporting the development of products characterised by intrinsic worth and enhanced profit margins for the company. The lower the raw material cost, the larger is the amount that could be spent on technologies and in to develop a product of higher value and profit margins of the company. A reduced product cost, coupled with superior material performance, serves as an incentive for consumers to invest in recycled materials over conventional counterparts. Besides, elevated raw material costs may undermine the feasibility and profitability of upcycling initiatives. It is also important that the economics of upcycling projects are pivotal, distinct from downcycling, where plastic cost is not a determining factor, given that waste disposal is the primary objective. In the table, the plastic is rated from low-to-high cost of raw material.

Density of the material

The price of plastic is significantly influenced by its density and the intended application. Higher density of plastics generally requires more raw material to produce a given volume of plastic since they require more energy, processing time, or specialised equipment. In contrast to the low-density plastics, those with high density exhibit superior durability and enhanced mechanical properties influencing their pricing.

Mechanical properties

The key mechanical properties influencing the material choice for façade component include tensile strength, compressive and bending strength. Tensile strength is the maximum amount of tensile stress a material can withstand without breaking. Facade components are subjected to forces such as wind, temperature changes and potential impact forces and high tensile strength ensures that the material can resist stretching and deformation under tension, maintaining structural integrity.

Compressive strength is the maximum compressive stress a material can endure without collapsing or deforming. This parameter is also important to consider if the façade component is subjected to compressive force if they are load bearing and prevents product from crushing or buckling under pressure ensuring stability and safety.

Bending strength or flexural strength measures the material's ability to resist deformation under bending loads. High bending strength prevents the material from sagging and cracking contributing to overall stability.

Thermal properties

Thermal resistivity, also referred to as thermal conductivity, measures a material's capacity to conduct heat. This property is important in the selection of plastic for façade components, as it directly affects the product's resilience to exterior temperatures. It is important to also consider that the chosen material doesn't compromise with the occupant comfort by conducting excessive heat.

The melting point refers to the temperature at which a solid material transitions to liquid state. This material property helps in determining the material's suitability for processing without undergoing degradation and ensures that the plastic can undergo manufacturing processes without compromising its integrity.

Glass transition temperature is a temperature range at which an amorphous polymer transitions rom a glassy, rigid state to a rubbery, more flexible state. This parameter significantly influences a material's stiffness and dimensional stability and decides whether the product will maintain specific mechanical characteristics under different conditions.

Durable properties

The durability and flammability of material are two of the significant characteristics particularly in the choice of plastics for product design.

UV resistance is essential to maintain aesthetic appeal of the product and accelerates the aging process of materials making them more vulnerable to degrade and deteriorate leading to wear and tear. This property contributes hugely to longevity and overall performance of the product. The degradation of material concurrently impacts the structural integrity of the product, preventing brittleness and weakening of the component.

Flammability is another critical property in evaluation of façade products. To ensure safety of the building and its occupants, it is necessary to choose a material with high resistance to ignition and low flammability.

2.9.2 Decision criteria

The flammability of plastic is a crucial factor because it has an immediate effect on safety, compliance with law, and a construction project's overall risk management. It is important for making sure that materials meet certain flammability ratings in order to prevent fire hazards, safeguard occupants, and comply with construction guidelines. The fire-resistance ratings of the materials used in building construction must be adequate to stop a fire from spreading and to ensure the safety of the occupants. Common plastic building materials, such as PVC, PP, and PE, for example, can melt at low to medium temperatures and turn into a hazardous liquid.

In building construction, UV degradation is another factor that impacts the longevity, structural integrity, and safety of materials exposed to sunlight. Prolonged exposure to UV radiation can weaken materials, making them brittle, prone to cracking, and to material deterioration.

Hence, the go-no go factor for the decision depends the flamability performaance and the UV resistance of the plastic. Figure 56 shows the graphical representation of the comparision between two different go-no go factors.The well performing thermoplastics are PEEK, ETFE and PTFE. But the amount of waste generated is very low compared to any other thermoplastic.

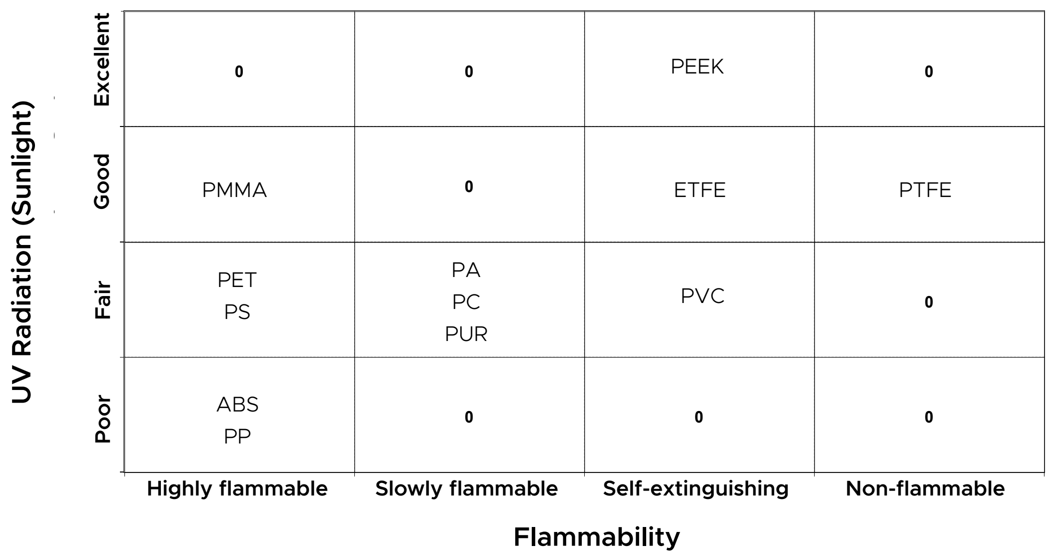


Figure 24: Comparision between UV Radation and flammability of polymers (Source: Edupack)

2.9.3 Conclusion

Following the assessment, Polyvinyl chloride (PVC) favors all the requirements as optimal material for achieving the project's objectives. The significant ratio of waste generated to waste recycled aligns with the project's aim of addressing the challenge of waste generation (see Table 1). PVC possesses favorable material properties that remain workable even after slight degradation and recycling. Additionally, the overall positive material's flammability and durability ratings make PVC a viable solution for the design of architectural components.

3

PolyVinyl-Chloride (PVC)

Manufacturing | Processing | Challenges

3.1 PolyVinyl Chloride

3.1.1 Introduction

Polyvinyl Chloride, commonly known as PVC, has become a common material in the built environment, playing a pivotal role in various construction applications. Its versatility, durability, and cost-effectiveness have positioned PVC as a preferred choice for architects, engineers, and builders alike.

PVC is a common building material used for siding, doors, and window frames. The material is a sustainable option for improving energy performance and preserving aesthetics because of its high thermal efficiency and weather resilience. PVC profiles are well-known for needing minimal maintenance, offering architects and homeowners with a long-lasting and aesthetically pleasing alternative. PVC is versatile enough to be used in interior design for decorative elements, wall coverings, and flooring. Its success in producing both useful and aesthetically beautiful interior spaces can be attributed to its ease of installation, resilience to dampness, and vast range of available colors and patterns.

The basic building block of PVC is chloroethene (H2C=CHCl), better known as vinyl chloride monomer or VCM. The vinyl chloride monomers are polymerized to prepare polyvinyl chloride. Figure shows polymerisation of vinyl chloride monomer to poly vinyl chloride.

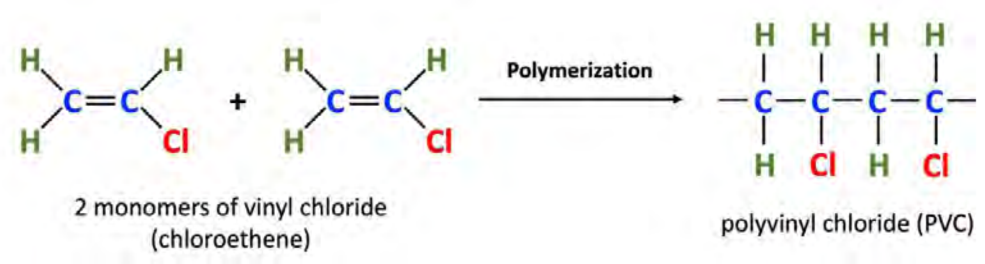


Figure 25: Polymerisation of VCM to PVC (Source: Lahl & Zeschmar-Lahl, 2024)

PVC is commonly used as a material as it offers several properties:

Versatility and Durability
- PVC's adaptability makes it a preferred choice for structural applications, including formwork, window frames, doors, and siding.
- Its durability ensures a prolonged lifespan, providing resistance against environmental factors such as weathering and corrosion.

Environmental Considerations
- The sustainability profile of PVC is evolving, driven by responsible manufacturing practices and recycling initiatives.
- The recyclability and extended lifespan of PVC position it as a responsible choice, aligning with the increasing emphasis on sustainable construction.

Heat Resistance and Fire Prevention
- Inherent insulation properties contribute to the reduction of condensation and resistance to internal temperature changes.
- PVC's self-extinguishing nature adds an extra layer of fire prevention, enhancing its safety profile across various construction scenarios.

Recyclability
- The recyclability of PVC is in harmony with the broader push for sustainable construction practices.
- Recycled PVC, with the potential for multiple usage cycles, actively supports environmental stewardship within the construction industry.

3.2 Manufacturing process

The manufacturing and processing stages focus on the creation of semi-finished (or semis) products and finished products, respectively. Various manufacturing processes are used, e.g. extrusion, calendering, injection molding, and other manufacturing processes. Outflows from these processes have been grouped into five macro-categories including pipes and fittings, tubes and profiles, films and sheets, wires and cables, and other semis goods.

In some cases, semis products can be used standing alone (e.g., pipes and fittings); in some other, they are incorporated into complex products such as cars and electronics (e.g., wires and cables).Figure 56 from Petrović & Hamer, 2018 summarises the overall manufacturing process of PVC, the different stages of processing and the additives added in the procedure.

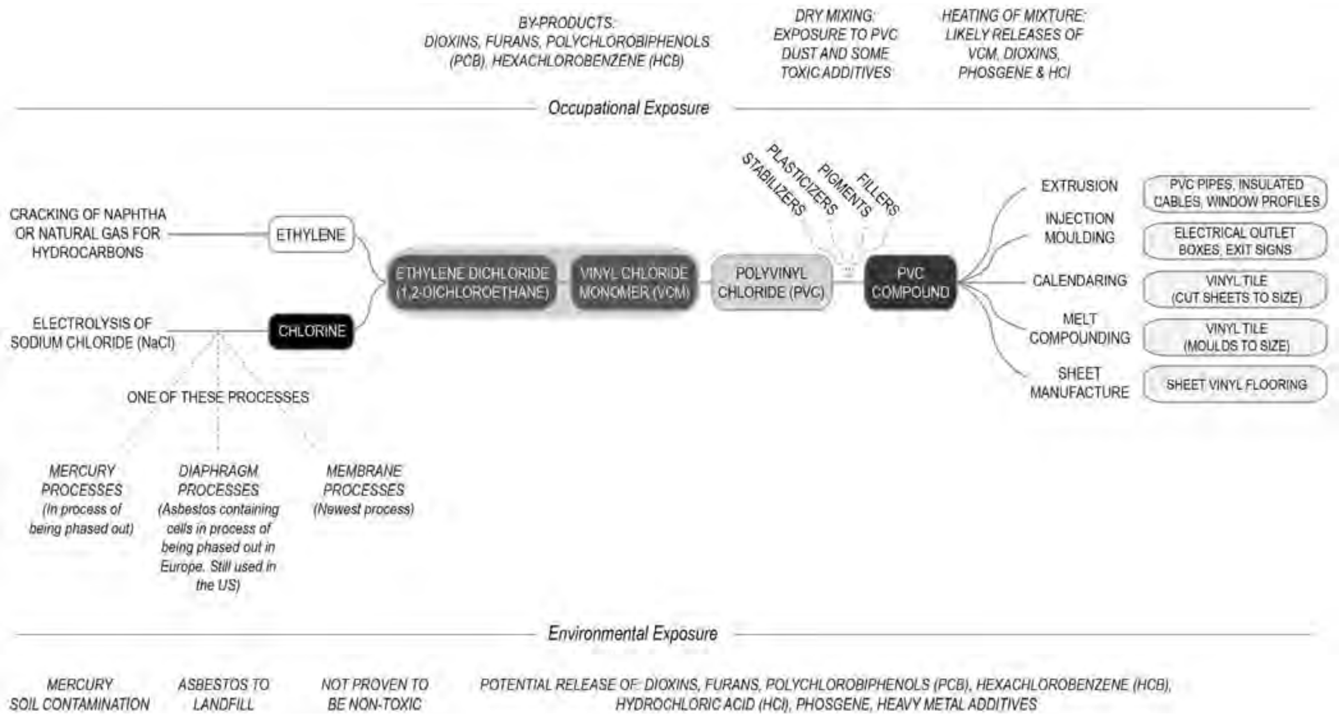


Figure 26: Summary of the most common manufacture of PVC process (Source: Lydia Hamer and Emina Kristina Petrović.)

3.2.1 Processing techniques

PVC's versatility is also due to its compatibility with various molding processes, including injection molding, extrusion, calendering, among others (IHS Markit, 2021).

Two key processing techniques for PVC are extrusion and calendaring:

- **Extrusion:** Melted PVC is pushed through a shaped die in this technique to generate continuous lengths of material with a uniform cross-section. It is commonly used for producing profiles, sheets, and pipes.
- **Calendaring:** To produce thin sheets or films with exact thickness and smooth surfaces, PVC is fed through a sequence of heated rollers in this method. The finished product's thickness and texture can be tailored by altering the rollers. PVC flooring, wall coverings, and other flat materials requiring a consistent finish and flexible qualities are often manufactured with calendaring.

The different processing techniques used for preparation of PVC and production methods are summarised in Figure 27 as detailed by Gomez (1984).

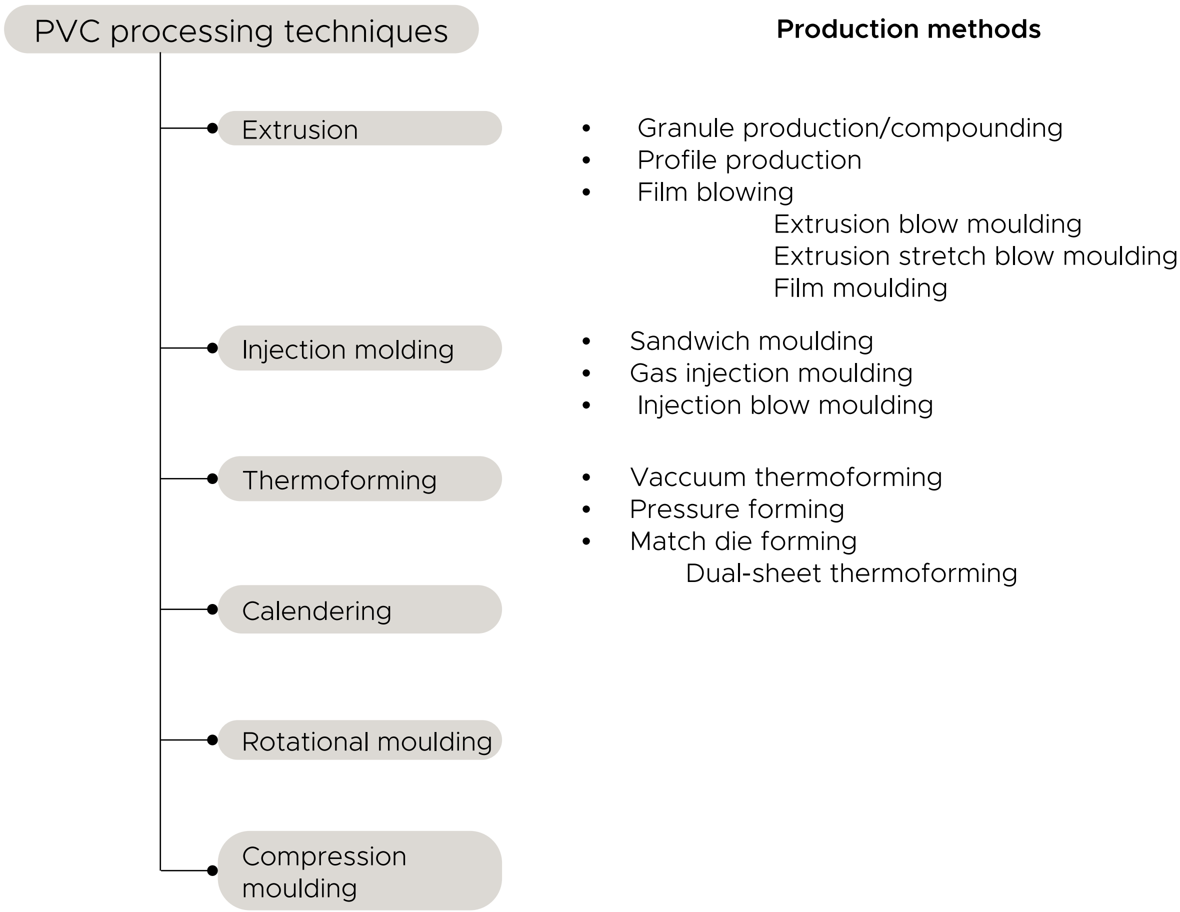


Figure 27: Representation of different processing techniques of PVC

3.2.2 Additives used in PVC polymer preparation

The preparation of PVC polymer involves several processing steps to achieve the desired finished product. Unmodified PVC resins are inherently difficult to process due to their rigidity and thermal instability. Therefore, to enhance their processability and achieve the required material properties, various additives are added into the PVC composition. According to Gomez (1984) , these additives include:

Heat stabilizers :
These are necessary to prevent PVC from deteriorating during processing and prolonged use. Heat stabilizers protect the polymer against thermal deterioration, which when exposed to high temperatures may lead to discoloration and the loss of physical characteristics.
Lubricants :
To lessen friction between the PVC and the processing machinery, lubricants are used. This increases the manufacturing process' efficiency by enabling easier processing and avoiding the material from reacting to the equipment.

Processing aids :
These additives improve PVC's melt flow characteristics, which ease molding and shaping. Processing enhances the end product's homogeneity and helps to minimize defects that might develop during the molding or extrusion operations.

Impact modifiers :
Impact modifiers are added to the final product in order to improve its toughness and resistance to impact. Because of this, PVC is suitable for uses where durability and longevity are essential, like outdoor and pipe applications.

Colorants :
Colorants are added to the PVC composition in order to achieve the desired aesthetic features. These may

include dyes or pigments which give the finished product with the necessary color and opacity without changing its physical characteristics.

UV Stabilizers :
UV stabilizers are required to shield PVC products from UV radiation-induced degradation when they are exposed to the sun. UV stabilizers protect against issues like discoloration and brittleness over time, helping to preserve the PVC's structural integrity and appearance.

Compounders :
these are formulations that blend the PVC resin with all necessary additives to create a material with the necessary characteristics. In order to prepare the PVC mixture for processing into different products, compounders ensure it is uniform and homogenous.

The processability and performance qualities of PVC are greatly enhanced by the addition of these additives, making it suitable for a variety of uses in the building and construction sector. The end product is a more adaptable, stable, and durable material that meets the demands of various construction environments.

3.3 Review of PVC plastic recycling

3.3.1 Recycling technologies

Primary PVC recycling processes are twofold. The first method is mechanical recycling, which makes use of PVC's thermoplastic qualities to repeatedly heat, melt, and extrude the material into new goods. The second technique is feedstock recycling, which entails using procedures like pyrolysis or gasification to break down the PVC molecules into smaller, low molecular weight molecules in order to recover carbon. Figure 18 adapted from ChemTech publishing, 1996 summarizes the various techniques used to recycle PVC.

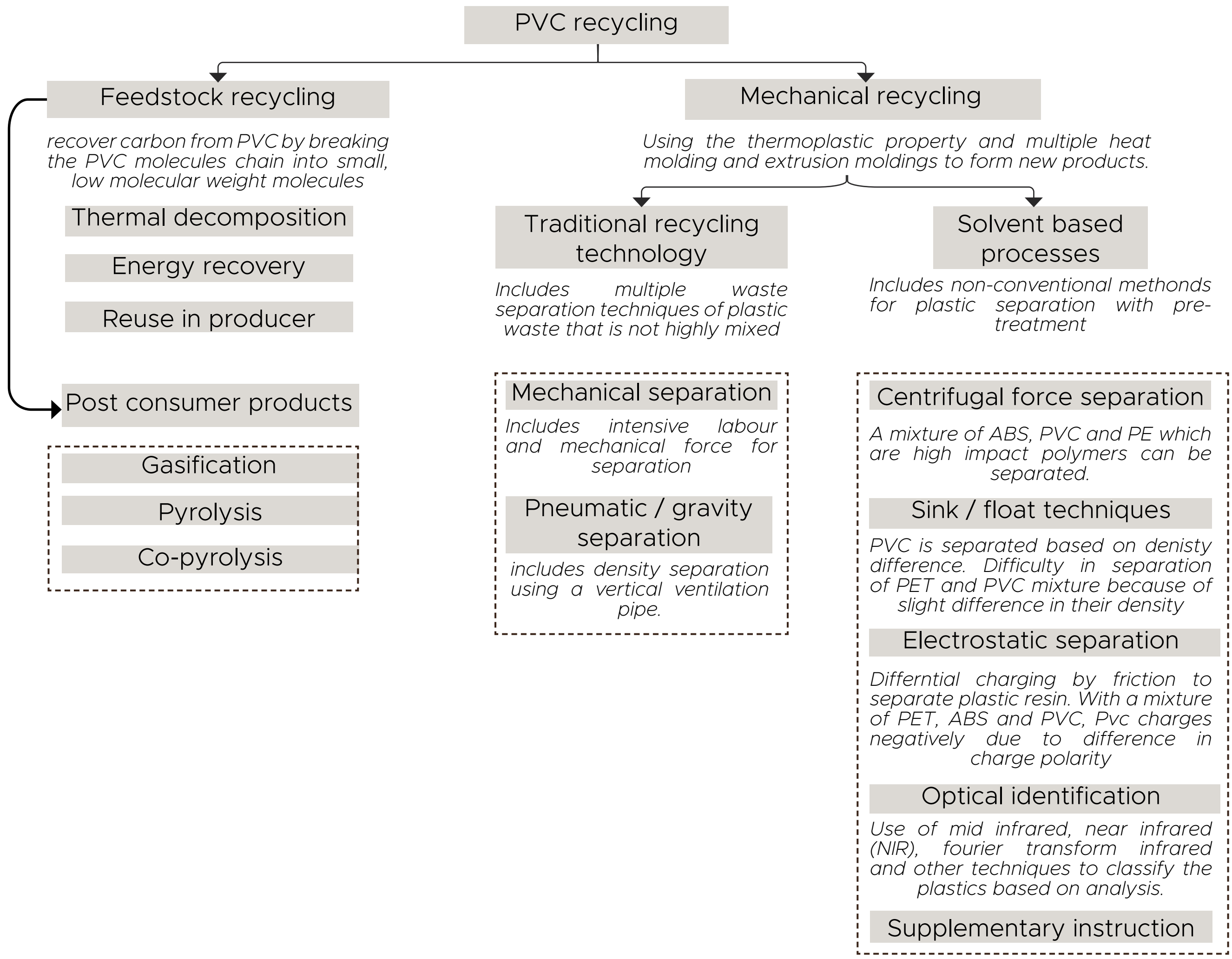


Figure 28: Summary of recycling technologies for PVC polymer

3.3.2 End-of-life scenarios of PVC products

In the building and construction industry, PVC products are typically designed for long-term use. The data in the figure indicates that windows, flexible PVC, and pipes are the primary contributors to PVC waste. While PVC pipes and windows generally do not contain harmful additives, flexible PVC often includes fire retardants, complicating the recycling process.

For the purposes of this thesis, PVC windows and pipes have been selected as the focus waste streams due to the absence of complex additives.

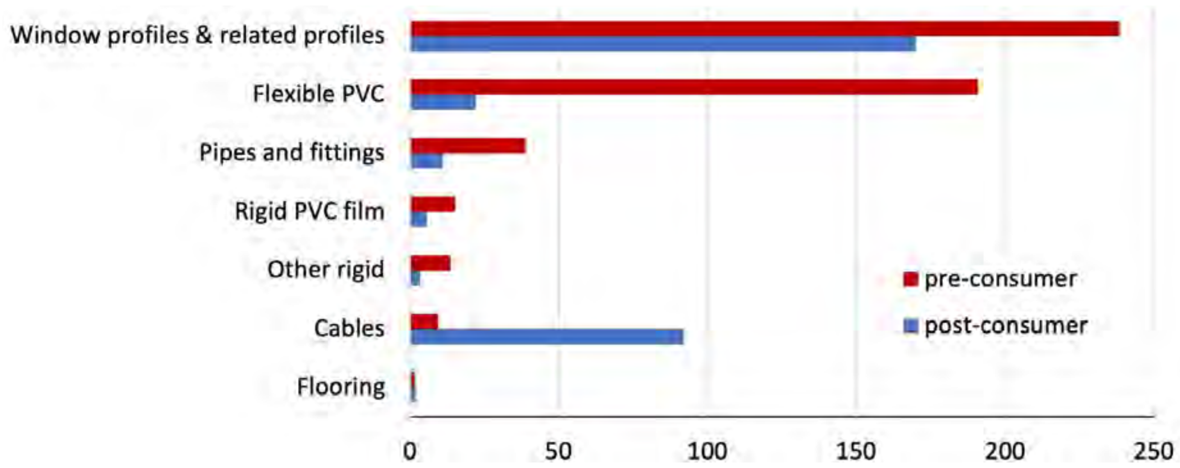


Figure 29: Graphical representation of recycled PVC compunds in 2022 (Source: Lahl & Zeschmar-Lahl, 2024)

PVC products currently undergo four main types of disposal: recycling, landfilling, incineration, and chemical recycling. Figure 11 from Wythers (2019) summarizes the end-of-life scenarios for major PVC resin products.

- Landfilling and Incineration: These methods are most commonly preferred due to their cost-effectiveness. Landfilling involves disposal of the waste in designated sites, while incineration involves burning the waste to generate energy. Both methods raises environmental and health concerns. Landfilling can lead to soil and water contamination, wheras incineration can release harmful pollutants into the air.

- Mechanical Recycling: This process involves physically breaking down PVC products into smaller pieces that can be repurposed into new products. The feasibility of mechanical recycling depends on the benefits it offers to the costs involved during the process. Factors like properties of the recycled product, processing conditions, and the types of chemicals used in the original manufacturing process play an important role in determining the quality of the recycled material.

- Chemical Recycling: This high-cost disposal method aims to break down the chemical structure of PVC resin to yield monomers, which can then be re-polymerized into new PVC products. Although it is expensive, chemical recycling has the potential to produce high-quality materials and offers a way to recycle PVC that might not be suitable for mechanical recycling due to contamination or degradation.

In summary, while landfilling and incineration are the most common disposal methods for PVC due to their lower costs, recycling—both mechanical and chemical—offers more sustainable solutions that can reduce the environmental impact of PVC waste. However, these recycling methods are often limited by economic factors and technical challenges.

Ciacci et al.'s 2017 research reported a 'top down' approach to estimate the amount of PVC waste and products is discarded at end-of-life. In this approach, the annual flows into use by end-use is considered and applied lifespan distribution to estimate when the product enters the waste management stage. The results provided a measure of magnitude of PVC accumulated in use and available for future recovery. The PVC waste and PVC containing products recovery majorly depends on the waste management system in place.

Disposal technique	Degree of pollution	Cost effectiveness	Product formed	Properties of the final product
Landfilling	Very high	Low-cost	No product	-
Incineration	Very high	Low-cost	No product or Energy	Incineration generally used for the demolition of the waste as well as energy recovery. Energy recovered from PVC depends up on the incinerator efficiency.
Mechanical recycling	Low	Middle-cost	Various products depending up on the value addition	Properties of the final products depend up on the processing condition, chemicals employed for the value addition.
Chemical recycling	Moderate	High-cost	Monomers, oligomers or raw products	Properties depend on the chemicals employed for the chemical recycling technique.

Figure 30: Tabular representation of various end-of-life techniques for PVC products (Source: Wythers, 2019)

3.3.3 Challenges associated with PVC recycling

Technical challenges

- There are restrictions on mechanical separation when handling highly mixed and polluted wastes. Even little variations in density make it difficult for pneumatic or gravity techniques of separation to distinguish among the two kinds of plastics. Furthermore, excessive material adsorption might impair electrode functioning and prohibit continuous operation, which presents a difficulty for electrostatic separation. In order to preserve accuracy, optical separation requires pauses between testing in order to guarantee efficacy.
- Despite advances in contemporary procedures, mechanical separation provides little assessment when it comes to product purity. Optical identification requires more expensive equipment because of the cost of the sensors and the requirement to create spectral libraries .
- Based on Ciacci et al.'s 2017 research, gasification offers a distinctive set of difficulties. The key problem is from the tar precursor found in plastic, which causes tar to be formed during the gasification of granular waste plastic. When this tar cools and solidifies, it can harm industrial machinery, mainly gas turbines, engines with combustion, and pipelines. Lowering the gasification temperature makes the issue worse since the tar mist clogs pipes and solidifies into thick materials. Tar and gasification gas mix at high temperatures, but as the temperature drops, non-flammable droplets form and burning produces black carbon particles, which are bad for combustion equipment like gas turbines and internal combustion engines and lower the value of the syngas which is produced

Logistical challenges

- The research conducted by Ciacci et al., 2017, reports a model that estimates approximately 140 million metric tons (Mt) of PVC accumulated in anthropogenic reservoirs.This provides a theoretical projection of the PVC available for recycling. This huge accumulation poses a challenge regarding how to effectively implement recovery and recycling efforts.
- Sorting waste plastic is an important part of mechanical recycling since it can be combined with the recycling of feed-stock materials later on. To choose the best separation technique, variables including material density, surface angle, electric charge, and optical properties of various polymers are taken into consideration. Every separation approach has benefits regarding effectiveness and identification accuracy, as well as disadvantages concerning equipment expenses and separation area.
- The on-site PVC pipe sorting process's reliance on manual labor because limits the possibility for greater assessments in terms of separation efficiency, in certain situations, there is no access to contemporary machinery.

3.4 Review of PVC pipe recycling

Mechanical recycling of PVC pipes

The mechanical recycling is one of the most recommended methods. For this process several essential steps must be meticulously executed prior recycling . These include sorting, purification, reprocessing, and blending, alongside thorough evaluation methods.

Within the construction industry, PVC pipes are commonly collected during either the construction or the demolition phase of projects. These pipes are systematically collected and transported in bulk to waste management facilities. This accumulation of PVC pipes from various sources within the construction and demolition sector offers an advantage — a standardized composition. These waste are usually originating from similar constructions, installed around the same period, and often bearing the insignia of the same brand, these bulk quantities of PVC pipes facilitate a streamlined composition process.

The regeneration of PVC pipes follows a sequence of steps, as illustrated in the figure Figure 28 . Initially, the pipes undergo a pre-sorting phase, followed by compression using a press. This compression helps in the identification of materials such as polyethylene (PE), which have flexibility and thus remain intact during this process. Subsequently, the material is sifted to remove any extraneous sand particles before being conveyed to a manual sorting station. Here, the material is manually separated from rubber and non-PVC materials from the PVC components.

The PVC material is then subjected to further processing, undergoing reduction into smaller shreds through a series of grinders and sieves. Following this, a magnetic separator is employed to effectively eliminate any ferrous materials present. Sometimes, the recycling facilities also opt to micronize the materials to achieve a higher degree of homogeneity in the final material.

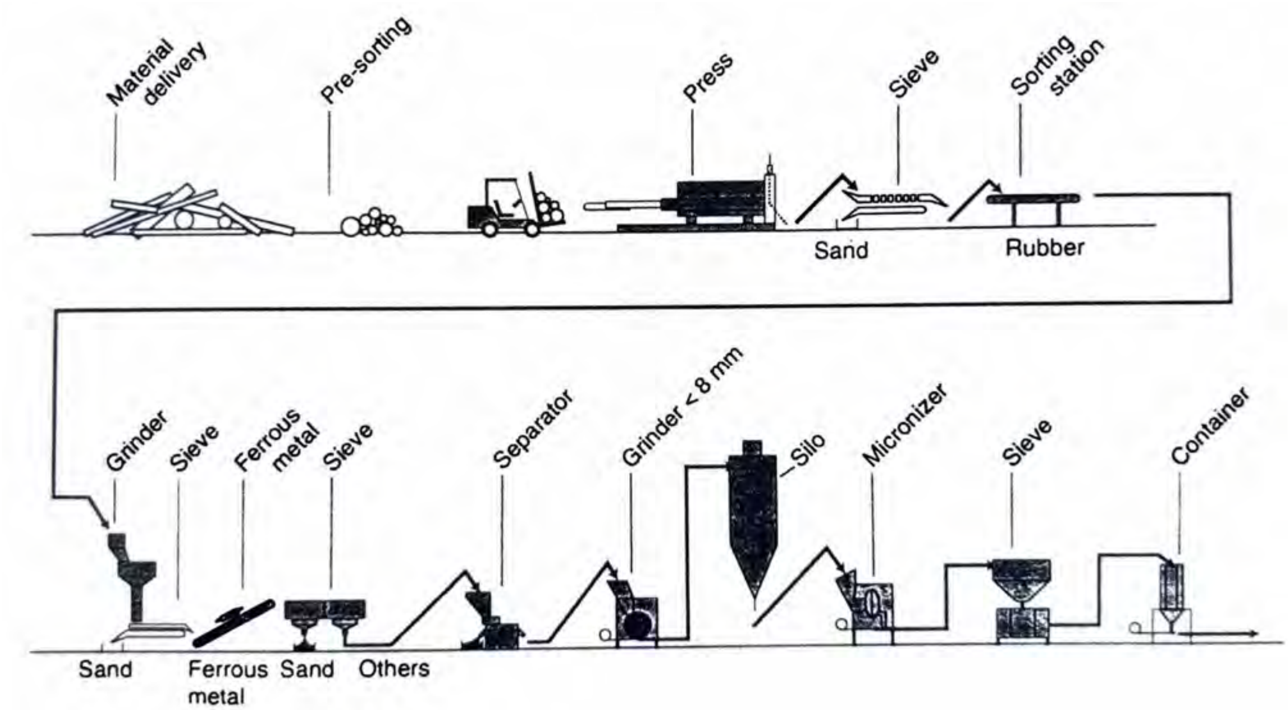


Figure 31: Diagrammatic representation of the PVC pipe regeneration process (Source:Chem Tech Publishing (1996)

Re-use of pipes into co-extruded pipes

The process includes 2 extrudes to make a 3-layered parison. According to Chem Tech Publishing (1996), a market study showed that using the recycled material in the intermediate layer shows a significant opportunityfor utilizing recycled plastic.

The formation includes 3 layers - compact inner layer, formed or compact intermediate layer and compact outerlayer. The process emphasizes on creating a strong annular restriction in the flow channel and extruding the recycled plastic into the intermediate layer. Co-extruded pipes have been in the market for some time and offer advantages over single-layer PVC pipes, including good mechanical properties, resistance to deformation under soil pressure, extended lifespan, high chemical resistance, superior impact resistance, ease of handling and installation, and compliance with technical standards for building drainage and sewage systems.

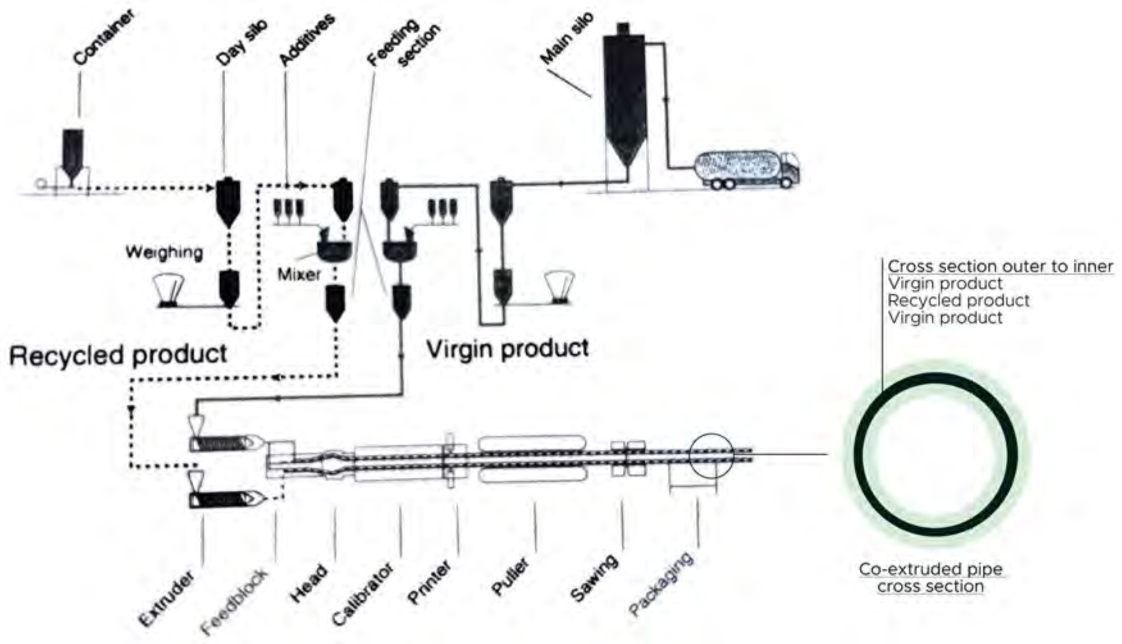


Figure 32: Diagrammatic representation of the PVC pipe regeneration process (Source:Chem Tech Publishing , 1996)

3.5 Field study : Pretty Plastic , NL

URL: https://www.prettyplastic.nl/

Pretty Plastic aims to stop PVC waste from ending up in landfills and incinerators by offering a sustainable alternative. Repurposed building components, including rain gutters, downspouts, and old window frames, are used to make the company's environmentally friendly tiles. These tiles are an excellent example of how waste can be turned into valuable resources. Pretty Plastic additionally offers a return policy, that allows their tiles to be recycled into new tiles. With this method, the material's lifespan can be extended by over 300 years, and each tile is capable of lasting up to 40 years and be recycled up to eight times.

Insights from an interview with **Hajo Reinders**, Managing Director and partner at Pretty Plastic:

- Because building products naturally contain fire retardants, Pretty Plastic consciously utilizes recycled materials from those products. As a result, their tiles require less additional additives.
- However, unwanted materials like lead, which was once used as a stabilizer and in colors, may be present in recycled PVC (rPVC). Lead is no longer permitted for these uses, however traces still exist in the rPVC. Under REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals), the European Chemicals Agency (ECHA) is in charge of regulating laws related to these compounds.
- Pretty Plastic recognizes that over time, there may be a gradual degradation of the hue of their tiles. They are now finishing UV evaluation to give official statistics on the degree of color degradation expected over the course of the product's lifetime in order to address this problem.
- Utilizing old exterior architectural materials, including window frames, has the benefit of preserving their natural fire retardant and additive content, which reduces the need for additional substances during production.

The company sells three different types of tiles as shown in Figure 34, and they can be attached to the wall using screws.The tiles also come in various colours and can be cleaned using mild cleaning household products.

Figure 34: The three variations of tiles by pretty plastic (Source: Pretty plastic)

Figure 33: Exhibition pavilion at dutch design week displaying the pretty plastic facade tile (Source: Pretty plastic

3.6 Need of recycling PVC into an architectural product

The study emphasizes the utilization of PVC waste from construction and demolition activities in the production of other goods, thus contributing to material flow and circularity. However, it also highlights a significant challenge posed by high waste accumulation. To tackle this issue, it is very important to develop multiple alternative uses to fully tap into the potential of recycled materials. This thesis specifically focuses on architectural components as a promising avenue for utilization. By integrating recycled feed-stock with additives such as Calcium carbonate filler for pipes and UV resistance additives for PVC windows, there is an opportunity to creatively reuse the chemical composition, thereby enhancing product performance and functionality.

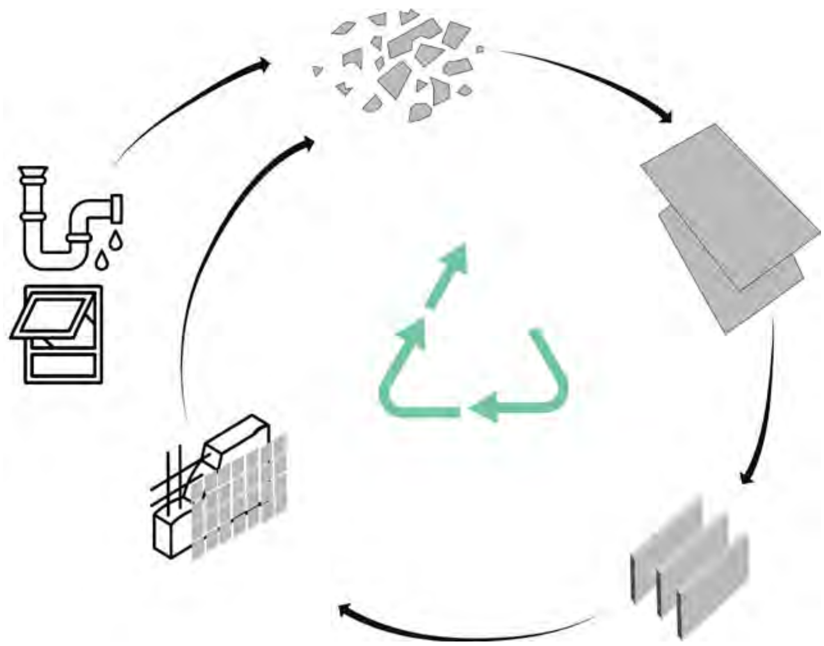


Figure 35: Diagrammatic representation of the thesis outline (Source: Author)

4

Material exploration and experimental validation

Material characterization | Production | Testing

4.1 Shred characterisation

4.1.1 Section overview

Scope

The chapter aims to evaluate the purity of plastic shreds, emphasizing their composition and quality. Experimental methods consists of rapid tests for swift confirmation and detailed examination of their glass transition temperature (T_g) and composition, with the objective of eliminating hazardous substances such as Bromine (Br).

Roadmap

Shred characterization
- Rapid tests → Fourier Transform Infrared Spectroscopy (FT-IR)
  Laser-induced breakdown spectroscopy (LIBS)
- In-detail examination → X-ray Fluorescence (XRF)
  Differential scanning calorimetry (DSC)

- Confirmation of the waste stream to be PVC resin.
- Phase-change temperature such as T_g, T_c and T_m .
- Overview of composition of the sample -range of elements present in the waste stream.

4.1.2 Fourier Transform Infrared Spectroscopy (FT-IR)

FT-IR analysis was performed quickly to confirm if the sample was PVC. In the FTIR analysis, samples are subjected to contact with infrared (IR) radiation. The IR radiations then have impacts on the atomic vibrations of a molecule in the sample, resulting in the specific absorption and/or transmission of energy. This makes the FTIR useful for determining specific molecular vibrations contained in the sample (Kirk and Othmer, 1953).

This test was performed using the Nicolet iS50 FT-IR machine at the Stevin II lab, The Faculty of Civil Engineering, TU Delft.

Methodology

- The PVC shred from each waste stream - pipes (PVC_p) and windows (PVC_w), which have a flat surface are selected and are cleaned with isopropyl, to prevent any impurities.

- The analysis starts by tightening the knob on the platform until a distinct click confirms the placement. The background noise is collected.

- Once the collection is completed, we take the cleaned shred and is placed on the platform, aligning it with the path of the IR source, and the knob is tightened until another audible click is heard.A detector reads the analogue signal and converts that to a spectrum.

- The OMNIC software was used to analyse the signals and identify the peaks, which are then matched with the pre-existing spectrum library. This process allows for the determination of the probability that the sample corresponds to a specific plastic resin, providing a rapid estimation of the sample's composition.

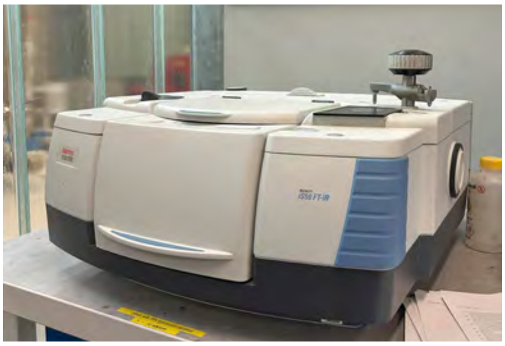


Figure 38: FT-IR spectrometer

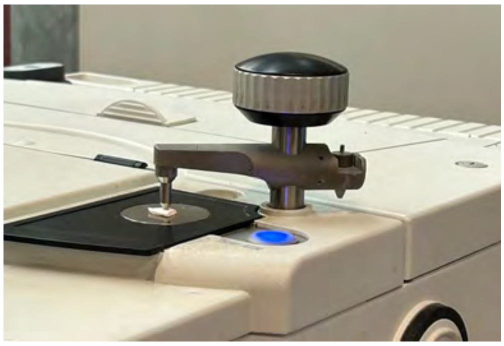
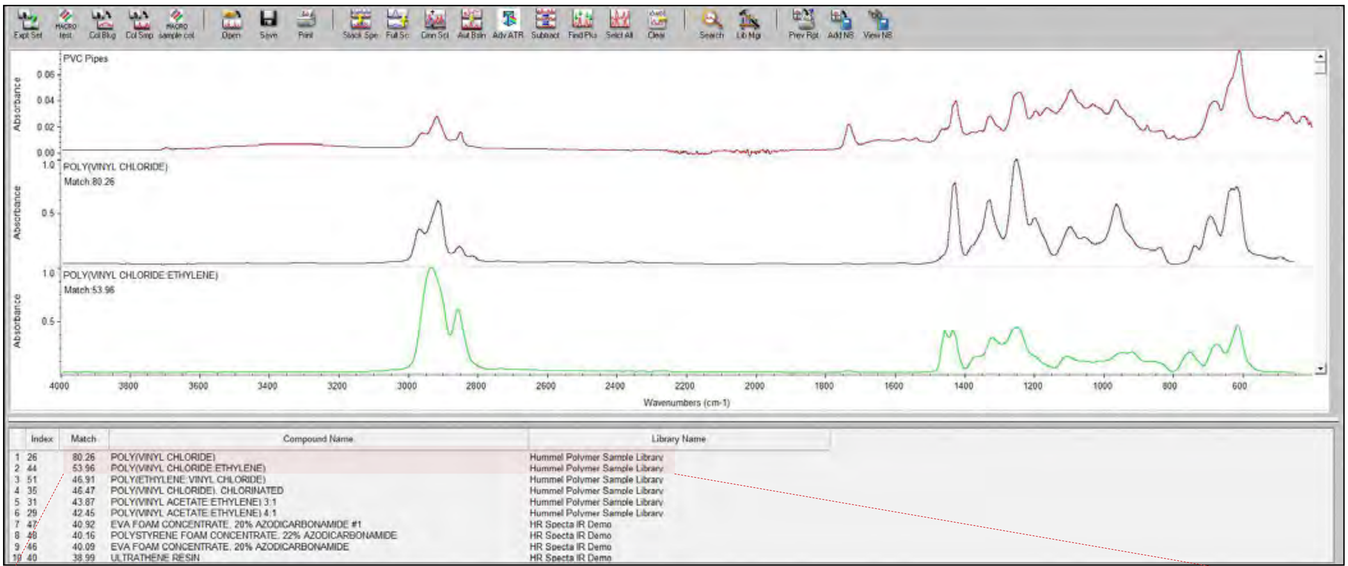


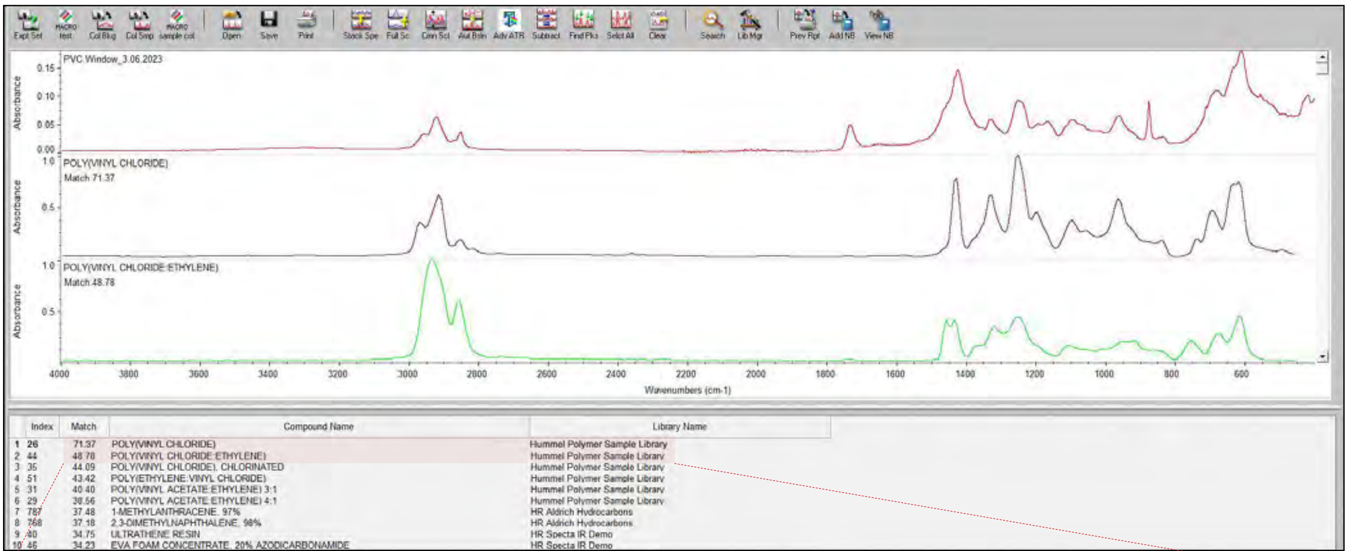
Figure 39: Placement of PVC sample under the knob

Result



	Index	Match	Compound Name	Library Name
1	26	80.26	POLY(VINYL CHLORIDE)	Hummel Polymer Sample Library
2	44	53.96	POLY(VINYL CHLORIDE:ETHYLENE)	Hummel Polymer Sample Library
3	51	46.91	POLY(ETHYLENE:VINYL CHLORIDE)	Hummel Polymer Sample Library

Figure 36: Results from FT-IR analysis of PVC_p (Source: Author)



	Index	Match	Compound Name	Library Name
1	26	71.37	POLY(VINYL CHLORIDE)	Hummel Polymer Sample Library
2	44	48.78	POLY(VINYL CHLORIDE:ETHYLENE)	Hummel Polymer Sample Library
3	35	44.09	POLY(VINYL CHLORIDE), CHLORINATED	Hummel Polymer Sample Library

Figure 37: Results from FT-IR analysis of PVC_w (Source: Author)

Discussion

The analysis reveals that the peaks of the sample align with those in the PVC IR database. However, it does not confirm the presence or absence of additives or the purity level of the PVC within the sample. Furthermore, the accuracy of the data is dependent upon the purity of the PVC within the database sample. A more effective comparison could have been achieved by analyzing the sample alongside PVC plastics of known compositions. The data from this approach would provide a more reliable basis for assessment.

4.1.3 Laser-Induced Breakdown Spectroscopy (LIBS)

Laser-induced breakdown spectroscopy (LIBS) is a technique used for rapid real-time analysis, particularly useful for identifying surface contaminants. LIBS uses a pulsed laser is used to remove, atomize, and excite a small portion of the sample, creating a plasma in the process. As the excited particles return to their normal states, they emit energy in the form of light. This emitted light, once detected, produces a detailed spectrum that reveals the elemental composition of the sample.(Gajarska et al., 2021)

This test aims to detect chlorine which will confirm that the plastic shred is PVC. Additionally, this technique can also be used to detect substances like bromine, which are flame retardants, as well as any other potentially harmful additives from the history of the sample.

The elemental analysis is conducted using Keyence VHX digital microscope under the guidance of Dr.Maarten Bakker at the Stevin II lab, The Faculty of Civil Engineering, TU Delft.

Methodology

A flat sample is selected and cleaned using isopropyl to get rid of dirt.The analysis starts by placing the sample on the platform of the microscope, ensuring no contact with the lens. The focus is adjucted to the flat surface either by using the auto-focus feature or by manual adjustment using the zoom steering. The point for lazer pulsing is then chosen. Elemental analysis is initiated by directing the laser beam onto the sample and triggering the shoot command. The instrument can also analyze elemental composition at specific depths within the sample using the drill option.

Figure 40: LIBS spectrometer

Result

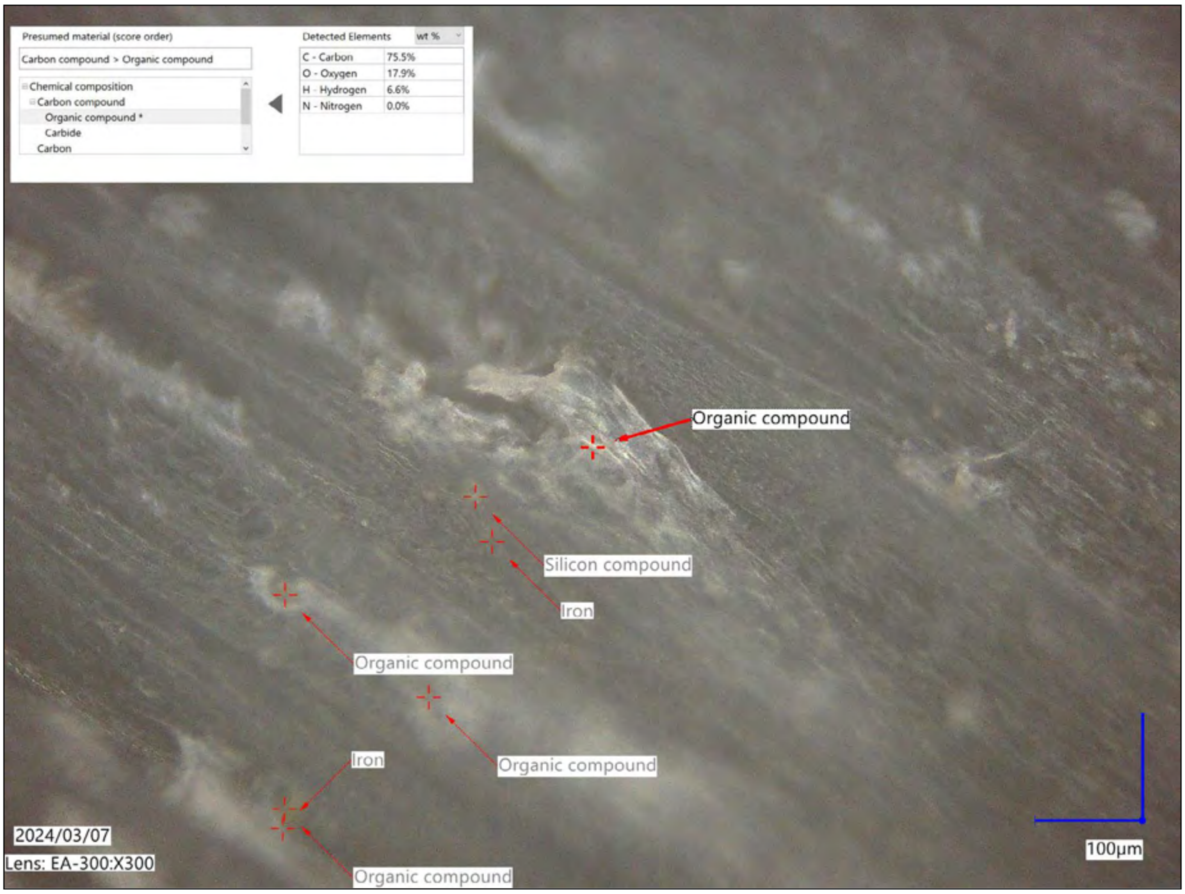


Figure 41: Results from LIBS analysis of PVC_p (Source: Author)

Figure 42: Results from LIBS analysis of PVC_w (Source: Author)

Discussion

In the analysis of the (PVC_p) sample, the results indicate the presence of organic compounds, with smaller traces of silicon and iron detected. The iron content suggests minimal contamination, possibly originating from the bandsaw used during sample slicing. Besides, examination of the (PVC_w) sample revealed only the presence of organic compounds, with no other elements detected. This technique was unable to detect bromine due to its low molecular weight. Similarly, chlorine, another halogen essential for PVC identification, was not detected, which does not confirm the sample composition. This further initiates in-depth compositional analysis.

4.1.4 X-ray Fluorescence (XRF)

The test aims to confirm the presence of Chlorine and Calcium while ensuring the absence of Bromine. The absence of Bromine assures the absence of hazardous substances like the flame retardants, while the presence of Chlorine confirms that the sample is PVC.

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Cl	83.489	0.1
2	Ca	13.838	0.1
3	Ti	1.122	0.03
4	Pb	0.602	0.02
5	Si	0.265	0.02
6	Zn	0.219	0.01
7	Al	0.158	0.01
8	Na	0.128	0.01
9	Mg	0.058	0.007
10	Fe	0.055	0.007
11	P	0.034	0.006
12	S	0.018	0.004
13	Sr	0.016	0.004

Figure 43: Results from XRF analysis of PVC_p (Source: Author)

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Cl	84.758	0.1
2	Ca	5.822	0.08
3	Ti	5.039	0.07
4	Pb	3.333	0.05
5	Si	0.351	0.02
6	P	0.138	0.01
7	Na	0.128	0.01
8	Al	0.118	0.01
9	Mg	0.111	0.01
10	Zn	0.065	0.008
11	Cd	0.057	0.007
12	S	0.031	0.005
13	Fe	0.03	0.005
14	Sr	0.011	0.003

Figure 44: Results from XRF analysis of PVC_w (Source: Author)

Result

The results shows that the sample has a very high concentration of chlorine, confirming the sample to be PVC. The absence of bromine is advantageous, indicating the absence of hazardous substances like the flame retaradants in the tested samples. Additionally, the presence of calcium aligns with the sample's material data sheet, confirming the incorporation of calcium carbonate as filler, which is also in higher percentage in pipe sample compared to windows. Titanium content is primarily because of coloring purposes.

The presence of lead in the window sample indicates the inclusion of lead stabilizers. While, the pipe sample shows minimal lead concentration in comparison to window samples, this may be because of additives introduced for UV resistance . This variance may be attributed to additives introduced for UV resistance, aimed at mitigating plastic photo-degradation

4.1.5 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) is a technique used to investigate the response of polymers to heating and can be used to determine the thermal properties of the polymer such as the glass transition temperture, melting and crystallisation point.

The DSC set-up consists of a measurement chamber which contains 2 pans - one for reference sample and another for the test sample (PVC shred) and a computer to monitor the procedure.

Aim of the test

The test aims to determine the glass transition temperature (T_g) for the two different waste streams of PVC sample. Additionally, the pipe shreds consist of different colours. A DSC analysis between different colours of shreds is also performed to understand the effect of colouration on the (T_g) of the samples. The DSC test helps in extracting the thermal behaviour and operational range of the sample. The samples were heated at a constant rate of 5° C.

Methodology

Important- Make sure the nitrogen supply is switched on. Always use fresh sample pans to get accurate results.

Preparation of sample

- Take the polymer sample (preferably powder) of 10mg weight and then place the lid. Place the pan on crimping dye and press the lever to produce a cell. Use tweezers and transfer the pan to the left pan of the heating chamber. The right side is the reference chamber.
- Open the data analysis software and set the temperature program. The temperature program used for this experiment is shown in figure below.
- Click run to start the analysis

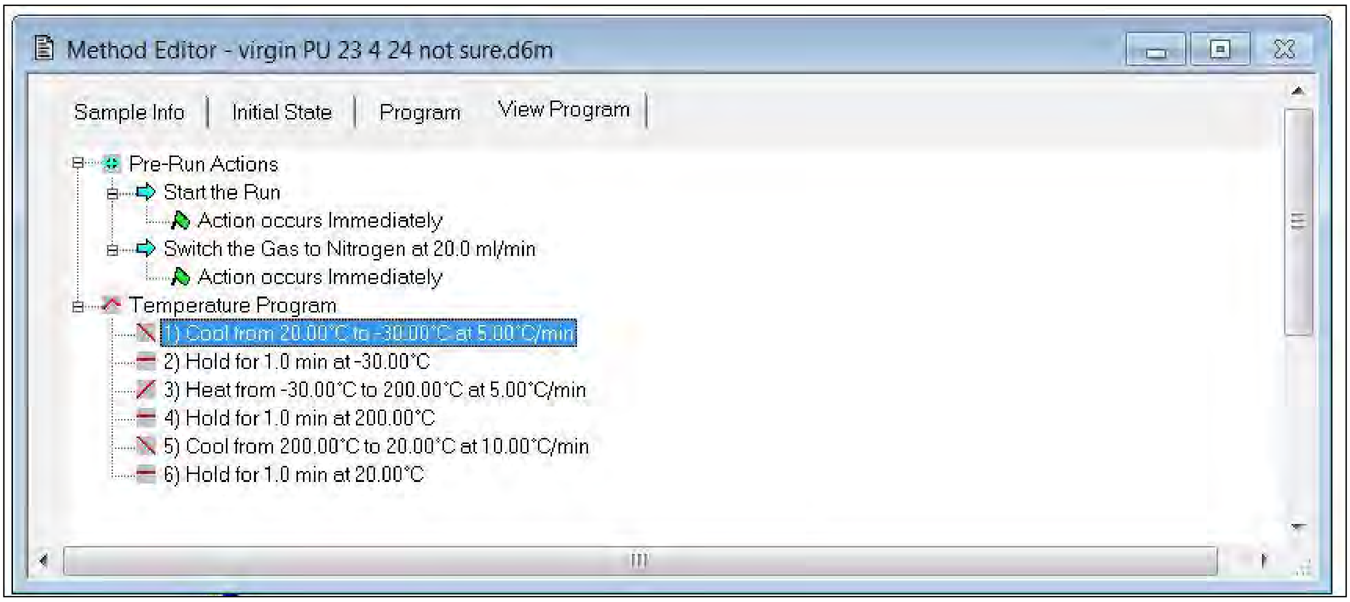
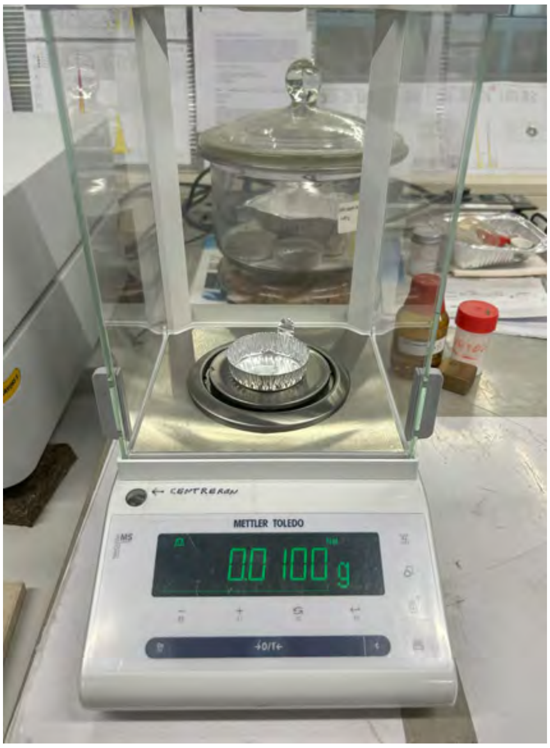


Figure 45: Program set-up for DSC (Source: Author)

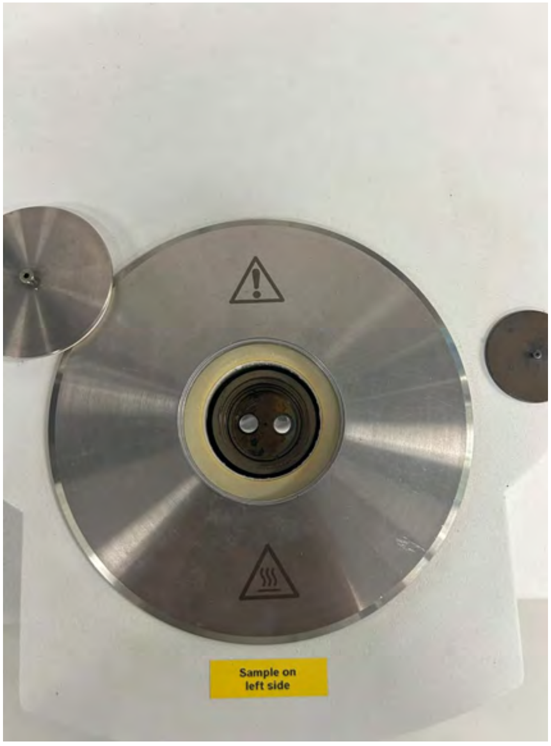
Experimental procedure



(a) Sample of 10mg of weight is measured on weighing scale

(b) The cell containing the sample with covering lid is placed in the compressor

(c) The compressed cell is removed and a hole is pierced



(d) The capsule placed in the heating chamber

Figure 46: Pictures showing the DSC experimental set-up (Source: Author)

Result

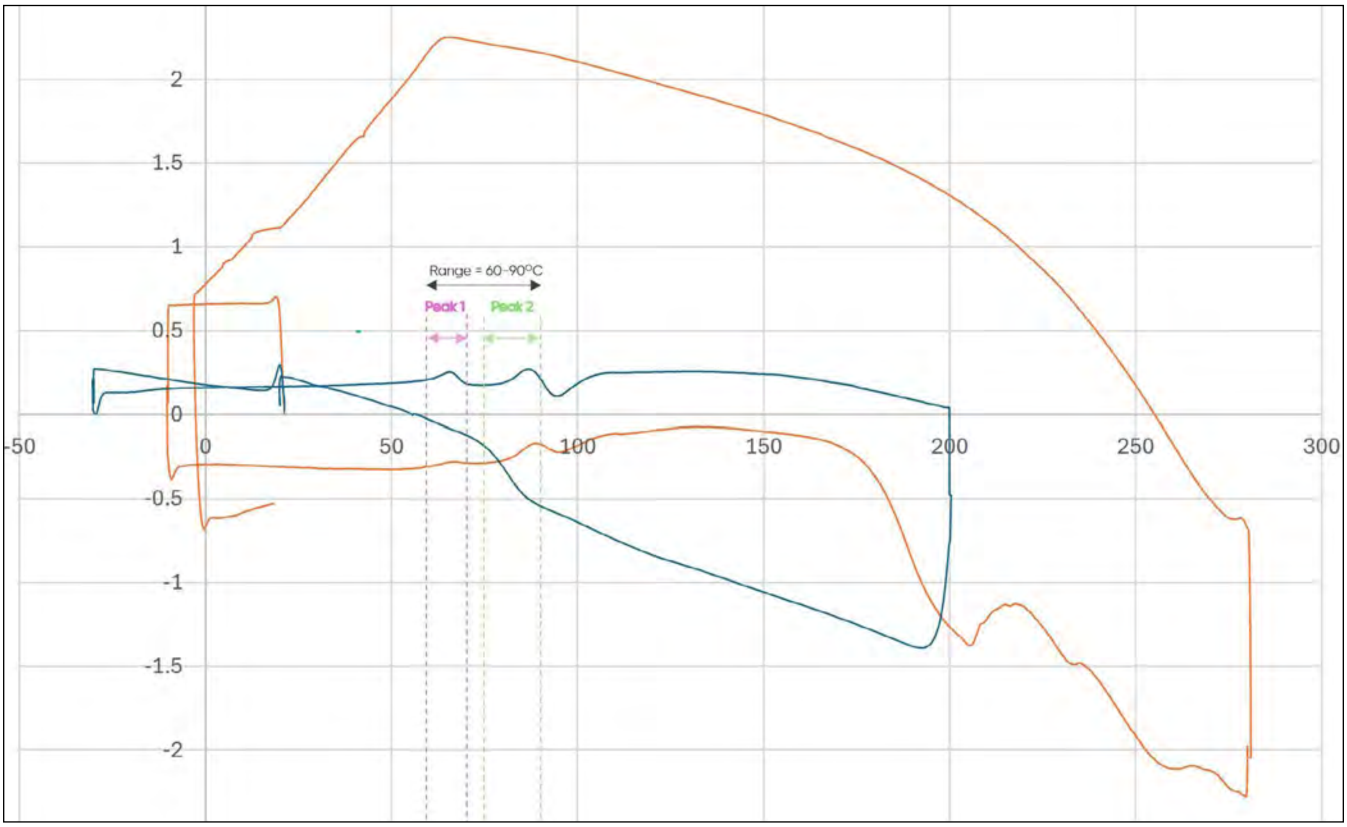


Figure 47: Results from DSC analysis of PVC_p and PVC_w sample (Source: Author)

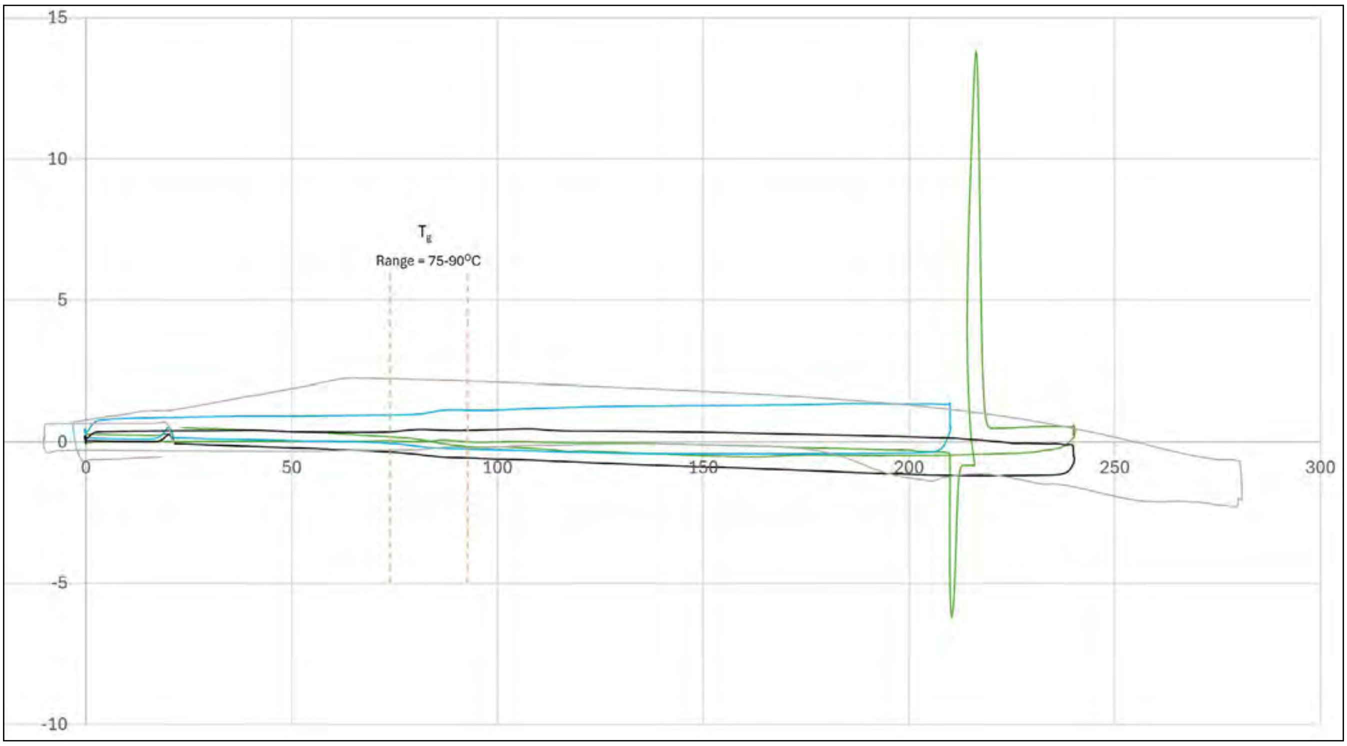


Figure 48: Results from DSC analysis of different colours of PVC_p samples (Source: Author)

Discussion

The DSC results confirms the operational range is between 60°C - 90°C. The curve also observes two peaks which sepculates the presence of other elements whose (T_g) is different. Graph aa shows (T_g) curves of different colours of (PVC_p) samples.

4.1.6 Conclusions

From previous paragraphs, the following conclusions are drawn:

- The FT-IR test confirms the sample to be PVC by aligning with PVC IR database but does not confirm the purity of the samples.
- The LIBS test conducted on the sample was unable to detect bromine and chlorine due to its low molecular weight.
- The X-ref results confirm the absence of bromine, the flame retardant. The test also confirms PVC with the high concentration of chlorine.
- The (T_g) of the all (PVC_p) and (PVC_w) shreds fall under the range of 60-90° C.

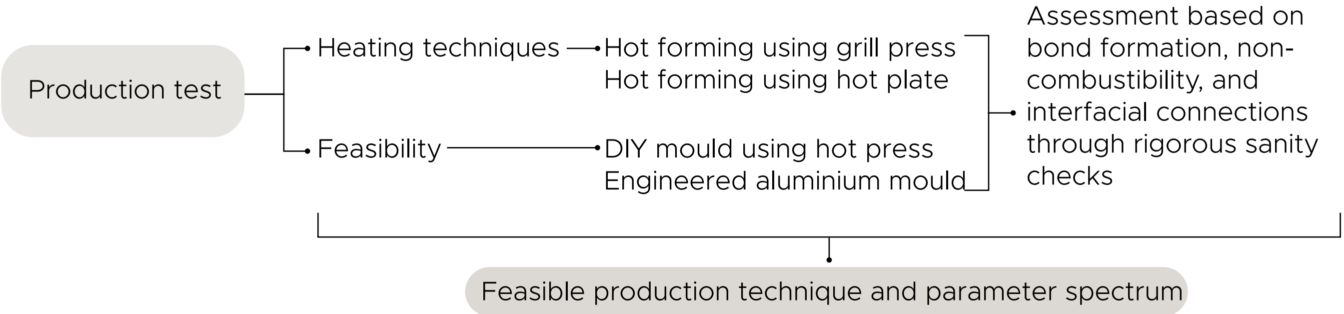
4.2 Production tests

4.2.1 Section overview

Scope

The chapter aims to explore different hot forming technique and the feasible production methodology. The experimental results are assessed primarily on bond formation and inter-facial connection, with a focus on non-combustibility. The heating techniques provide opportunities to explore the hot press machine with different moulds.

Roadmap



4.2.2 Preliminary tests for heating techniques

Hot forming using hot-plate

To understand the approximate temperature range at which PVC_p pellets begin to soften, plastic shreds were subjected to a heating process ranging from 160°C to 230°C, beyond which they undergo thermal decomposition and burn. This experiment was conducted by placing the plastic shreds in a stainless steel bowl on a hot plate at the Stevin Lab II of the Civil Engineering Faculty, TU Delft, under proper ventilation and face protection.

Observations around 180°C showed that the plastic started to soften, at which point weights were applied to flatten them into sheets. While the results primarily showed burning, they also confirmed the necessity of applying both pressure and increased temperature to mold the plastic shreds into sheet form. This finding suggests that controlled temperature and pressure are essential for achieving the desired sheet formation from the plastic shreds.

(a) Case I - Showing burnt surface *(b) Case II - Showing burnt surface* *(c) Case III - Onset of thermal degradation*

Figure 49: The experimental results showing trials of PVC_p sample results from hot forming with hot plate technique (Source: Author)

Conductive heating using grill press

A grill press was used to explore the effectiveness of applying both pressure and temperature simultaneously as a method of heating. The grill press also gives the freedom to increase the temperature in a controlled manner, which helps in the observation of any resulting changes. The table below shows the different parameters of temperature and pressure applied to see the changes, suggesting some positive outcomes. This observation suggests that the hot press should be investigated as a potential application in an industrial setting.

Sample ID	Type of shred	Temperature of heating (Degree C)	Time of heating (in minutes)	Weight applied (in kgs)	Time period of weights applied (in minutes)	Visual changes
Sample 1	PVC_p 3mm shred	127	5	4	5	No changes observed
Sample 2	PVC_p 3mm shred	150	10	20	5	No changes observed
Sample 3	PVC_p 3mm shred	175	10	20	5	Slight formation, brittle, easily breakable
Sample 4	PVC_p 3mm shred	175	15	20	5	Slight formation, brittle, easily breakable
Sample 5	PVC_p powder	80	10	20	5	No changes observed
Sample 6	PVC_p powder	110	15	20	5	No changes observed

Table 2: Tabular representation of different combinations of parameters used to explore the heating technique (Source: Author)

(a) Case IV - Image showing slight formation

(b) Case V - Image showing brittle sheet formation

Figure 50: The experimental results showing trials of PVC_p sample results from hot forming with hot plate technique (Source: Author)

Results and discussion

The result from the experiment emphasises the necessity of applying pressure to PVC samples, particularly in cases where increasing the temperature may lead to material degradation. The pressure might facilitate a more uniform distribution of heat throughout the sample, thereby ensuring a more homogeneous melting process and exposure of the interior of the shred to the heat source. It can also help in the reduction of air bubbles within softened PVC, resulting in a smoother texture.

Additionally, the application of pressure helps in expelling any trapped air pockets within the sample, yielding a denser and smoother final product. Although pressure does not directly alter the heating mode, its application can significantly influence the melting process and the resultant properties of the sheet material.

4.2.3 Production check with DIY mould

Objective

The test aimed to subject the sample to heating at 180°C, a temperature at which alterations were observed. According to Fangli Extrusion (accessed: April 17, 2024), the pipes are extruded in the temperature range between 160°C and 210° C. Using a hot press seemed appropriate as it allowed for the simultaneous application and maintenance of temperature and pressure. Additionally, the literature review of Thermogravimetric Analysis (TGA) of the pre-blend of PVC indicated the onset of chlorine release around 260 ° Celsius, potentially leading to material degradation. Therefore, heating the sample to its softening point and applying pressure was deemed advantageous in producing a sheet material without chlorine release.

Methodology

For the trials, anodised aluminium IKEA baking trays (see figure) were used. To gain insights into the behaviour of the two types of PVC shreds, both $PVC_w$and PVC_psamples were evenly distributed within the trays. Subsequently, a lid was placed on top, with a steel plate measuring 3cm in thickness above, subjecting the samples to a pressure of 1 bar. The samples were then heated for 30 minutes, maintaining a consistent temperature and pressure throughout. After the designated heating period, the heat source was deactivated, allowing the samples to cool for 20 minutes before obtaining the experimental results.

Sample ID	Composition	Temperature (°C)	Dwell time (Minutes)	Pressure (bar)
Trial 1	PVC_p	180	30	1

Table 3: Tabular representation of the parameters of the experimental samples used for the hot press (Source: Author)

Program set-up

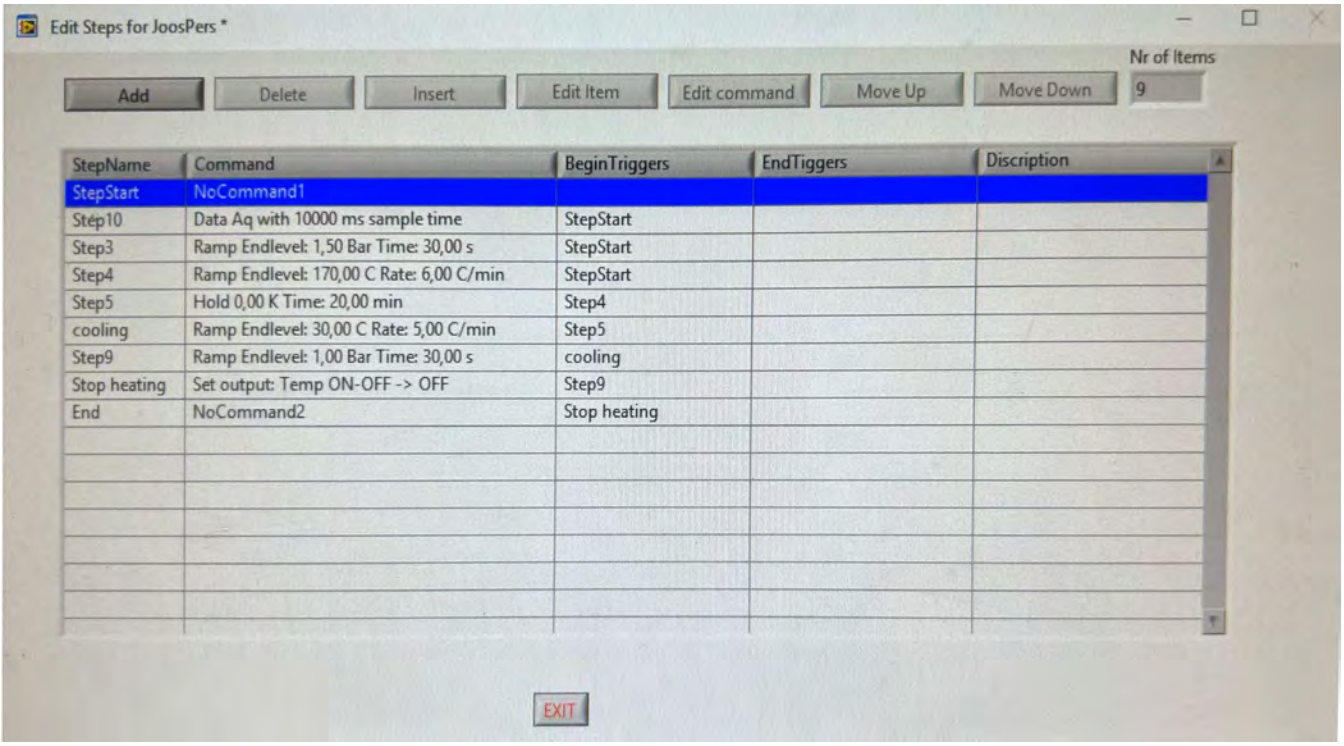


Figure 51: Image of program set-up for the hot press (Source: Author)

(a) Sample of 10mg of weight is measured on weighing scale

(b) Placing PVC samples to see the impact of temperatures and pressure on two types of samples

(c) Placing additional plates to achieve the required thickness

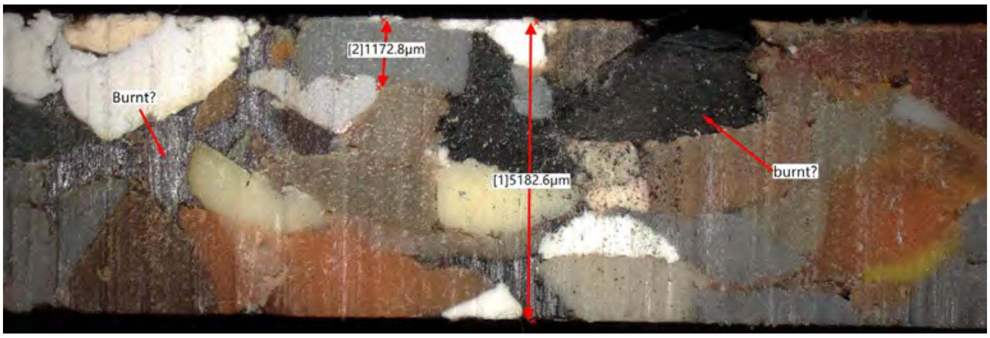
(d) The experimental set-up placed in the hot press for heating

(e) Hot press used for the experiment

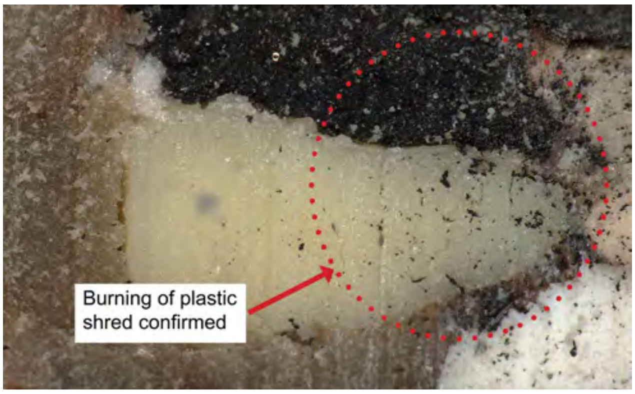
(f) PVC tile obtained as a result of the experiment

Figure 52: Pictures showing the experimental set-up and result (Source: Author)

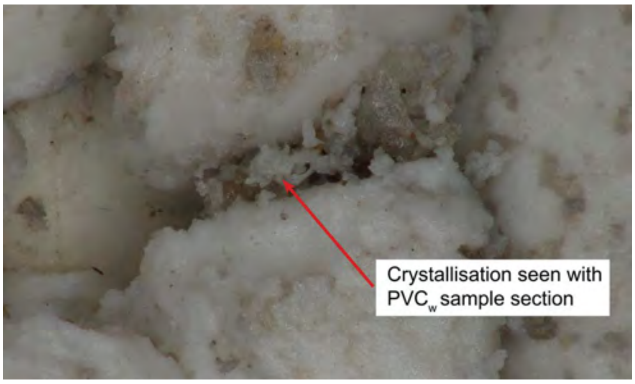
Microscopic inspection



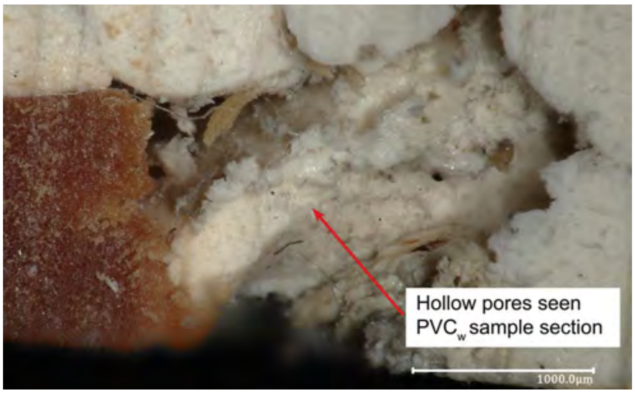
(a)



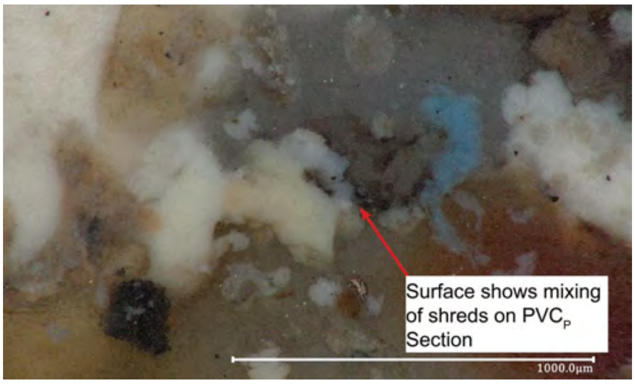
(b)



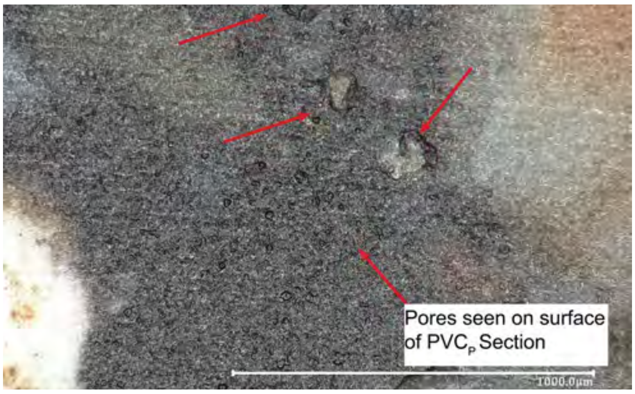
(c)



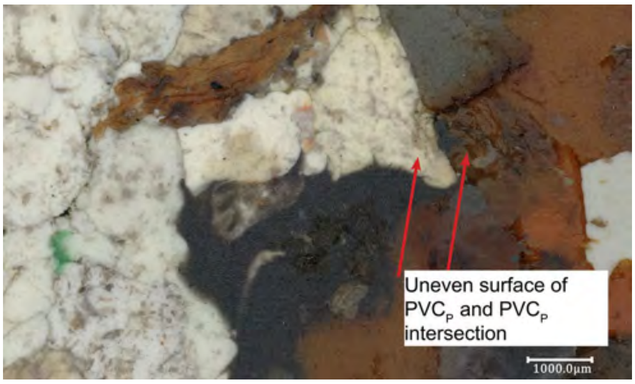
(d)



(e)



(f)



(g)

Figure 53: Pictures showing the experimental set-up and result (Source: Author)

Temperature - 180°C	Temperature - 175°C	Temperature - 180°C	Temperature - 190°C
Pressure - 2 Bars	Pressure - 1.5 Bars	Pressure - 1.5 Bars	Pressure - 3 Bars
Dwell time - 30 mins	Dwell time - 30 mins	Dwell time - 30 mins	Dwell time - 30 mins

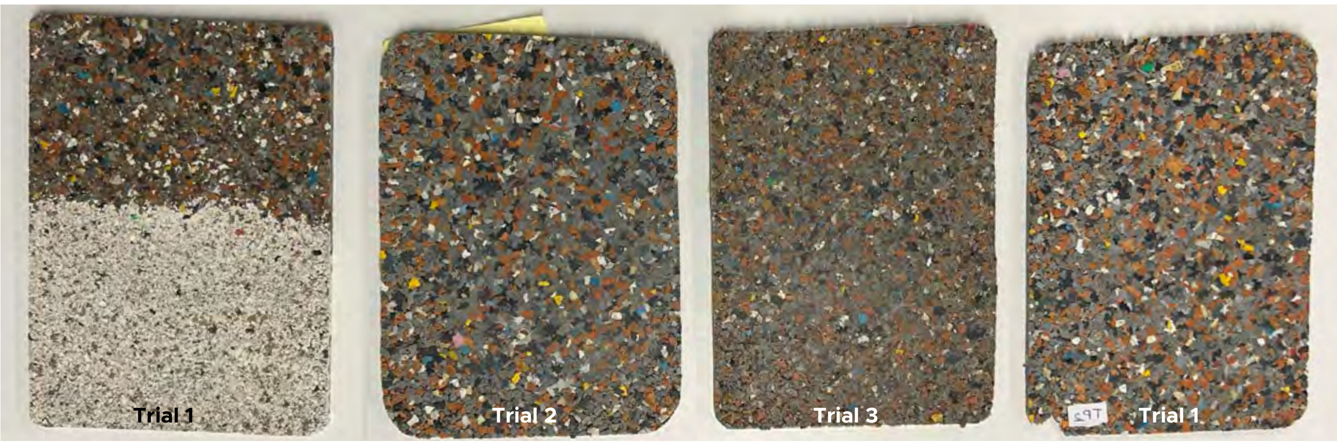


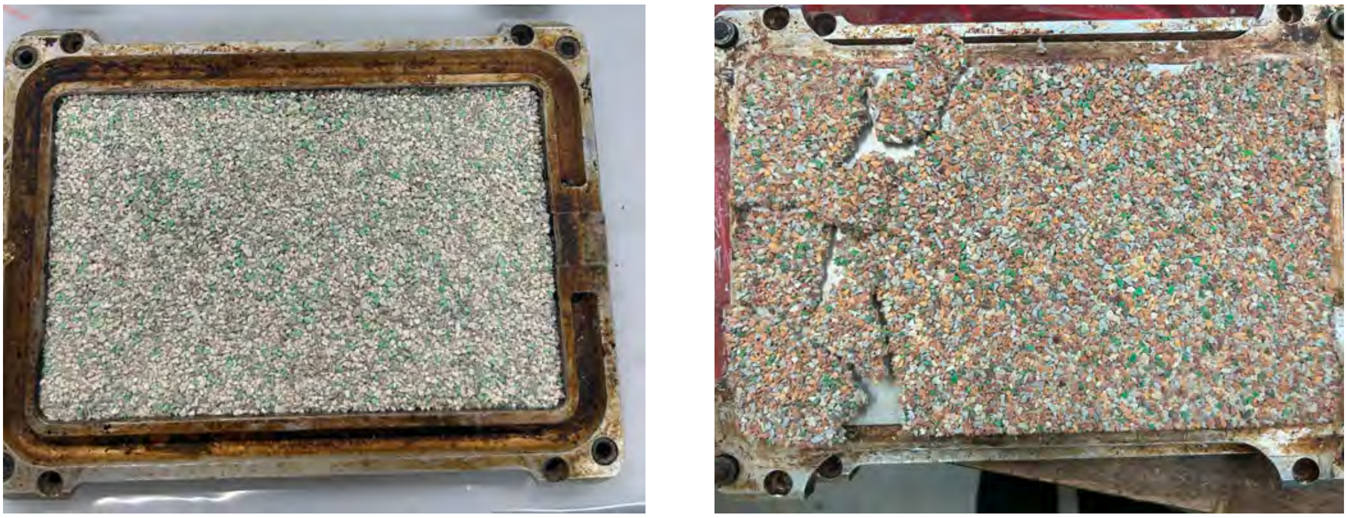
Figure 54: Different samples produced with different parameters (Source: Author)

Result

The samples show that the hot press is a feasible solution and offers flexibility in determining the desired output size. The mould design is a critical factor and aluminium demonstrates positive outcomes. The strength of the material and the yield also provides favorable results. However, the areas lacking pressure have a brittle nature, while those subjected to pressure demonstrate strong interfacial interaction, forming strong physical bonds.

4.2.4 Production with aluminium mould

The results of the previous experiments raised the need for an engineered mould to get the required results. NPSP B.V, The Netherlands offered to lend mould for the experiment and the test experiment was carried out with only PVC_p samples.The mould was made of aluminium and had a wall thickness of 10mm. The program settings are kept same as the previous.



(a) Input sample *(b) Output sample*

Figure 55: Pictures showing the input and out put samples (Source: Author)

Conclusion

The samples show that the aluminium mould yields a complete finish and a large, flat surface.. However, it is anticipated that longer heating times are necessary due to the thickness of the mold, and additional pressure is required to achieve samples with good strength. An equally important observation is the alteration in the color of the shreds, raising concerns about the possible onset of thermal degradation.

4.3 Parameter optimisation and quality control

4.3.1 Section overview

Scope

The chapter aims to optimise the production parameters namely -temperature, pressure, dwell time , shred size, the output thickness and the selection of material waste stream. The chapter consists of series of sampling where one or two parameters is subjected to variation keeping the rest constant to discern the most favorable outcome from various parameter combinations. Following each series of sampling, the samples undergo quality evaluation through mechanical testing and microscopic inspection to assess inter-facial connections, combustion behavior, and homogeneity levels.

Roadmap

Shred characterization

Production tests

Parameters	Range
Temperature	135 - 180°C
Pressure	1 - 10 Bars
Dwell time period	30 minutes - 60 minutes
Shred size	Powder - 10mm
Tile thickness	3mm - 7mm
Material waste stream	Sewage pipes rigid grade and windows

Sampling

- Pressure, temperature and dwell time series [TP series]
- Shred size series [S series]
- Waste stream composition series [C series]

Validation and quality evaluation
Mechanical testing
Microscopic inspection

- Optimized Production Parameters
- Mechanical strength
- Degree of interfacial connection, combustion, and homogenization.

4.3.2 Methodology

a) Sample and mould preparation

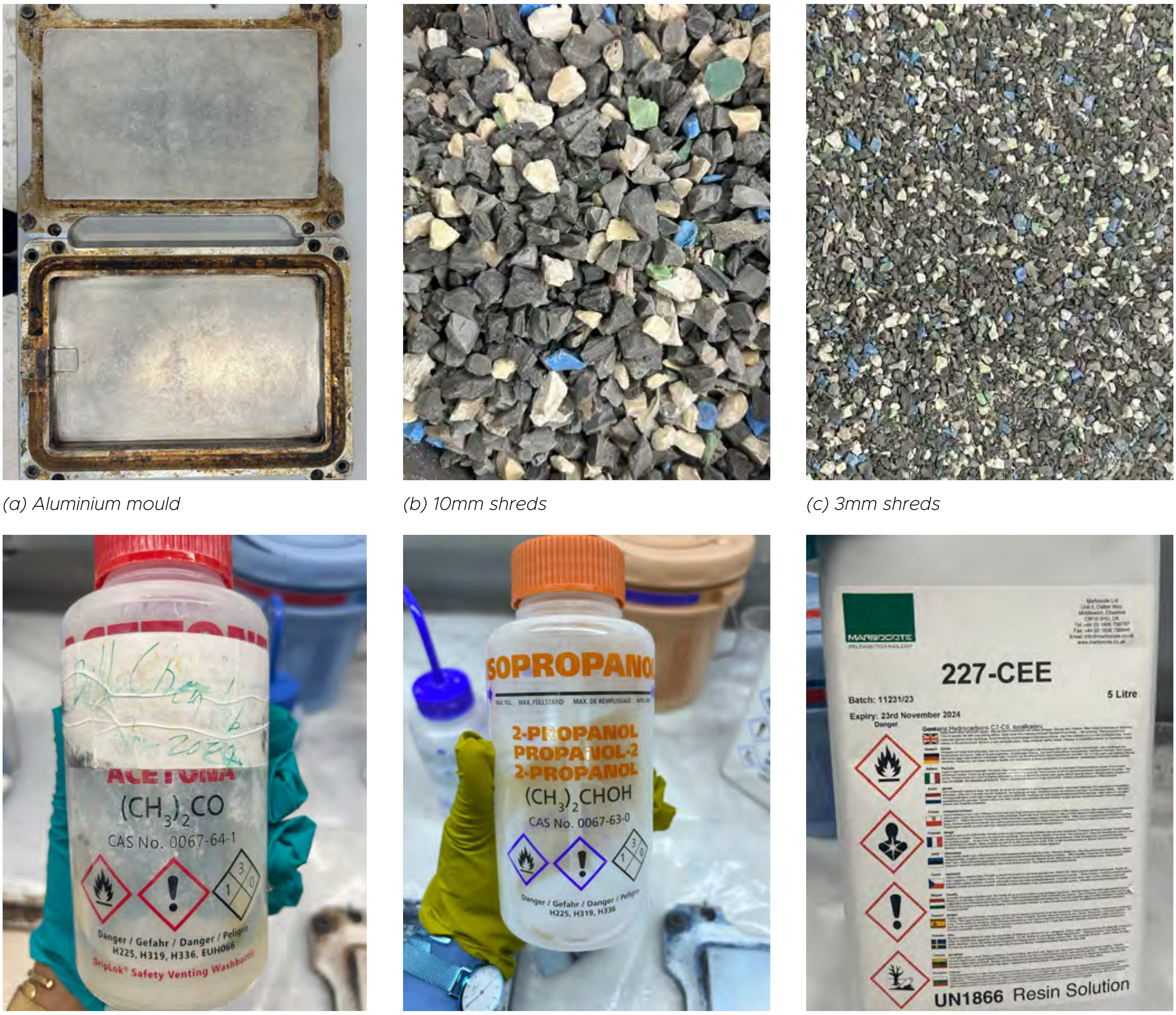
Material required

- The mould was given by NPSP B.V, The Netherlands (https://www.npsp.nl/en/). The mould (see Figure 56 - a) could produce the tile of size 300mm X 185 mm X 4mm in size.

- The PVCp samples provided by Cifra Recycling measured 10mm (see Figure 56 - b)overall size which was shredded to 3mm (see Figure 56 - c) shred using the shredder at the faculty of civil engineering at TU Delft.

- The materials required for mould preparation were provided by the Aerospace faculty of TU Delft for the standard mould preparation process before hot pressing.

- The hot press machine is located at the Aerospace faculty of TU Delft.



(a) Aluminium mould

(b) 10mm shreds

(c) 3mm shreds

(d) Acetone used to clean

(e) Isopropyl used to clean

(f) Release agent

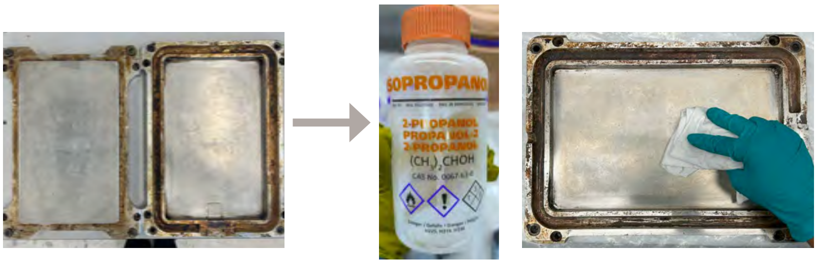
Figure 56: The material required for the mould preparation(Source: Author)

Production process

1. Use a clean tissue or a cloth to clean the mold with isopropyl alcohol (see Figure 56 - e). Isopropyl alcohol helps in removing the dirt and residual of the previous experiment. If there is any stain that is difficult to remove, use a scrub to remove the stain.
2. The release agent solution UN1866 (see Figure 56 - f) was applied to the mold in 3 cycles. Every cycle included taking 20ml of the solution onto the mold and spreading it throughout the mold in a circular motion including the corners and walls of the mold and the lid of the mold and let it dry for 5 minutes before you begin the next cycle.
3. Once the mold is prepared, the PVC sample was transferred to the mold and spread evenly. The lid is then placed on the mold and covered.
4. The mould is then covered with a release film in order to cover the mould and avoid over flowing of the sample onto the surface of press.
5. To initiate an even heating all around the mold, the graphite sheets were placed on the top and bottom of the mold and then placed in between the heating surface of the press.
6. Set the program (see Figure 57) and remove the mould from the press once the program is complete.

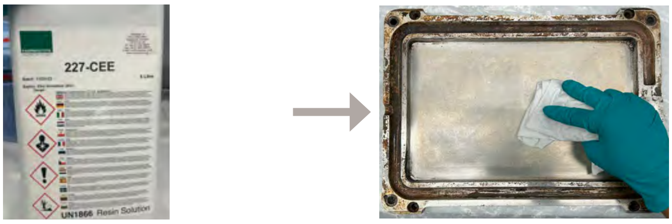
Step 1

Place the mould on a table and clean with isopropyl.



Step 2

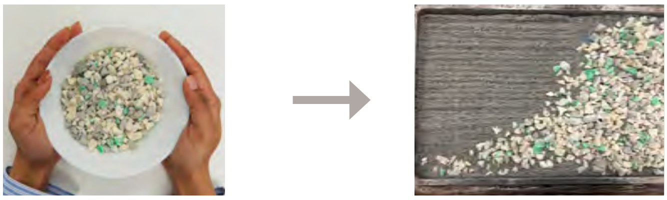
Apply 3 cycles of release agent to the mould



Let the mould dry for 5 minutes

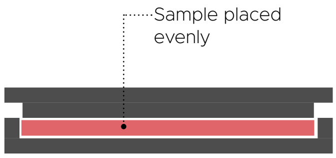
Step 3

Lay the shreds into the mould



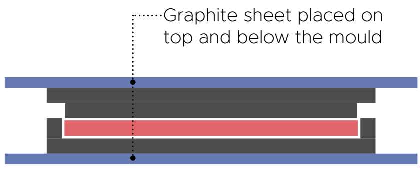
Step 4

Cover the mould with the lid and with release film.



Step 5

Place the mould in between the graphite sheets



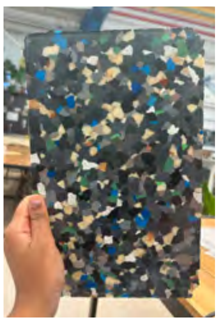
Step 6

Place the mould in the press and run the program

After completion of the program

Step 7

Remove the tile from the mould once its cool.



c) Production scheme

Production plan

The production plan is outlined in the following table. The samples are produced in 3 series based on analysis parameter.

- The temperature, pressure and dwell time / TP series - for optimising production parameters
- The shred / S series - for analysing effect of shred size on material properties
- The composition / C series - for analysing effect of functional grading on material properties

Series	Sample ID	Composition and choice of waste stream	Temperature A (in °C)	Dwell time B (in mins)	Pressure C (in bars)	Analysis parameter
Temperature and pressure [TP Series]	S1	3 mm PVC_p shred	180	30	1	Optimisation production parameters
	S2		180	60	10	
	S3		140	60	10	
	S4		135	60	10	
	S5		130	60	10	
	S6		130	60	100	
Shred size [S Series]	S7	0.2 mm PVC_p powder	Dependent on TP Series			Effect of shred size on material properties
	S6	3 mm PVC_p shred				
	S8	7 mm PVC_p shred				
	S9	10 mm PVC_p shred				
Composition [C Series]	S6	0.2 mm PVC_p powder	Dependent on TP Series			Effect of functional grading on material properties
	S9	10 mm PVC_p powder				
	S10	30% PVCp 0.2mm powder + 70% PVCp 10mm shred				
	S11	50% PVCw 0.2mm powder + 50% PVCp 10mm shred				
	S12	70% PVCw 0.2mm powder + 30% PVCp 10mm shred				
	S13	50% PVCw 0.2mm powder + 50% PVCw 10mm shred				

Table 4: Tabular representation of overall production plan (Source: Author)

Program set-up

The program steps for temperature and pressure control is outlined in fFigure 57. The parameters A, B and C refer to temperature, dwell time and pressure settings, respectively. refer Table 4 .

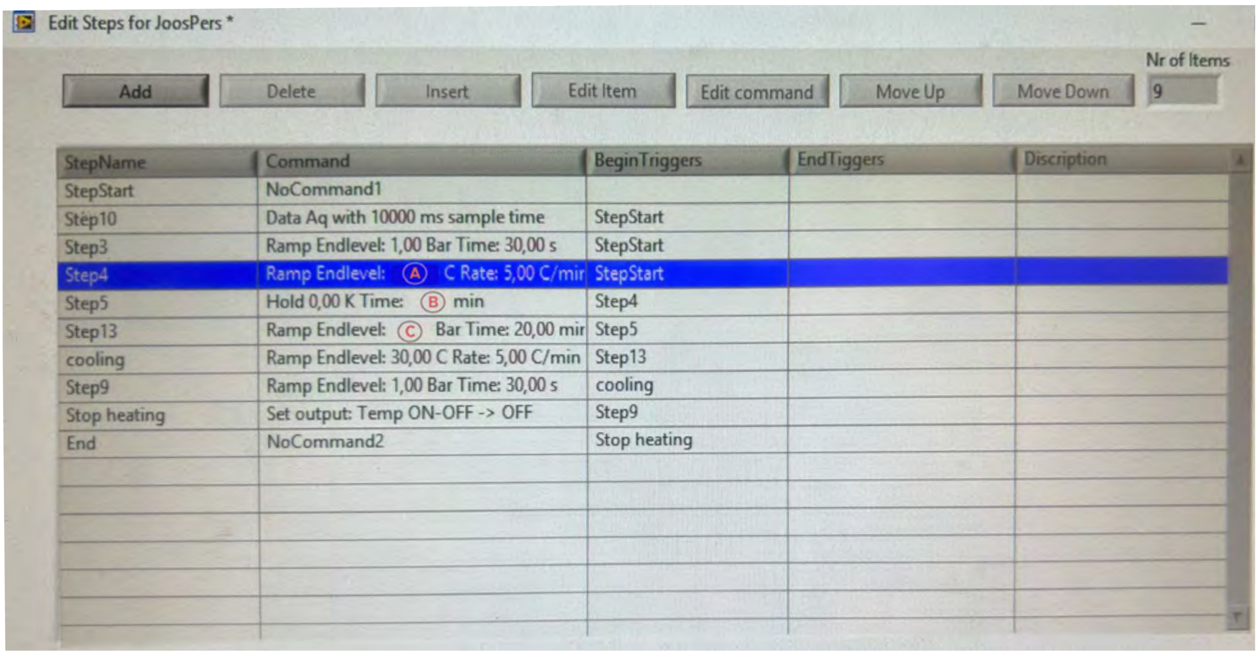


Figure 57: Image of program set-up for the production scheme (Source: Author)

d) Validation and quality evaluation procedures

Mechanical test

The samples were prepared with different combinations of temperature with the maximum pressure the mould could take. The flexural bending test was conducted on the samples . The test of all the samples was conducted to observe the difference in their strength arising due to temperature differences. All tests were conducted under the supervision of **Prof.Fred Veer** at the Material testing lab, 3mE, Mechanical, Maritime and Materials Engineering department, TU Delft.

The Flexural strength Protocol - ASTM D790
The flexural strength serves as an important method to assess the mechanical properties of the material under bending load and helps in analysing the structural behaviour of materials. The American Society for Testing and Materials (ASTM) standard D790 was used to prepare specimens for flexural strength testing, of dimensions 120 X 20 X 5mm. The sample was cut using a band saw at the Model hall of the architecture faculty of TU Delft. The 3-point bending test was preferred over the 4-point bending test due to low thickness and low stiffness of the sample. The loading rate is 5MPa per minute.

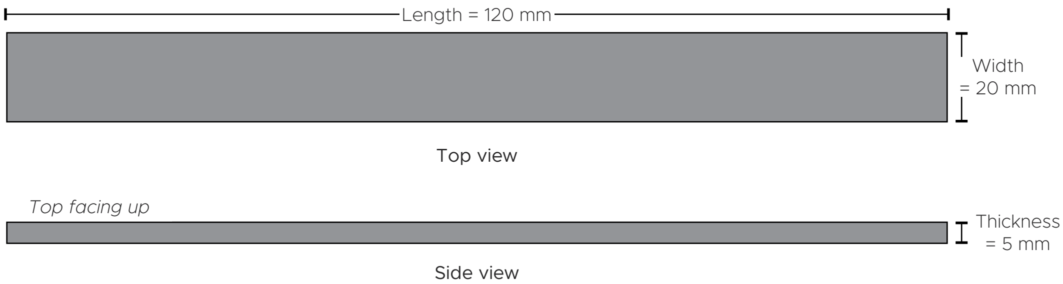


Figure 59: Image showing dimensions of the sample used for testing (Source: Author)

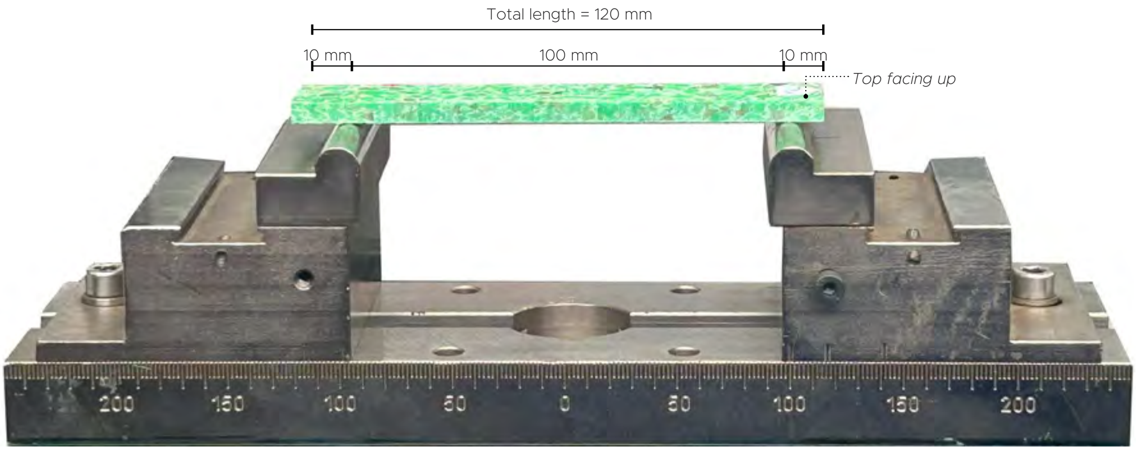


Figure 58: Placement of the sample on the distance guage (Source: Author)

During the test, the sample is positioned on the two support points, creating a span of 100mm in between where load is applied on the center.

The data of the specimens is analysed and the flexural stress for 3-point bending test, also known as the modulus of rupture, is calculated using the formula for a rectangular cross-section:

$$\boxed{\sigma = \frac{3FL^2}{bd^2}}$$

where :
F - the maximum load applied (N)
L - the support span length (mm)
b - the width of the specimen (mm)
d - the depth of the specimen (mm)

Microscopic morphological analysis of fracture surfaces

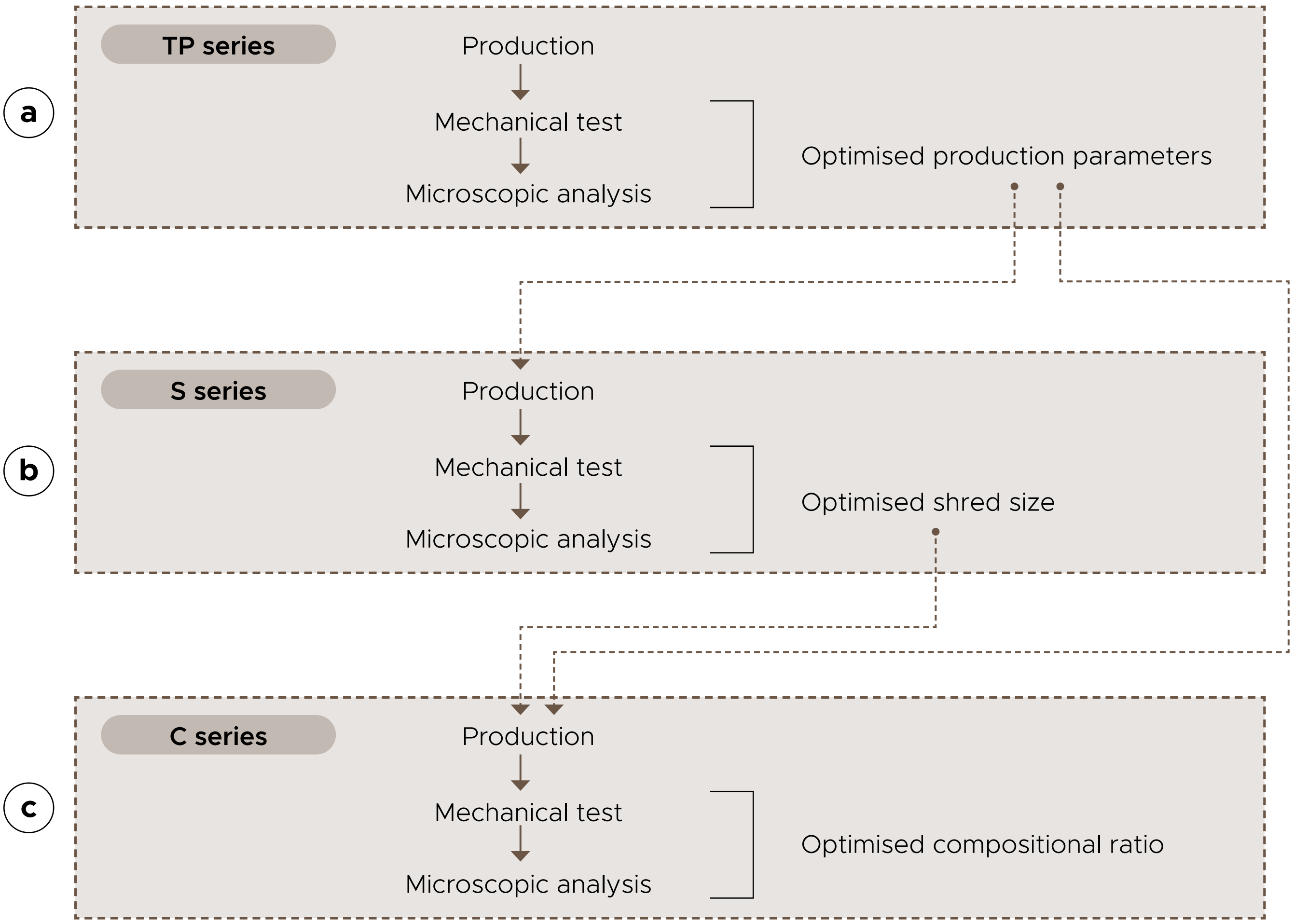
Many studies on granulated materials highlight the complex interplay of material properties, porosity, and failure modes in the interfacial connections of granulated materials. Escobedo et al. (2014) show that while some voids developed along the grain boundaries , an increasing amount of trans granular damage was observed as the grain size increased. This observation is analysed in the context of the availability of potential nucleation sites and the number of slip systems inherent to each crystalline structure. The influence of these factors on promoting or hindering plastic processes leading to damage nucleation and growth is thoroughly examined.

To understand the cause of material failure, the fracture surfaces are subjected to microscopic morphological analysis. High-resolution imaging techniques, such as scanning electron microscopy (SEM), are used to observe the fracture surfaces and identify specific features related to the failure mechanisms.

The effect of pressure on consolidation is also evaluated. The primary objective is to determine whether the pores or interfacial connections are the primary points of weakness..In later samples, efforts have been made to reduce porosity by mixing the samples with powder to evaluate its influence on material strength. It aims to fill the voids and improve the interfacial connections, thereby enhancing the material's overall strength

4.3.3 Production and evaluation

Roadmap of production series



Important :

It is important to note that the conclusions drawn are based on a single round of testing. To achieve more reliable results, it is essential to conduct multiple identical samplings and repeat the tests several times.

a) Pressure, temperature and dwell time series [TP series]

The previous experiment results (see Figure 55) show the breaking of the sample and change in colour of the shred. Table 6 shows the different combination of the pressure and temperature used to prepare the tiles.

Series	Sample ID	Composition and choice of waste stream	Temperature A (in °C)	Dwell time B (in mins)	Pressure C (in bars)	Analysis parameter
Temperature and pressure [TP Series]	S1	3 mm PVC_p shred	180	30	1	Optimisation production parameters
	S2		180	60	10	
	S3		140	60	10	
	S4		135	60	10	
	S5		130	60	10	
	S6		130	60	100	

Table 5: Tabular representation of various combinations of temperature, dwell time and pressure for the sample used(Source: Author)

With the initial sampling, Sample S1 exhibited low structural integrity, initiating an increase in pressure to 10 bars. Sample S2 demonstrated material strength; however, discolouration was observed.

The investigation by Geddes,1967 highlights the correlation between colour changes and the loss of hydrogen chloride in PVC. Geddes,1967 observes that the degradation of PVC is influenced by several factors, including temperature, polymer history, atmosphere, and the presence of additives. As a result, it is challenging to draw direct comparisons with published spectra due to variations in polymers and reaction conditions. Despite these complexities, Geddes concludes that discolouration is an indicator of material degradation. The further sampling aimed at lowering the material degradation by lowering the heating temperature and evaluating the results based on visual inspection.

To reach the goal of producing tiles with good strength, insights from Wędrychowicz et al. (2022) were incorporated. Their study focuses on manufacturing solid PVC plates from flexible PVC waste and provides critical parameters for the PVC sheet press moulding process.

The paper established parameters are based on the following considerations:

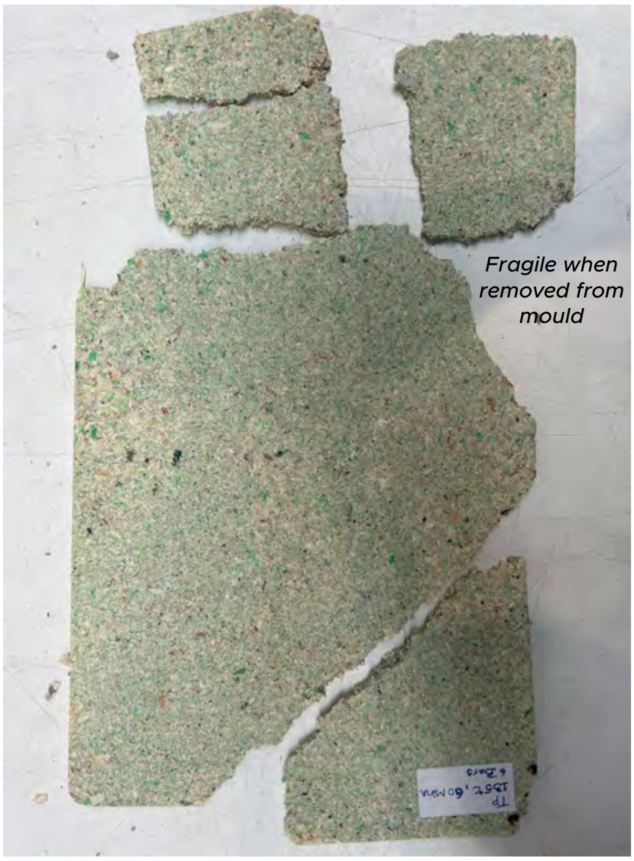
- The glass transition temperature (Tg) of PVC is approximately 85°C, or up to 75°C for materials with high plasticiser content.
- PVC degradation begins in the temperature range of 140–170°C, accompanied by the release of hydrogen.
-

Based on these considerations, the following process parameters were adopted in their experiments:

- Material temperature (T) set at 135°C.
- Heating time (t) set at 1 hour.
- Pressure (p) set at 10 MPa.

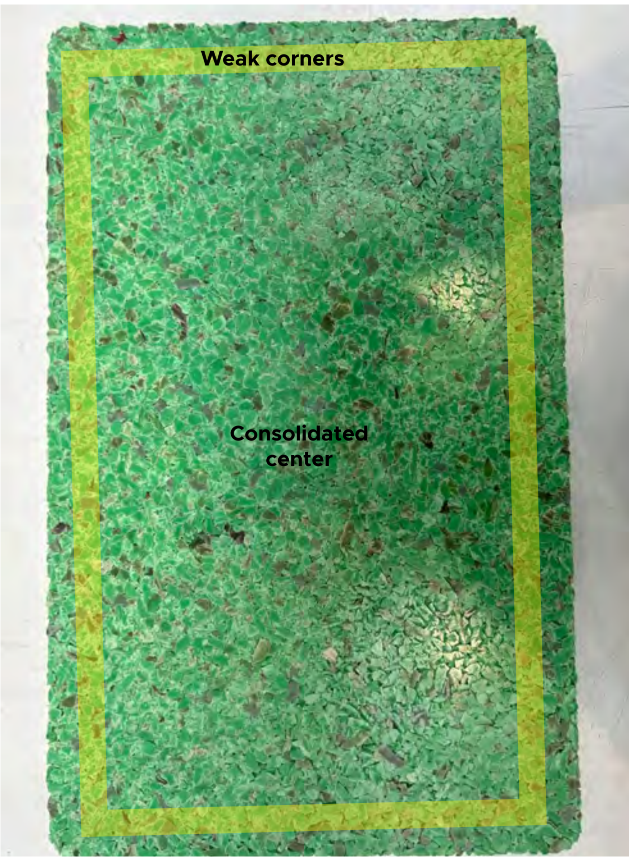
The following samples, S3, S4, and S5, were produced at temperatures of 140°C, 135°C, and 130°C, respectively, to evaluate the effect of temperature on discoloration. At 135°C, the sample (S4) still exhibited spots of brown discoloration, prompting a further reduction in temperature to 130°C for sample S5. After a visual inspection, the temperature was maintained at 130°C as it showed stability without further discoloration.

Production results



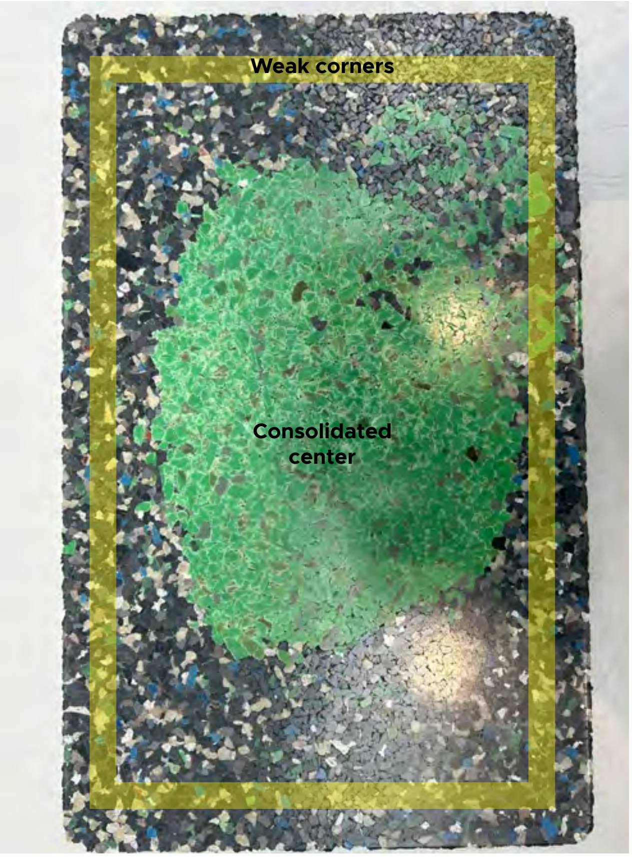
Sample S1

Sample S2



Sample S3

Sample S4



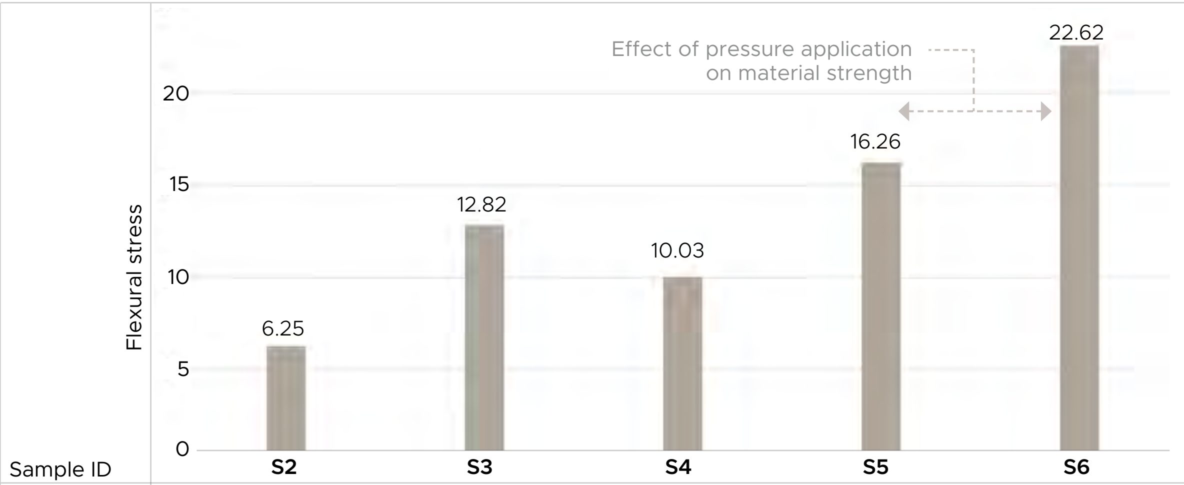
Sample S5

Sample S6

Figure 60: Samples from TP series (Source: Author)

Mechanical test

The samples produced were cut into specimens of 120X20X4 mm and subjected to the Flexural strength Protocol - ASTM D790. The results are below.



<table>
<tr><td>Sample ID</td><td>S2</td><td>S3</td><td>S4</td><td>S5</td><td>S6</td></tr>
<tr><td>Shred size</td><td colspan="5">3mm shreds</td></tr>
<tr><td>Temperature (in°C)</td><td>180</td><td>140</td><td>135</td><td colspan="2">130</td></tr>
<tr><td>Pressure (in bars)</td><td colspan="4">10</td><td>100</td></tr>
<tr><td>Dwell time (in mins)</td><td colspan="5">60</td></tr>
</table>

Figure 61: Overview of results of mechanical test of TP series (Source : Author)

The samples S2, S3, S4, and S5 were used to study the impact of temperature and pressure on material degradation and structural integrity. Samples S2, S3, S4, and S5 focused on reducing temperature to stabilize the material degradation process under lower pressure. Sample S5 showed positive results with the lower colour degradation. Following this, Sample S6 was subjected to 100 bars of pressure which the maximum pressure the mould could be subjected to. The mechanical tests clearly demonstrate the effect of this increased pressure, resulting in a consolidated material with enhanced strength.

Microscopic morphological analysis of fracture surfaces

The fracture surface of sample S6 showed greater area of material consolidation compared to the rest, confirming the effect of pressure is good on the material strength. A zoomed image of zone marked in red in Figure 56 is below. The sample showed presence of pores and wideneing of interfactial connecting surfaces which might be a possible weak zones in the material resulting in failure.

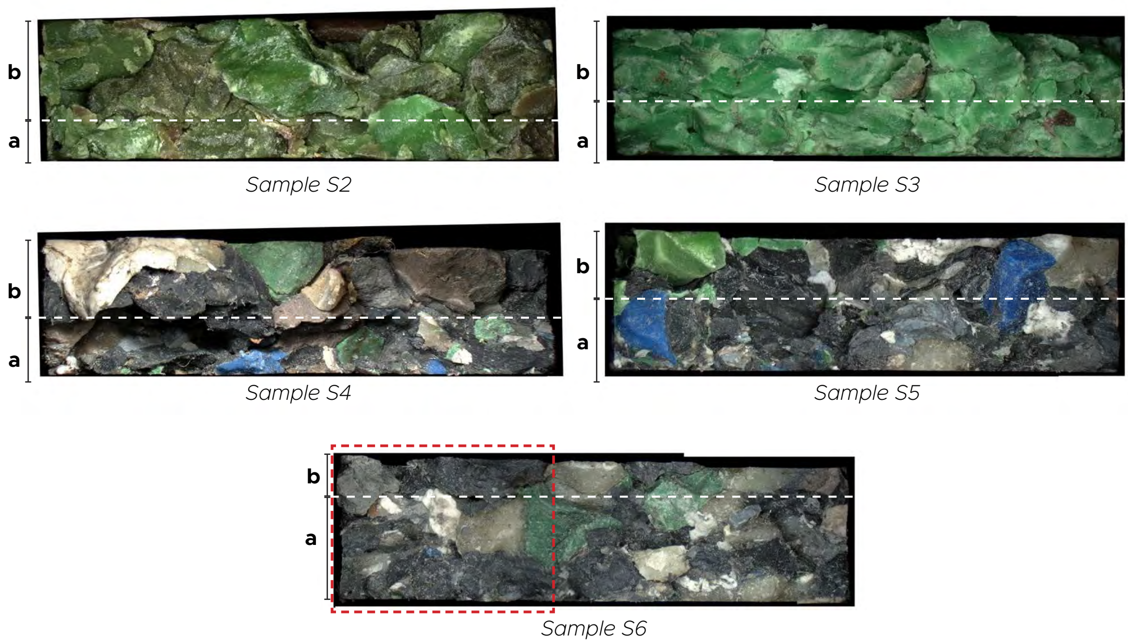


Figure 62: Microscopic view of the fractured surface showing the two zones (Source : Author)
*Legend : **a** - Zone of compaction ; **b** - Zone of shreds with interfacial connections*

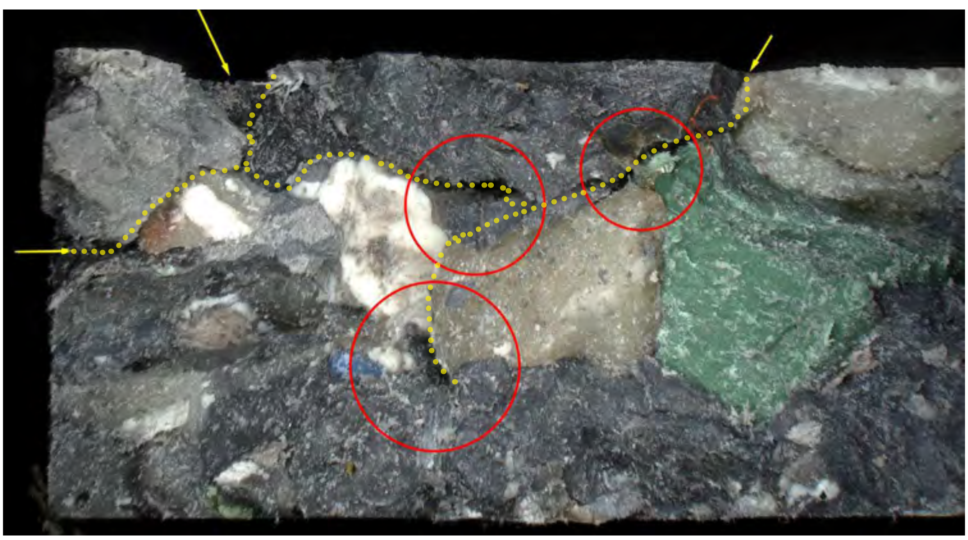


Figure 63: Zoomed view of the fractured surface of sample S6 showing loosened interfacial connection in red and cracks leading to surface with yellow (Source : Author)

Conclusion

In conclusion, after thorough experimentation, the following optimal processing parameters were identified:

- **Temperature:** 130°C was determined to be optimal as it showed no onset of discoloration, indicating the absence of thermal degradation.
- **Pressure:** 100 bars proved to be the optimal pressure level. This decision was influenced by the maximum pressure limit that the mold could withstand.
- **Dwell Time:** A dwell time of 1 hour was deemed optimal based on the recommendation by Wędrychowicz et al. (2022).

The microscopic analysis speculates that pores and interfacial connections may be the weak points in the samples. Therefore, it is necessary to analyze samples with reduced porosity and higher compaction and assess the influence of shred size on the material's strength.

b) Shred series [S series]

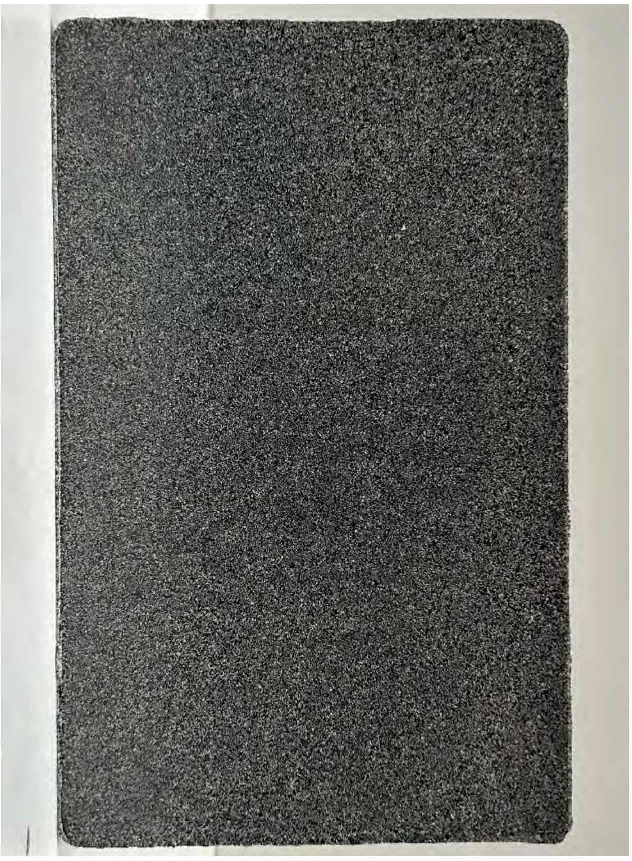
The optimization of temperature, pressure, and dwell time was performed using 3mm shreds. Microscopic evaluation speculates the presence of numerous pores resulting from uneven packing to be the weak zones. To evaluate the influence of pores and interfacial connections on the mechanical strength of the material, powdered samples, which exhibit the least porosity, and 10mm shreds, which display porosity spread away from each other, along with intermeddiate shred sizes of 3mm and 7mm were analysed.

Series	Sample ID	Composition and choice of waste stream	Temperature A (in °C)	Dwell time B (in mins)	Pressure C (in bars)	Analysis parameter
Shred size [S Series]	S7	0.2 mm PVC_p powder	130	60	100	Effect of shred size on material properties
	S6	3 mm PVC_p shred				
	S8	7 mm PVC_p shred				
	S9	10 mm PVC_p shred				

Table 6: Tabular representation of various combinations of shred size of the sample used(Source: Author)

Production results

Sample S6



Sample S7

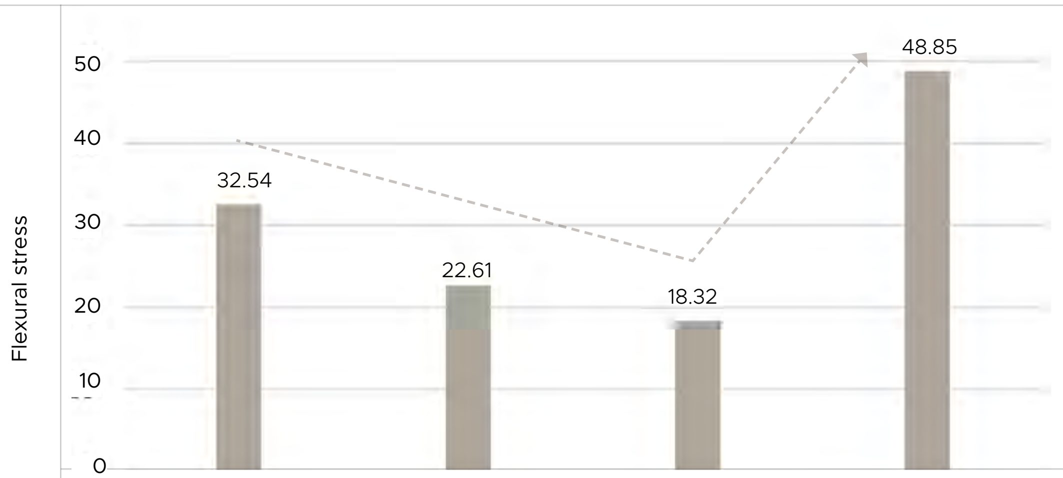
Sample S8

Sample S9

Figure 64: Samples from S series (Source: Author)

Mechanical test

The mechanical tests reveal an interesting trend. Sample S7, composed of powder and Sample S9 with bigger shreds and with dispersed porosity, both demonstrate superior performance compared to the 3mm and 7mm samples.



Sample ID	S7	S6	S8	S9
Shred size	0.2 mm powder	3 mm powder	7 mm powder	10 mm powder
Temperature	130°C			
Pressure	100 bars			

Figure 65: Overview of results of mechanical test of S series (Source : Author)

This suggests two l possibilities: firstly, there might be gaps between the 3mm and 7mm pieces that need to be filled for better connection, or second, the unsieved samples of 3mm and 7mm might cause the powder to settle down while the larger pieces stay on top.

The results trend prompts the question of whether it is easier to establish connections in materials that are more homogeneous. This raises the question of whether it's easier to connect materials when they are all the same or if they have a uniform composition.

Microscopic morphological analysis of fracture surfaces

The microscopic evaluation of the fracture surface of samples S6,S7,S8,S9 were examined. Sample S7 showed very good compaction with very less pores. Sample S8 shows the interfacial connection joining well leading to good compaction.With sample S7 and S8, the shreds showed pores and widened interfacial connections between the shreds.

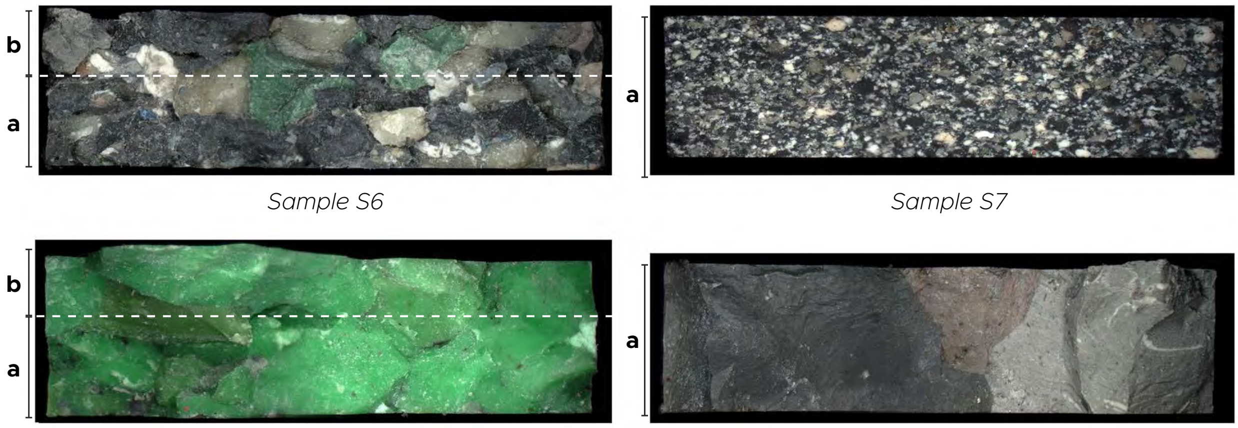


Figure 67: Microscopic view of the fractured surface showing the two zones (Source : Author)
*Legend : **a** - Zone of compaction ; **b** - Zone of shreds with interfacial connections*

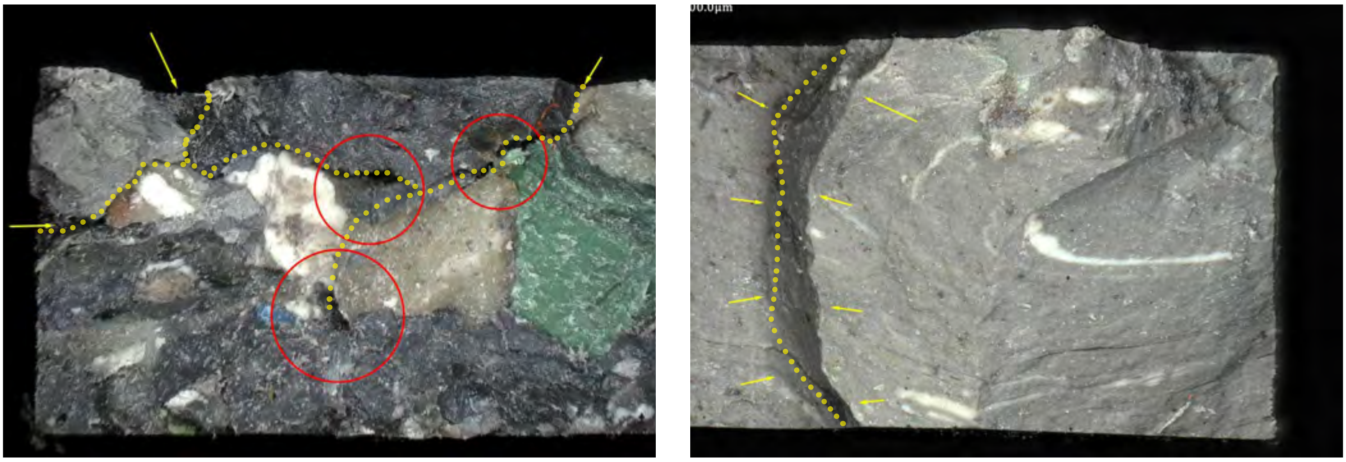


Figure 66: Left- Sample S6 shows clear gaps between shreds highlighting crack line ; Right- Sample S9 showing failure along the interfacial connection (Source : Author)

Conclusion

In summary, the series of shredded samples indicate that uniform samples are stronger than those made of mixed 3mm and 7mm shreds. Detailed microscope images reveal that most failures occur along the surface connections and tiny gaps between them, which could be where the failure begins.

The results highlight the need to investigate whether filling these gaps with powder, which would make the material more compact influences the strength of the materia and at what extent.

c) Composition [C series]

The results from the previous samples raised the need to mix the powdered and bigger shred version in order to compact the gaps with powder. The series production aimed to address the porosity issue by incorporating different-sized particles and evaluating their impact on enhancing the overall strength of the material.

Series	Sample ID	Composition and choice of waste stream	Temperature A (in °C)	Dwell time B (in mins)	Pressure C (in bars)	Analysis parameter
Composition [C Series]	S6	0.2 mm PVC_p powder	130	60	100	Effect of functional grading on material properties
	S9	10 mm PVC_p powder				
	S10	30% PVCp 0.2mm powder + 70% PVCp 10mm shred				
	S11	50% PVCw 0.2mm powder + 50% PVCp 10mm shred				
	S12	70% PVCw 0.2mm powder + 30% PVCp 10mm shred				
	S13	50% PVCw 0.2mm powder + 50% PVCw 10mm shred				

Table 7: Tabular representation of various combinations of composition for the sample used(Source: Author)

Production results

Sample S10

Sample S11

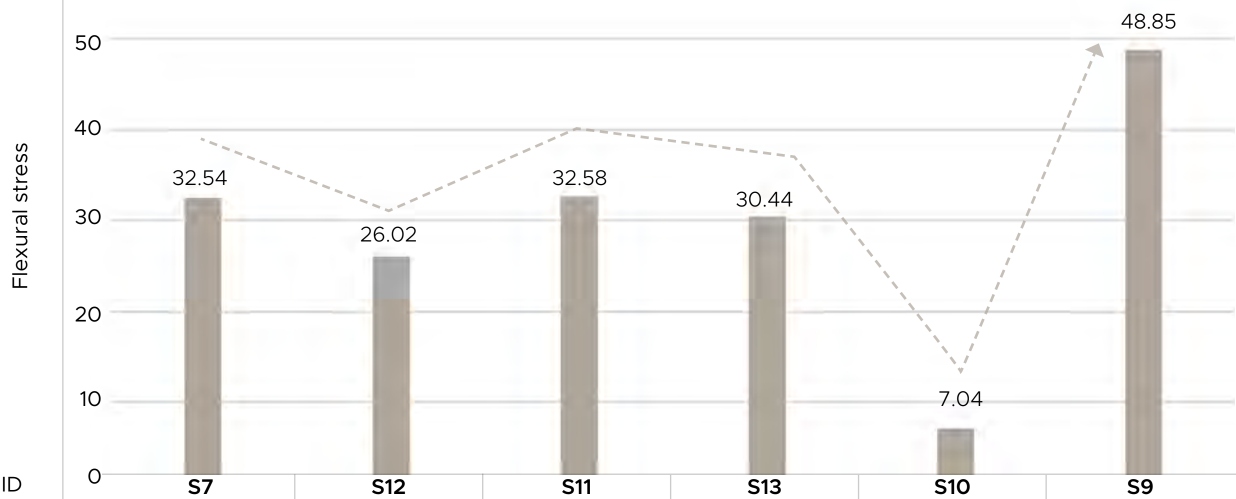
Sample S12

Sample S13

Figure 68: Samples from C series (Source : Author)

Mechanical test

The trend observed in the mechanical tests indicates that samples S7 and S9, which have homogeneous shred sizes, and samples S11 and S13, with equal powder and shred ratios, exhibit better performance compared to samples with unequal ratios of different grades. The sample with a 10mm shred size remains the best performer among all the samples produced.



		S7	S12	S11	S13	S10	S9
Sample ID		S7	S12	S11	S13	S10	S9
Shred %	0.2 mm powder	100	70	50	50	30	0
	10 mm shred	0	30	50	50	70	100
Temperature		130°C					
Pressure		100 bars					
Dwell time		60 mins					

Figure 69: Overview of results of mechanical test of C series (Source : Author)

This suggests two I possibilities: firstly, there might be gaps between the 3mm and 7mm pieces that need to be filled for better connection, or second, the unsieved samples of 3mm and 7mm might cause the powder to settle down while the larger pieces stay on top.

The results trend prompts the question of whether it is easier to establish connections in materials that are more homogeneous. This raises the question of whether it's easier to connect materials when they are all the same or if they have a uniform composition.

Microscopic morphological analysis of fracture surfaces

The microscopic evaluation of the fracture surface of samples S10,S11,S12,S13 were examined. Sample S11, S13 showed very good compaction with very less pores. The zoomed in microscopic images if sample S6 shows that the powder helps in filling the gaps between the shred when force is applied. Several tests needs to be conducted in order to get a reliable result.

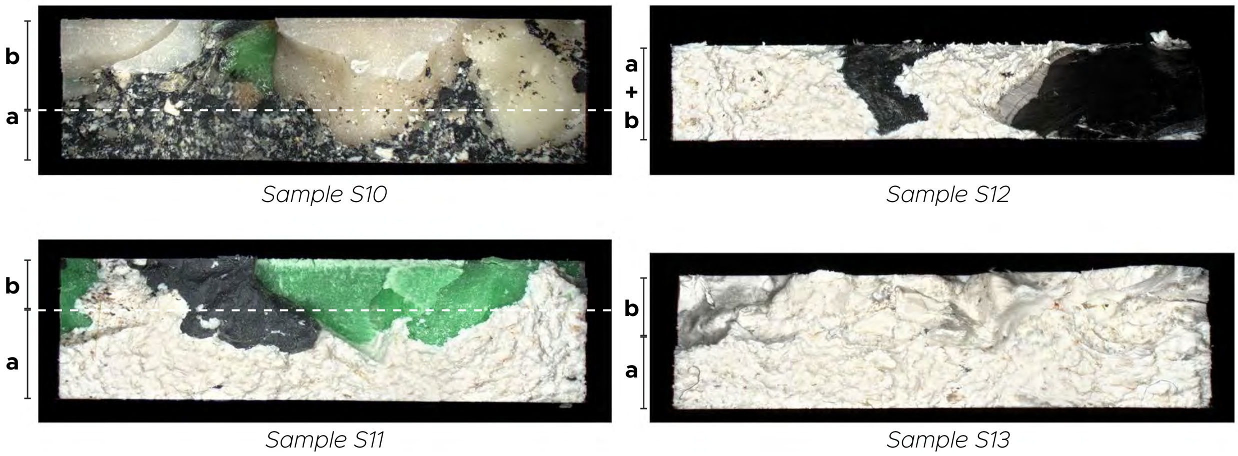


Figure 70: Microscopic view of the fractured surface showing the two zones (Source : Author)
*Legend : **a** - Zone of compaction ; **b** - Zone of shreds with interfacial connections*

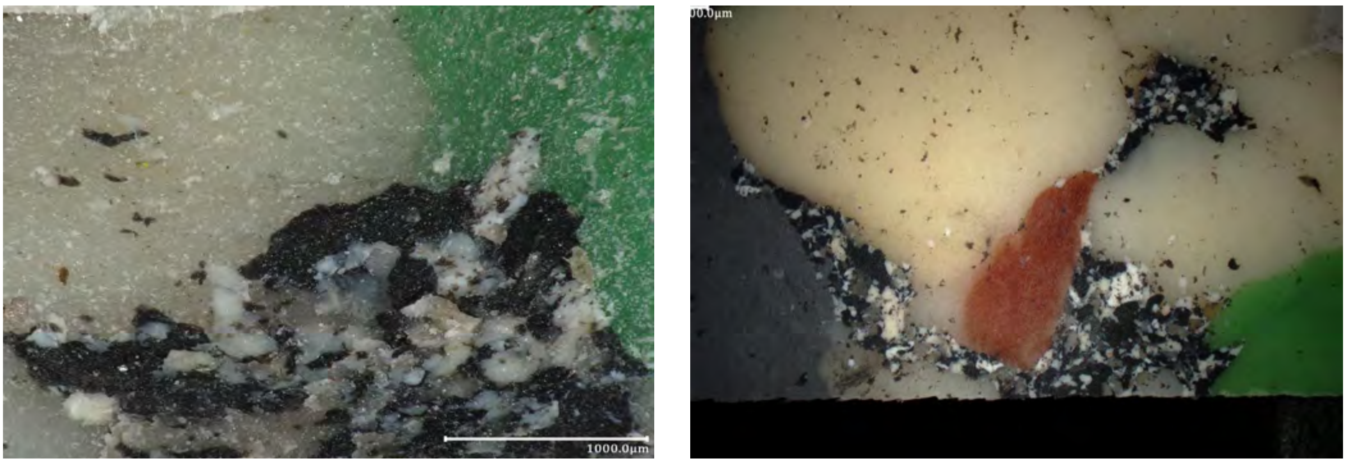


Figure 71: Left- Sample S6 shows powder compacting the gaps between shreds
(Source : Author)

Conclusion

The test results indicate that samples with a homogeneous shred composition perform best in terms of material strength, compared to those with a mix of powder and shred. However, an equal mix of powder and shred still performs better than samples with unequal ratios of these components.

Further testing is recommended to obtain more reliable and comprehensive results. Additionally, the use of mixed shreds offers significant design flexibility. Each sample exhibits unique textures and patterns, enhancing the aesthetic possibilities and expanding the design freedom the material provides.

4.3.4 Section summary

Production and mechanical test

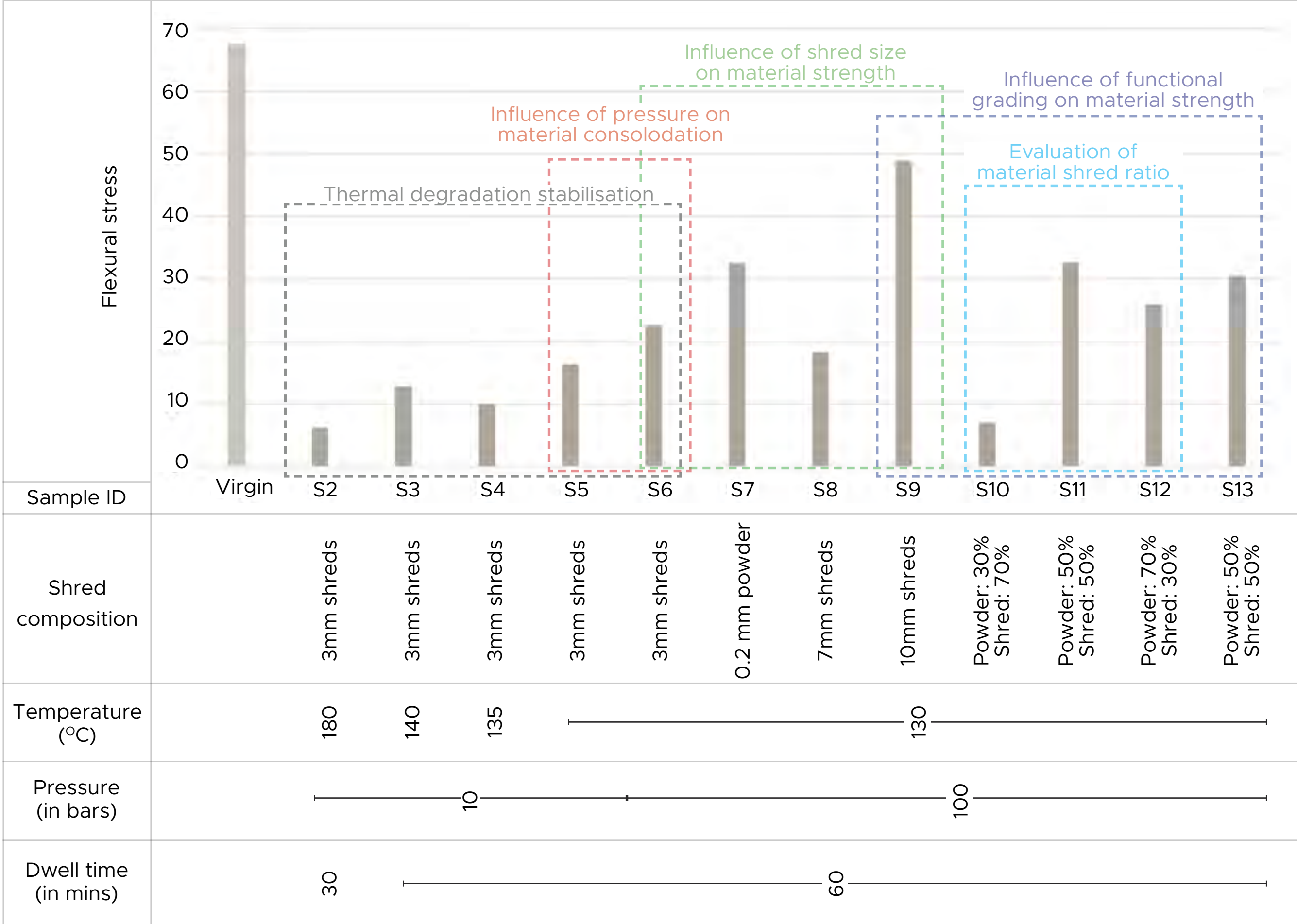


Figure 72: Overview of results of mechanical test and analysis parameters (Source : Author)

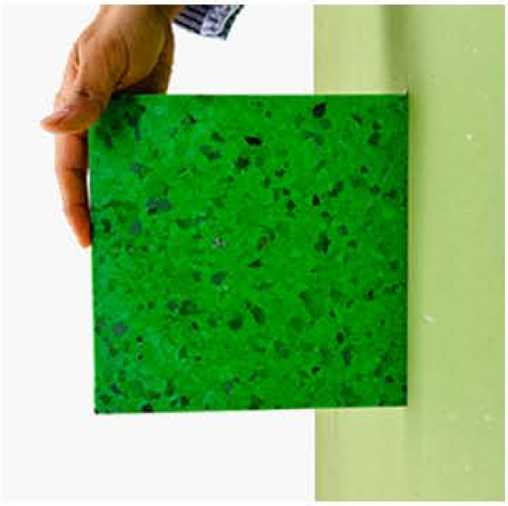
The summary of results from the mechanical tests are presented below.

Production series	Sample ID	Composition and choice of waste stream	F_{max} (in N)	L (in mm)	b (in mm)	d (in mm)	Flexural stress (MPa)
Virgin (for reference)			143.79	100	20	4	67.40
Temperature and pressure	S2		20.84			5	6.25
	S3		42.73		20	5	12.82
	S4	3 mm PVC_p shred	33.45	100		5	10.03
	S5		54.19			5	16.26
	S6		81.55			5.2	22.62
Shred size	S7	0.2 mm PVC_p powder	112.86			5.1	32.54
	S6	3 mm PVC_p shred	81.55	100	20	5.2	22.62
	S8	7 mm PVC_p shred	80.22			5.73	18.32
	S9	10 mm PVC_p shred	109.48			4.1	48.85
Composition	S9	10 mm PVC_p shred	109.48			4.1	48.85
	S7	0.2 mm PVC_p powder	112.86			5.1	32.54
	S10	30% PVC_p 0.2mm powder + 70% PVC_p 10mm shred	27.8			5.44	7.04
	S11	50% PVC_w 0.2mm powder + 50% PVC_p 10mm shred	124.32	100	20	5.35	32.58
	S12	70% PVC_w 0.2mm powder + 30% PVC_p 10mm shred	46.49			3.66	26.03
	S13	50% PVC_w 0.2mm powder + 50% PVC_w 10mm shred	103.93			5.06	30.44

Table 8: Tabular representation of overall production plan (Source: Author)

Samples production


Sample 9


Sample 8


Sample 6


Sample 7

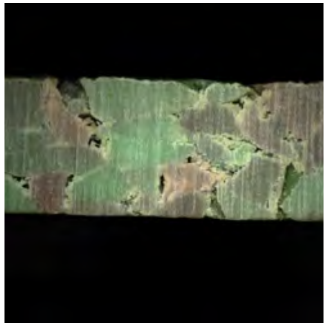
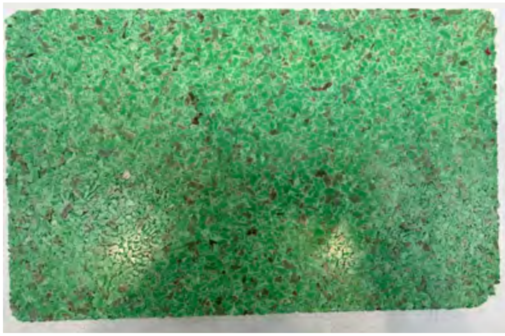
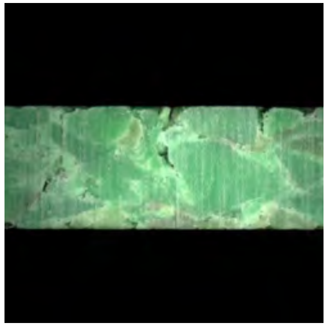
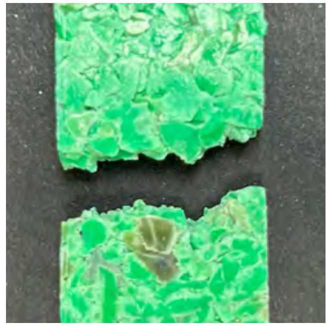
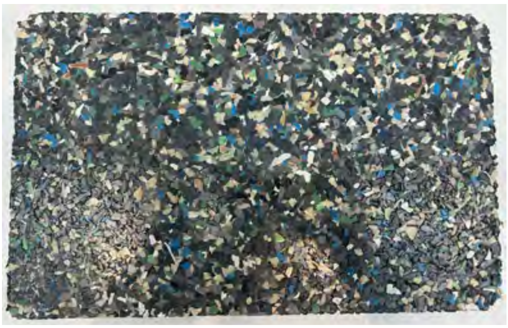
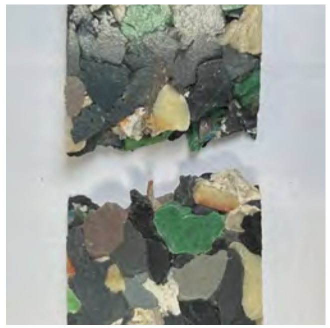

Sample 10


Sample 11

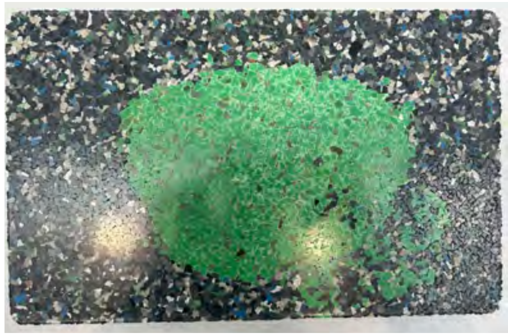
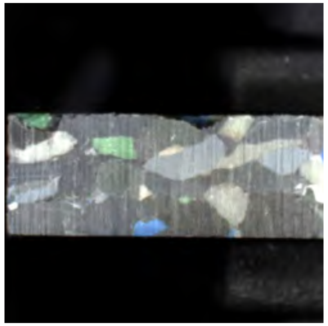
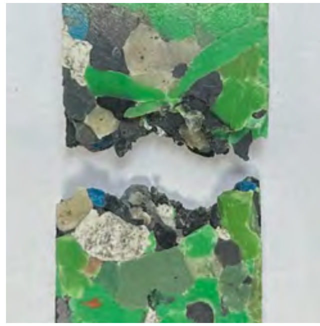
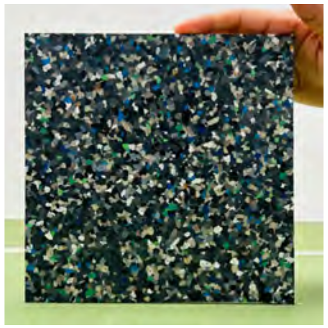
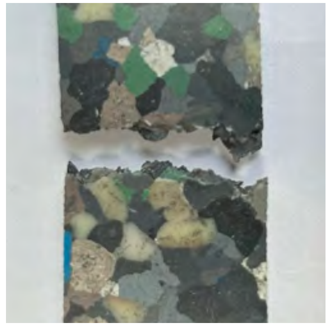
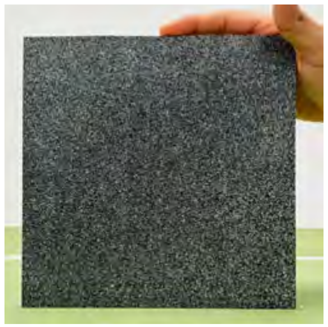
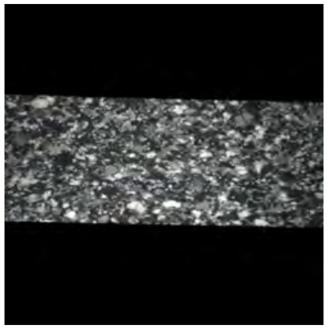
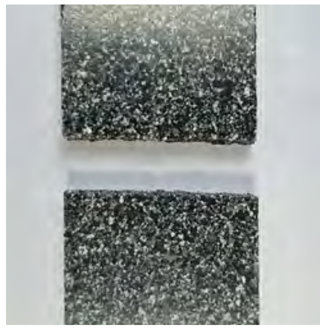

Sample 12


Sample 13

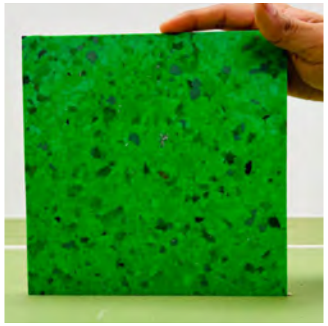
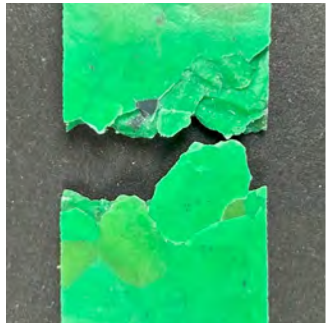
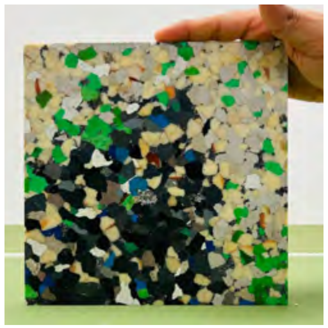
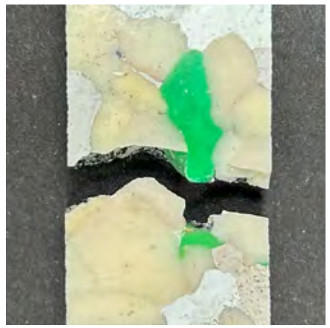
Summary

Sample ID	Sample description	Image of sample produced	Porosity in the section	Image of specimen's fracture line after flexural test	Flexural strength (MPa)
S2	**Composition:** 3 mm PVC_p shred **Production parameters:** • Temperature - 180°C • Pressure - 10 bars • dwell time - 60 mins **Sample thickness:** 5 mm				6.25
S3	**Composition:** 3 mm PVC_p shred **Production parameters:** • Temperature - 140°C • Pressure - 10 bars • dwell time - 60 mins **Sample thickness:** 5 mm				12.82
S4	**Composition:** 3 mm PVC_p shred **Production parameters:** • Temperature - 135°C • Pressure - 10 bars • dwell time - 60 mins **Sample thickness:** 5 mm				10.03

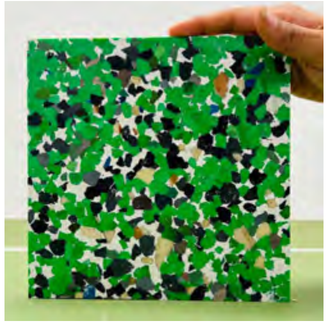
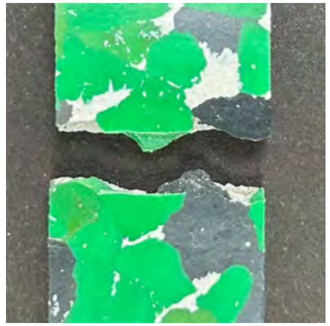
Summary (Continued)

Sample ID	Sample description	Image of sample produced	Porosity in the section	Image of specimen's fracture line after flexural test	F_{max}
S5	**Composition:** 3 mm PVC_p shred **Production parameters:** • Temperature - 130°C • Pressure - 10 bars • dwell time - 60 mins **Sample thickness:** 5 mm				16.26
S6	**Composition:** 3 mm PVC_p shred **Production parameters:** • Temperature - 130°C • Pressure - 100 bars • dwell time - 60 mins **Sample thickness:** 5.2 mm				22.62
S7	**Composition:** 0.2 mm PVC_p powder **Production parameters:** • Temperature - 130°C • Pressure - 100 bars • dwell time - 60 mins **Sample thickness:** 5.1 mm				32.54

Summary (Continued)

Sample ID	Sample description	Image of sample produced	Porosity in the section	Image of specimen's fracture line after flexural test	F_{max}
S8	**Composition:** 7 mm PVC_p shred **Production parameters:** • Temperature - 130°C • Pressure - 100 bars • Dwell time - 60 mins **Sample thickness:** 5.73 mm				18.32
S9	**Composition:** 10 mm PVC_p shred **Production parameters:** • Temperature - 130°C • Pressure - 100 bars • Dwell time - 60 mins **Sample thickness:** 4.1 mm				48.85
S10	**Composition:** 30% PVC_p 0.2mm powder + 70% PVC_p 10mm shred **Production parameters:** • Temperature - 130°C • Pressure - 100 bars • Dwell time - 60 mins **Sample thickness:** 5.44mm				7.04

Summary (Continued)

Sample ID	Sample description	Image of sample produced	Porosity in the section	Image of specimen's fracture line after flexural test	F_{max}
S11	**Composition:** 50% PVC_w 0.2mm powder + 50% PVC_p 10mm shred **Production parameters:** • Temperature - 130°C • Pressure - 100 bars • Dwell time - 60 mins **Sample thickness:** 5.73 mm				32.58
S12	**Composition:** 70% PVC_w 0.2mm powder + 30% PVC_p 10mm shred **Production parameters:** • Temperature - 130°C • Pressure - 100 bars • Dwell time - 60 mins **Sample thickness:** 4.1 mm				26.03
S13	**Composition:** 50% PVC_w 0.2mm powder + 50% PVC_w 10mm shred **Production parameters:** • Temperature - 130°C • Pressure - 100 bars • Dwell time - 60 mins **Sample thickness:** 5.44mm				30.44

4.3.5 Conclusion

The results from mechanical tests and morphology analysis identifies the optimal production parameters: a temperature of 130 degrees Celsius, a pressure of 100 bars, and a dwell time of 60 minutes. These parameters demonstrate the most favorable conditions for maximizing material strength and integrity during the production process. Adjusting these variables accordingly can lead to enhanced performance and reliability in the final product.

The results from mechanical tests reveal a clear trend: samples with homogeneous grades and balanced powder and shred ratios outperform those with unequal ratios of different grades. However, multiple tests needs to be performed to draw reliable conclusions.Samples S7, S9, and S12 are specifically benchmarked against the behavior of virgin plastic to compare the failure patterns.

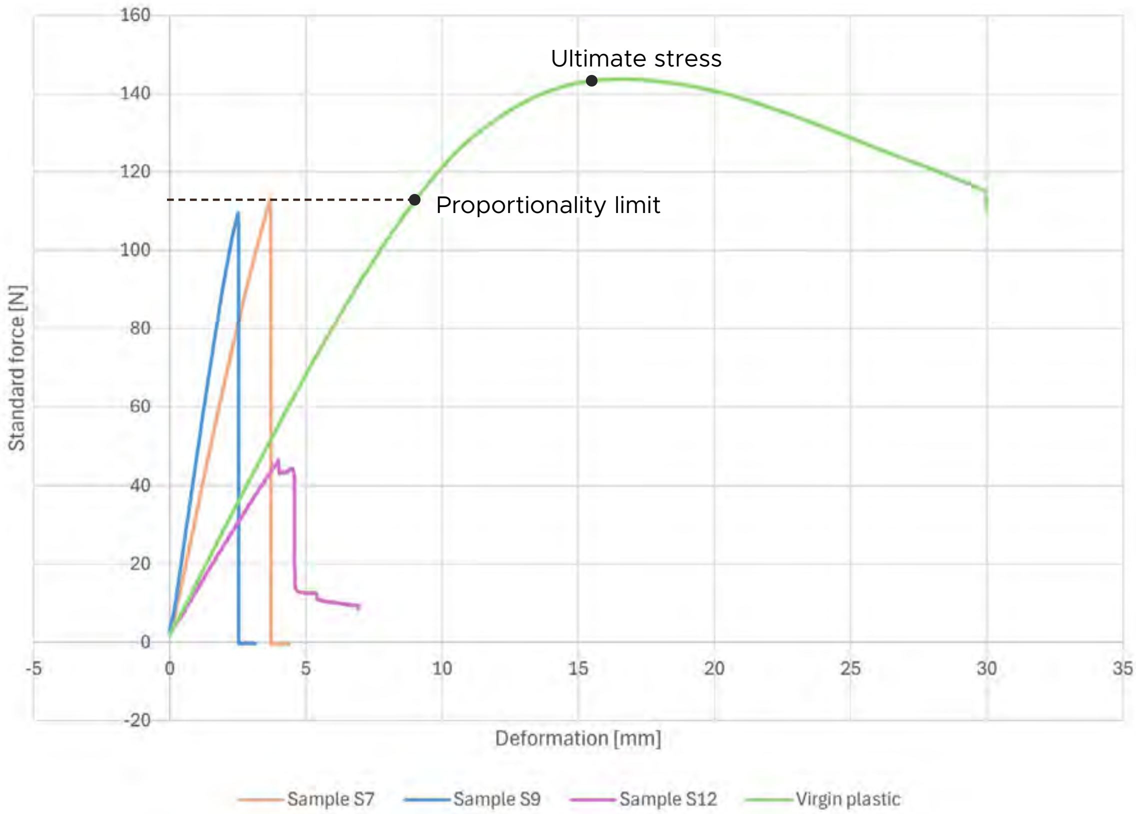


Figure 73: Comparision of material fracture pattern with virgin PVC solid plate (Source: Author)

The tile samples produced and an equivalent virgin plastic shows the mechanical behavious under stress. While both materials exhibit similar stress levels, they demonstrate different failure patterns—ductile failure and brittle failure—showing distinct material failure behaviors under similar loading conditions.

Ductile failure, typically observed in plastics, involves significant deformation before ultimate rupture. This failure mode is characterized by plastic deformation, where the material stretches or elongates under stress. In contrast, the engineered plastic demonstrates brittle failure, which occurs when the material fractures suddenly and without warning.The virgin plastic shows a typical plastic material behavious under load. The samples produced exhibit brittle failure which is typified by minimal or no plastic deformation before fracture, often resulting in sharp, clean breaks. This type of failure is more commonly seen in rigid plastics.

For applications like cladding panels where plasticity and deformation are not critical factors, the focus shifts to the benefits the material offers. These panels are engineered to bear loads in the plastic zone, rather than in the range between the proportional limit and ultimate stress. Recycled material also handles similar loads, potentially providing a safer option if designed to withstand such stresses. The advantage of using upcycled material lies in its ability to endure stress levels comparable to virgin plastic, ensuring structural integrity while promoting sustainability through recycling.

5

Application

Testing | Circularity | Prototype

5.1 Application of the material

The preceding chapter's findings make it clear that rPVC sheet material has a wide range of uses in the building and construction sector. The material performs well in a number of non-structural applications, but being unsatisfactory for structural applications because to its tendency for brittle failure. The illustration below outlines the testing required to ensure regulatory compliance and shows several uses for plastic sheeting:

Application	Recommended test	Feasibility
Exterior wall cladding	Fire test	- Not feasible, but can isolate interior and exterior.
	UV test	- Can be tested
Interior partition wall cladding	Fire test	- Not feasible
	Test for acoustics	- Out of scope
Furniture	Impact resistant test	- Feasible, but needs fire test as well.
	Chemical resistant test	- Can be tested
Flooring	Slip resistant test	- mechanical strength doesnt support application
	Flammability test	
Roofing	Weathering test	- mechanical strength doesnt support application
	Load bearing	

rPVC panel as exterior wall cladding material

For facade applications, recycled polyvinyl chloride, or rPVC, sheets offer an excellent choice because of their environmental advantages, aesthetic versatility, and durability. Because of their exceptional resistance to rusting, presence of UV resistant chemicals in window composition, rPVC sheets are suited for outdoor applications. Their affordable price and low maintenance add to their appeal, giving architects and builders an innovative and sustainable option for accomplishing facade goals that are both aesthetically pleasing and useful.

The materials used for the facade cladding have to pass both fire and UV testing. Conducting the UV test was practical because the architecture faculty possessed a dedicated testing facility. But the fire test required resources that TU Delft did not have, thus efectis and Peutz were contacted outside the university. It found out that this testing procedure was expensive and required long lead periods. Thus, the external facade was selected as the testing site for the purpose of ease in this thesis.

Figure 74: Render of rPVc used as facade panel (Source: Author)

5.2 Durability test for application of the material

The test of all the samples was conducted to observe the difference in their strength arising due to UV degradation. All tests were conducted under the supervision of **Dr.Telesilla Bristogianni** at the Think lab, Faculty of Architecture and the built environment, TU Delft.

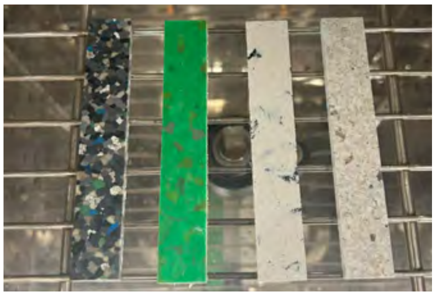
The test protocol - ASTM G154 - Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials.

This standard outlines procedures designed to simulate the effects of sunlight on materials to predict their long-term behavior when exposed to outdoor conditions.The samples were cut using a band saw at the Model Hall of the Architecture Faculty of TU Delft.

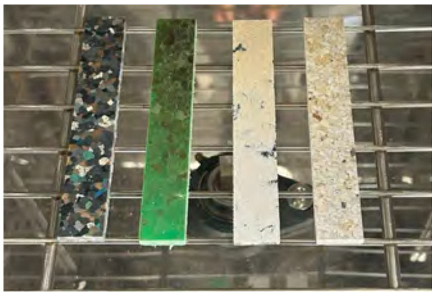
For the UV aging test, an advanced UV testing machine equipped with an OSRAM 300W Ultra Vitalux bulb was utilized. Prior to testing, the PVC tile samples were carefully cleaned and prepared for the experiment. The samples were then placed on the stand in the testing chamber. The temperature was set to maintain a consistent 40°C, and the timer was programmed for 480 hours.

According to ASTM G154, this duration of UV exposure (480 hours) is sufficient to reveal significant changes in many materials, including discoloration, fading, cracking, and loss of mechanical properties. This protocol ensures a thorough assessment of the rPVC tiles' durability and resistance to prolonged UV exposure.

At 0 hrs



At 480 hrs



Results

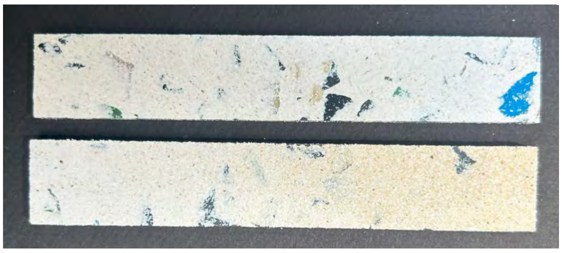
At 0 hrs
At 480 hrs

Sample 13

At 0 hrs
At 480 hrs

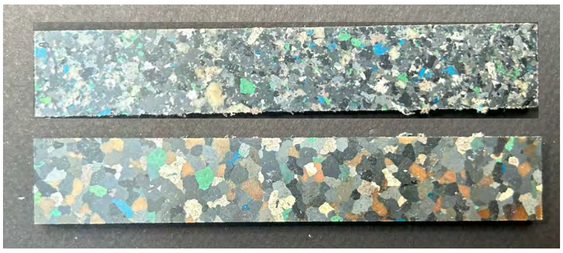
Sample 8

At 0 hrs
At 480 hrs



Sample 12

At 0 hrs
At 480 hrs



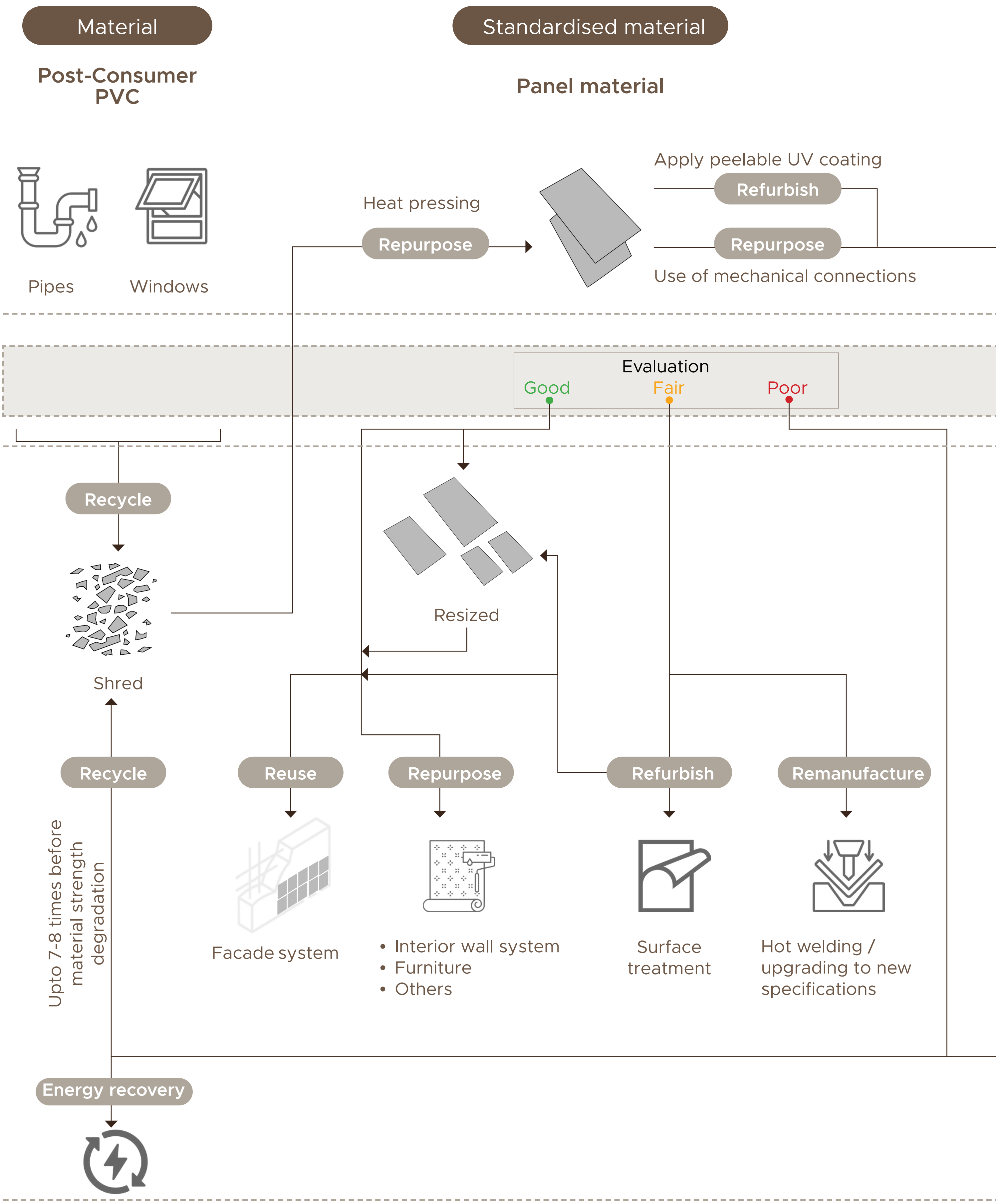
Sample 6

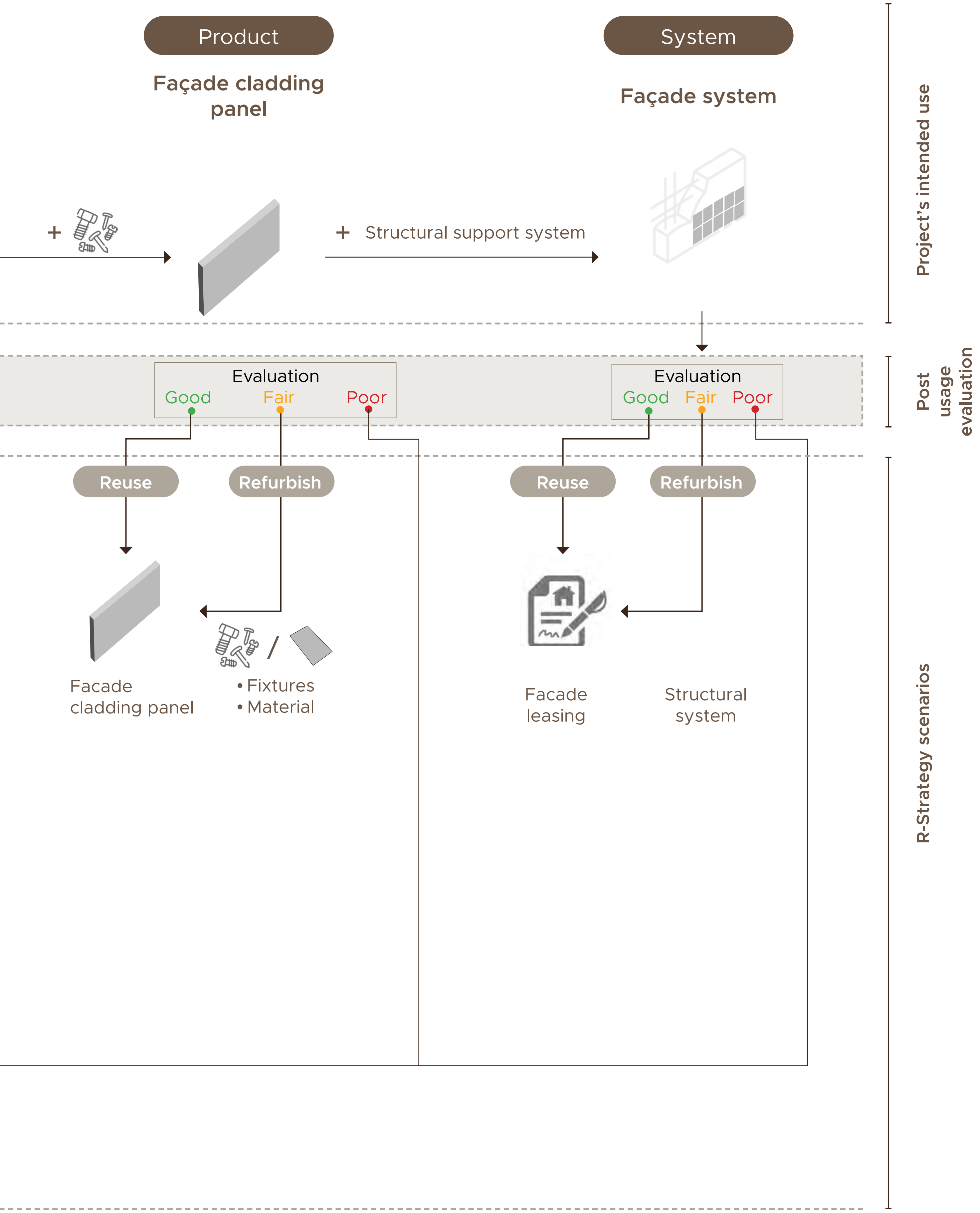
Figure 75: Results from the UV test (Source: Author)

Conclusion

The rPVC tiles exhibit limited UV stability, suggesting that prolonged exposure to sunlight can lead to significant aesthetic changes. The degree of discoloration shown could indicate possible deterioration of material characteristics with time, which can have an impact on the longevity and functionality of the tiles in outdoor applications. The data clearly shows some degradation in the window samples, with the sample 8 exhibiting the greatest damage. On the other hand, Sample 6 exhibits less degradation because of its natural dark tone. Tests for flexural strength, however, would provide more information about how UV exposure affects the material's strength. Additionally, performing fire tests is recommended to evaluate the feasibility of using rPVC panels in interior applications.

5.3 Mapping R-strategies for waste management hierarchy





Product
Façade cladding panel
System
Façade system
+
+ Structural support system
Evaluation
Good
Fair
Poor
Evaluation
Good
Fair
Poor
Reuse
Refurbish
Reuse
Refurbish
Facade cladding panel
/
• Fixtures
• Material
Facade leasing
Structural system
Project's intended use
Post usage evaluation
R-Strategy scenarios

5.4 Sustainability evaluation

5.4.1 Carbon footprint assesment for recycling PVC into facade tile

Goal

The main objective of comparing recycled PVC facade tiles with conventional cladding panels (such glass, aluminium, ceramic, bioobased and virgin PVC) in a Life Cycle Assessment (LCA) is to evaluate and determine the impact on the environment of each material throughout all stages of its life cycle. This comparison will show the potential beneficial effects of employing recycled PVC as an alternative cladding material and provide light on its sustainability.

Target audience : Architects and building designers, engineers, policy makers and egulatory bodies seeking sustainable material alternatives in the building sector.

Intended application : The intended end-use application would be exterior facade cladding panel with mechanical fixtures. For the study, only panel will be considered.

Comparative materials : Aluminium, ceramic, biobased and virgin PVC. (Note: the data is collected from literature)

Scope

The scope of the Life Cycle Assessment (LCA) defines the boundaries, assumptions, and details of the study to ensure a clear and comprehensive evaluation of the environmental effects of various cladding materials

Functional unit : The functional unit is a measure of the function of the studied system and provides a reference to which the inputs and outputs are related.
The functional unit is defined as ***1 square meter of facade cladding material***.

System boundaries : The system boundaries determine which processes are included in the LCA. The study will consider the following life cycle stages for each cladding material: ***material acquisition, production, distribution and use***. Although the material can be obtained locally, the material for this thesis was obtained from ***Cifra Recycling GmbH, Neukirchen-Vluyn, Germany***. Hence, the same location is considered.

Impact Assessment Methodology : *Global warming potential (GWP)*, a measure that measures a product's contribution to climate change, will be evaluated to assess its environmental impacts.The greenhouse gas footprint will be given in ***kilograms CO2 equivalent [kg CO2-eq]***, based on equivalency with respect to CO2.

Assumptions and limitations

Geographic scope : The Life Cycle Assessment (LCA) will take into account the production and consumption in Europe, considering account local differences in energy mixes and transportation infrastructure.

Time frame : The analysis will consider the entire life span of the cladding materials, typically 25 years for building applications.

Technological scope : Current technologies and practices will be used, with potential scenarios for future improvements in recycling and manufacturing efficiencies.

Operational energy : The use phase of the material is considered out of scope of life cycle inventory (LCI) due to variability and uncertainity.

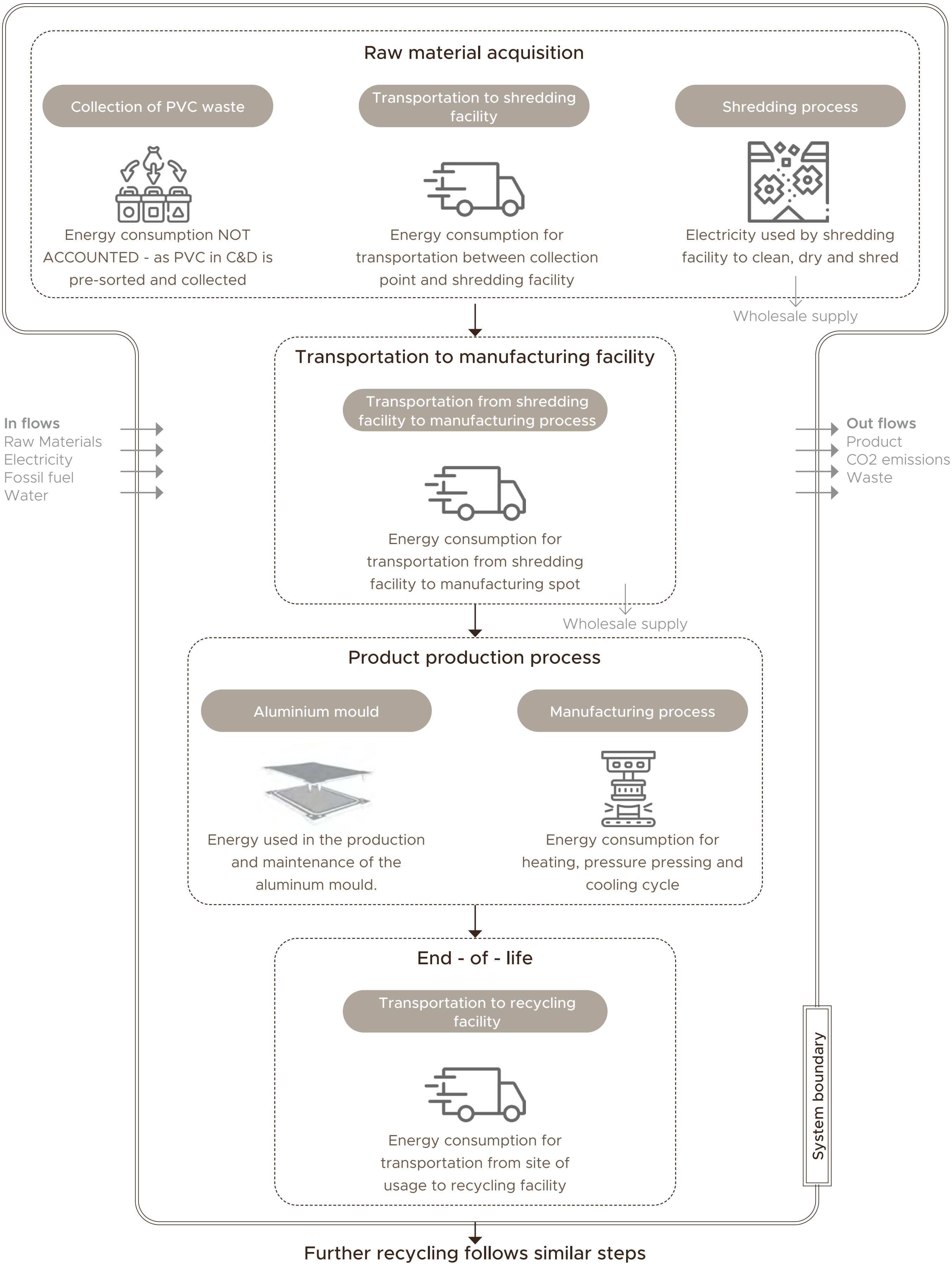
Comparitive analysis

The study will compare the following materials which are commonly used as facade cladding materials.

- Recycled PVC cladding panel (material developed as part of the thesis)
- Ceramic tile
- Aluminium panel

Life cycle inventory

The Life Cycle Inventory (LCI) involves a detailed compilation processes and quantification of inputs and outputs for every stage of the product's life cycle.



Life cycle inventory assessment

It's a long-term goal to reduce the negative environmental effects of using panels made of recycled materials in the construction industry. As a result, the impact assessment uses a ***gate-to-gate approach*** for the production processes and end-of-life phases and a ***cradle-to-gate approach*** for the procurement of materials and transportation to the manufacturing site.

Cradle-to-gate approach (Calculated per 100 kgs as processes are wholesale dependent)

(1) Raw material acquisition

(a) Transportation of raw material from waste collection facility to recycling facility

- Sources: PVC pipes and windows collected from demolition sites or waste management facilities.
- Geographical context : Germany (travel distance is assumed to be 100 kms)
- Quantity: The amount of PVC collected per batch (assumed to be 1000 kg/ batch).
- Energy consumption: Energy used for transportation (estimated at 0.3 litres of diesel per kilometer)
- Emissions: CO2 emissions from the collection process (using an emission factor of approximately 2.68 kg CO2 per litre of diesel).

Fuel consumption	=	Travel distance X Fuel consumption rate
	=	100 kms X 0.3 L/km
	=	30 litres
Carbon emission	=	Fuel consumption X CO2 emission per litre of fuel
	=	30L X 2.68 kg CO2/L
	=	**80.4 kg CO2 eq / 1000 kg of waste**

(b) Shredding process

- Sources: PVC pipes and windows from waste collection facility.
- Geographical context : Germany
- Quantity: 1000 kgs
- Energy consumption: Energgy used to clean, dry and shred. (assemed energy consumption to be 0.2 kWh per kg of PVC)
- Emissions: CO2 emissions from equipment used for cleaning and shredding (based on the German grid average of 0.4 kg CO2 per kW).

Energy consumption for 1000 kgs	=	Total quanitity per batch X Energy consumption per batch
	=	1000 kgs X 0.2 kWh/kg
	=	200 kWh
Carbon emission	=	Total energy consumption X CO2 emission per unit
	=	200 kWh X 0.4 kg CO2 per kW
	=	**80 kg CO2 eq / 1000 kg of PVC shreds**

(2) Transportation to manufacturing facility

- Distance: Distance from recycling facility in Cifra Recycling GmbH, Neukirchen-Vluyn, Germany to manufacturing facility in Delft, Netherlands (200 kms).Mode of Transport is assumed to be via road.
- Fuel consumption: Energy used for transportation (estimated at 0.3 litres of diesel per kilometer
- Emissions: CO2 emissions from transportation (using an emission factor of approximately 2.68 kg CO2 per litre of diesel).

Fuel consumption	=	Travel distance X Fuel consumption rate
	=	200 kms X 0.3 L/km
	=	60 litres
Carbon emission	=	Fuel consumption X CO2 emission per litre of fuel
	=	60L X 2.68 kg CO2/L
	=	**160.8 kg CO2 eq / 1000 kg of waste**
Total carbon emission in cradle-to-gate approach	**=**	**Total of (1) and (2)**
	=	(80.4 + 80 + 160.8) kg CO2 eq / 1000 kg
	=	321.2 kg CO2 eq / 1000 kg
	=	**2.60 kg CO2 eq / 1m^2 of recycled PVC panel (8.1 kg/panel)**

Gate-to-gate approach

(3) Product production process

(a) Manufacturing process

- Sources: PVC regrinds shreds from germany
- Geographical context : The Netherlands.
- Functional unit : ***1 m^2 of recycled PVC sheet.***
- Quantity: The amount of PVC used to get 4mm sheet material of 1 sqm size is esimated to be ***8.1 kg.***
- Electrical power rating of the machine = 43.7 kW
- Emissions: CO_2 emissions according to the Dutch electricity grid factor is 0.45 kg CO_2/kWh.

Total manufacturing time :

Phase	Heating time	Holding time	Pressure pressing time	Cooling time
Temperature difference	30°C to 130 °C	130 °C	-	130°C to 30 °C
Rate	5 °C / min	-	-	5 °C / min
Time	20 mins	60 mins	10 mins	20 mins
Total time		**110 mins (1.83 hours)**		

Power consumption = Power rating of equipment X Operational time
= 43.7 kW X 1.83 hours
= 79.971 kWh

Carbon emission = Power consumption X CO_2 emission per unit of electricity
= 79.971 kWh X 0.45 kg CO_2/kWh
= **35.98 kg CO_2 eq / 1m^2 of recycled PVC panel**

(b) Mould use

- Material: Aluminum mould.
- Energy Consumption: Considering energy for production and maintenance (assumed to be 500 kWh per mould over its lifetime).
- Emissions: CO_2 emissions according to the Dutch electricity grid factor is 0.45 kg CO_2/kWh.

Carbon emission = Power consumption X CO_2 emission per unit of electricity
= 500 kWh X 0.45 kg CO_2/kWh
= **225 kg CO_2 eq / mould**

The energy consumption for the aluminium mould is <u>NOT ACCOUNTED</u> as it is variable and design dependent. Hence, this value is omited from the total CO_2 calculation

(4) End-of-life

- Transportation energy consumption from construction site to PVC sheet material recycling facility.
- Geographical context : The Netherlands (distance is assumed to be 100 kms).
- Energy consumption: Energy used for transportation (estimated at 0.3 litres of diesel per kilometer)
- Emissions: CO_2 emissions from the collection process (using an emission factor of approximately 2.68 kg CO_2 per litre of diesel).

Fuel consumption = Travel distance X Fuel consumption rate
= 100 kms X 0.3 L/km
= 30 litres

Carbon emission = Fuel consumption X CO_2 emission per litre of fuel
= 30L X 2.68 kg CO_2/L
= 80.4 kg CO_2 eq / 1000 kg of waste
= **0.651 kg CO_2 eq / 1m^2 of recycled PVC panel**

Total carbon emission in gate-to-gate approach = **Total of (3) and (4)**
= (35.98 + 0.651) kg CO2 eq / 1m2 of recycled PVC panel
= **36.631 kg CO2 eq / 1m2 of recycled PVC panel**

Total carbon emmision 1m² of recycled PVC panel in the primary cycle of the facade product

= Cradle-to-gate carbon emission + Gate-to-gate carbon emission
= 2.60 kg CO2 eq + 36.631 kg CO2 eq

= 39.231 kg CO2 eq / 1m2 of recycled PVC panel

Life cycle impact assessment

The previous assessment identified various stages of raw material acquisition and manufacturing as major contributors to carbon emissions. The LCI assessment was conducted to account for the total greenhouse gas emissions produced during the entire lifecycle of the built asset. This assessment encompasses material acquisition, manufacturing, transportation, and potential maintenance phases.

To benchmark the rPVC panel against conventional materials such as ceramic cladding tiles and aluminum cladding panels, it is necessary to compare their environmental impacts. However, evaluating the full lifecycle emissions for all these materials is a complex process due to variations and uncertainties in data. Therefore, the comparison is focused on the embodied carbon stages A1-A3.

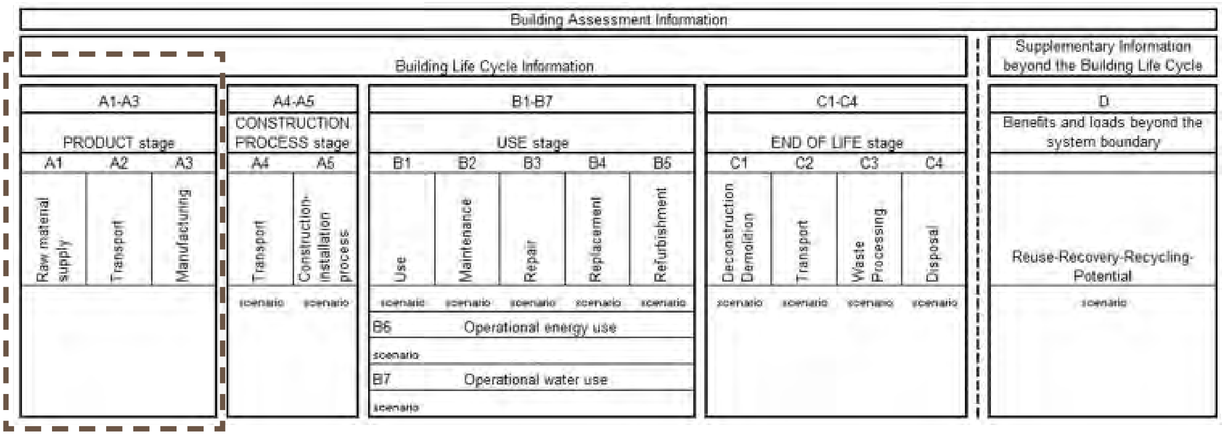


Figure 76: Life cycle phases and components that are utilized in CEN/TC 350 standards, EN 15804

The following figure illustrates the comparison of embodied carbon between recycled plastic (rPVC) and standard materials. It's important to note that this carbon footprint accounts for only ONE LIFECYCLE. Ceramic and anodized aluminum have significantly longer lifespans compared to rPVC panels, which makes it necessary for more frequent replacements for rPVC. However, advancements in surface treatments and other durability innovations could extend the lifespan of rPVC panels, making their performance more comparable to that of ceramic and aluminum panels.

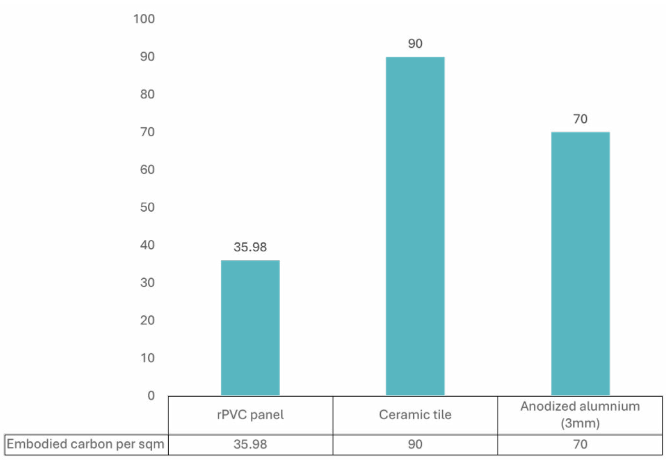


Figure 77: Comparision between rPVC panel vs conventional material (Data from EPD)

Interpretation

(1) Data analysis

The carbon emissions calculated in the study is further analysed under categories to identify stages with the highest carbon emissions. The categories are:

- Raw material acquistion = 1.299 kg $CO2$ eq / $1m^2$ of rPVC panel
- Transportation of shreds to recycling facility = 1.3 kg $CO2$ eq / $1m^2$ of rPVC panel
- Manufacturing process = 35.98 kg $CO2$ eq / $1m^2$ of rPVC panel
- End-of-life = 0.651 kg $CO2$ eq / $1m^2$ of rPVC panel

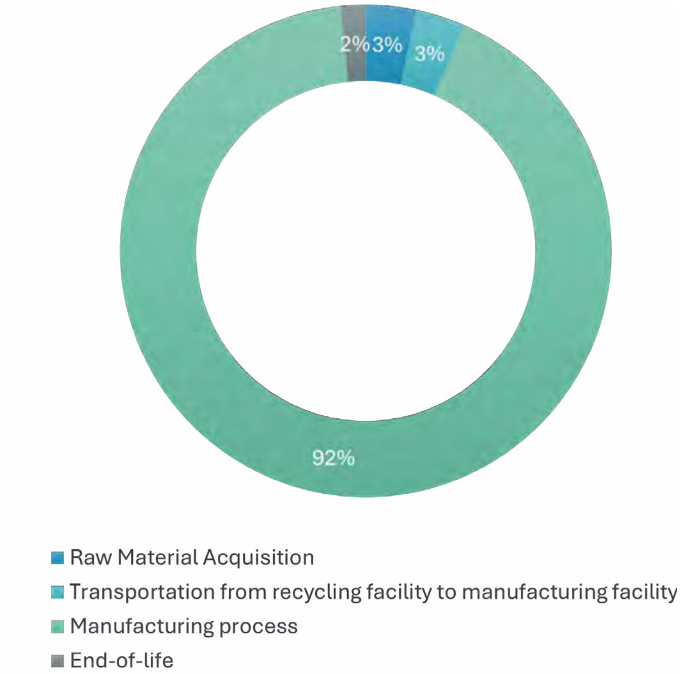


Figure 78: Graphical representation of carbon emission according to category (Source: Author)

The figure above clearly demonstrates that the manufacturing process is a significant contributor to carbon emissions. This is primarily because the material is maintained at a high temperature of 130°C during the process, which involves heating and cooling phases.The material is heated in this procedure at a rate of 5°C per minute until it reaches the 130°C target temperature. The substance is kept at this temperature for 60 minutes after it has been reached. The cooling phase starts after this holding period and continues at a pace of 5°C per minute.It is important, that these particular parameters—holding time, cooling rate, and heating rate—have not been optimised.

(2) Improvement strategies

- Optimise the process parameters such as holding time, cooling rate and heating rate.
- Invest in energy efficient system for heating, pressing and cooling.
- Optimise logistics efficiency - reduce the transportation distnaces and work locally with waste management services.
- Encourage multiple reuse of the product through design than being recycled or disposed.

Conclusion

When PVC is recycled into facade tiles, an LCA is carried out to give a thorough understanding of the environmental effects, including carbon emissions. Promoting sustainable practices in the building sector requires evaluating and reducing these emissions.

Recycling PVC provides a practical way to produce environmentally friendly building materials with a less carbon footprint in addition to preserving resources and minimizing waste. Using techniques to reduce emissions at every stage of the product's life cycle can greatly improve its overall sustainability.An overall decrease in greenhouse gas emissions is a result of a reduced dependency on energy-intensive virgin material production operations and good waste management.

5.5 Design flexibility of the material

5.5.1 Influence of mould on product

Recycled PVC (rPVC) panels are an excellent choice for an array of architectural and interior design applications because of their exceptional creative versatility. The mould used in the manufacturing process can have a big impact on the end product's quality and features.

- **Surface finish :** Moulds with specific textures or patterns can impart unique surface finishes to the rPVC panels. For example, the design mold produced a matt surface on the panel, whereas the mould that produced flat panels produced a smooth, glossy finish.
- **Modular element design and dimensional accuracy:** High-quality moulds ensure that the panels meet exact dimensional specifications. This is important for applications where precise tolerances are needed, including in modular building or where panels must fit perfectly into structures that already exist.
- **Customisation:** The ability to create custom moulds means that rPVC panels can be adapted to specific project requirements. This enables architects to execute distinctive architectural concepts by using customizable shapes, sizes, and patterns.

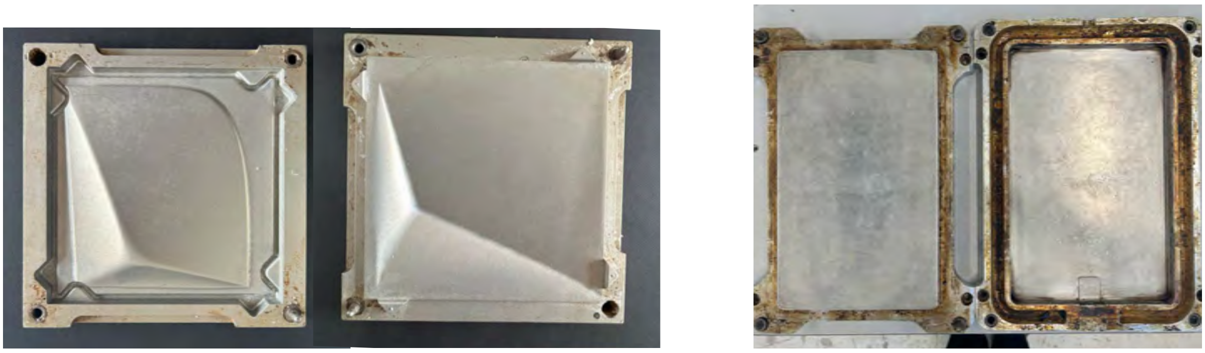


Figure 80: The two moulds from NPSP.B.V (Source : Author)

5.5.2 Functional grading as a design technique

Functional grading involves the intentional modification of material characteristics or structural properties across a component. This can be accomplished by:

- Changing the material composition: Modifying the type of composition of shred based on location of application to extract maximum benefits.
- Altering material properties: Changing the panel's shred size or delebrate placement of the shreds at zones.

Application

- Dual-pattern panel: The shreds can be arranged to produce a product with a dual surface pattern by utilizing various shred sizes and colors.
- Benefits in terms of functionality: By changing the composition, one surface can be utilized for aesthetic appeal and another to make it UV resistant by utilizing PVC window shreds.

Figure 79: The front and rear surface of the tile (Source: Author)

5.6 Prototype documentation

Using a design mould from NPSP B.V. , Delft, The Netherlands.

The technique used in creating this prototype is similar to previous methods. However, the unique mold design is what differentiates this prototype. This mold has hidden grooves designed especially for mechanical fittings, enabling more accurate and secure component installation.

This prototype is an excellent example of how precise mold design can improve the end product's quality significantly. This new mould gives the prototype a matte surface, in contrast to earlier mould that were developed to generate a shiny surface finish. The purposeful modification of surface texture intends to showcase the adaptability and possibility of personalized mold designs in accomplishing diverse visual and practical results.

The incorporation of hidden slots for mechanical fixtures is particularly worth mentioning. These spaces allow for the easy integration of extra pieces without sacrificing the product's overall aesthetic or structural integrity. As a result, the prototype has better durability and assembly precision in addition to having a better surface texture.

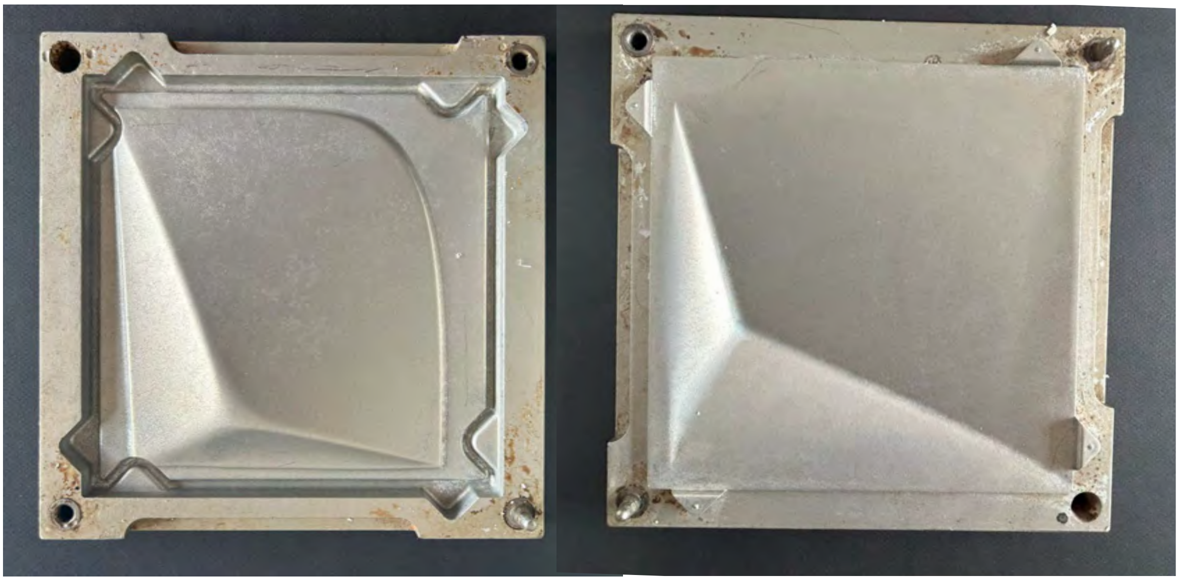
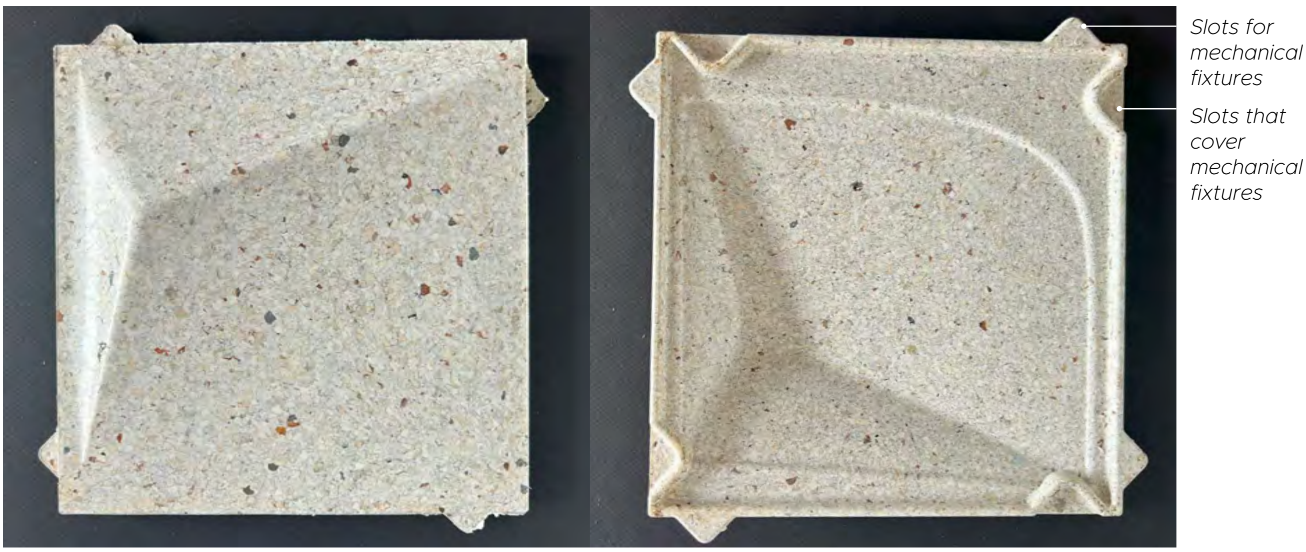


Figure 81: Mould for a facade panel , designed by NPSP B.V, Delft, The Netherlands (Source: Author)



(a) Front *(b) Behind*

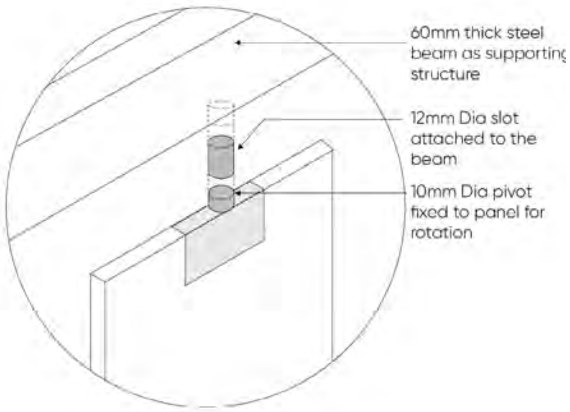
Figure 82: Modular facade panel from rPVC window shreds, panel design by NPSP B.V. (Source: Author)


rPVC used as exterior cladding panel
Panel design : NPSP B.V. , Delft, The Netherlands

Other application visualisation

rPVC panel as a rotating screen panel

(a) Panel elevation



(b) Isometric view of the fixture detail

(c) Dual sided panel that can be produced by functional grading

rPVC panel used as interior wall panel

Mockup : Freepik

rPVC tiles can also be utilized for interior applications, provided they meet with fire rating regulations. PVC is water- and chemical-resistant and easy to maintain due to its inherent material properties. Because of these qualities, rPVC tiles are a great option for interior wall panels since they are safe, easy to maintain, and durable.

6

Research conclusion

“ There is no such thing as garbage, just useful stuff in the wrong place ”

- Alex Steffen

This thesis offered insightful information about repurposing PVC to create architectural products. The section that follows contains the conclusions pertaining to the main study topics and their subquestions.

Subquestion 1 :
What are the key challenges in plastic recycling, specifically with PVC, and what strategies can be employed to address these challenges effectively?
The key challenges can be classified into five categories: economic, logistical, technical, regulatory, and societal challenges. These challenges are interconnected, often leading to a complex network of key problems. Based on analysis, the primary obstacle is the wide range of resin types produced, which means that each type needs to be sorted in order to facilitate recycling. This sorting process requires infrastructure, machinery, and manual labor, contributing to the high cost of plastic recycling.

Specifically with PVC, a significant challenge is accurately identifying the resin type. However, in cases such as PVC found in construction and demolition waste, items are sometimes pre-sorted prior to demolition. This presents an opportunity to leverage pre-sorting as an advantage, making recycled components more competitive in the market.

Subquestion 2 :
How do we determine the compositional differences and material behaviour in PVC waste from various sources, colors, and applications, which complicate the recycling process?
To identify the composition, FTIR and LIBS are suitable analytical techniques. The construction and demolition industry generates a substantial amount of waste from single-site sources, originating from the same production companies, having similar lifespans, and sharing common compositions. This uniformity promotes easier identification. For detailed compositional analysis, XRF can be utilized to exclude flame retardants. Conducting DSC provides an operational temperature range which is essential to modify production parameters accordingly. Despite conducting analyses on different colors, the DSC results did not reveal significant variations, leading to the decision to disregard the color's impact on final production.

Subquestion 3 :
How do the compositional differences in the waste streams and production parameters, such as temperature, pressure, and dwell time, influence the processing of PVC into flat tile materials?
The production was conducted in three distinct series to address various aspects: the Temperature and Pressure (TP) series focused on optimizing production parameters, the Shred (S) series analyzed the impact of shred size on material properties, and the Composition (C) series examined the effects of functional grading on material properties.

In the TP series, temperature was carefully adjusted to minimize heat-induced material degradation, following a dwell time of 60 minutes as recommended by literature references. Pressure settings were optimized based on the material's strength characteristics. Ultimately, the optimal production parameters identified were a temperature of 130°C, a pressure of 100 bars, and a dwell time of 60 minutes.

Subquestion 4 :
How do variations in shred size and composition affect the mechanical properties of the resulting tiles?
Within the S series, different shred sizes were evaluated, revealing that 10mm shreds and powdered shreds exhibited superior performance compared to other sizes.Additionally, the C series investigated compositional variations, affirming that even with these variations, the 10mm shred consistently demonstrated superior strength properties.

Subquestion 5 :
How can we effectively evaluate the strength of recycled PVC tiles and analyse the causes of failure using morphological analysis and sample homogeneity?
To effectively evaluate the strength of recycled PVC tiles and analyze the causes of failure, a comprehensive approach integrating morphological analysis and ensuring sample homogeneity is crucial.Morphological analysis involves detailed examination of fracture surfaces through advanced imaging techniques like scanning electron microscopy (SEM). This method allows for the identification of specific features indicative of failure mechanisms, such as void formation, crack propagation paths, and interfacial debonding.

Sample homogeneity plays a critical role in ensuring reliable strength evaluation and hence efforts to increase the homogeneity was made by reducing porosity by adding powdered sample to fill in voids . By combining morphological analysis with rigorous control of sample homogeneity, the study facilitates finding possible solutions to enhance the material strength of the sheet material.

Subquestion 6 :
How do aesthetics and material application correlate with sustainability, considering factors like R-strategies to map the waste management hierarchy, carbon footprint, and benchmarking against conventional materials typically used in façade systems??
Firstly, applying R-strategies involves prioritizing waste management hierarchies such as Reduce, Reuse, and Recycle. Sustainable material choices in façade systems prioritize materials that minimize waste generation during production, installation, and eventual removal. By opting for materials that support these strategies, such as recycled content or materials with high recyclability rates, projects can significantly reduce their environmental footprint.

Secondly, evaluating the carbon footprint is essential. Sustainable façade materials should aim to minimize greenhouse gas emissions throughout their lifecycle, from extraction and manufacturing to transportation and installation. Recycled content gives a scope for alternative material choices for the facade application instead of conventional materials like brick cladding, aluminum or ceramic.

The production of rPVC panels relies significantly on the layering technique and the quality of molds employed. Therefore, even with identical compositions, variations in the final product can arise depending on the specific characteristics of the molds used in the production process. This highlights the critical role of mold quality in shaping the consistency and quality of rPVC panels manufactured through this technique.

Hence the main reserach question:

"How can PVC waste steams originating in windows and pipes be processed to develop sheet materials for facades cladding??"

The research highlights the significant potential of PVC waste streams, which are generated in large quantities, particularly from windows and pipes, leading to huge accumulation over the years. Many of these items, widely used in the past two decades, remain in circulation and pose ongoing challenges of waste management. Therefore, it is crucial to explore pathways for upcycling these waste streams back into useful materials. Pipes offer the advantage of being available in various colors, enhancing aesthetic versatility, while windows inherently contain UV retardants, adding functional value.

Utilizing a hot press process, these materials can be transformed into sheet materials with dimensional flexibility, dictated by the press size and mold design. Facades are chosen as the application site due to the unavailability of fire testing facilities. By using these materials as facade cladding, we can enhance both exterior aesthetics and interior insulation.

Mapping out the R strategies (Reduce, Reuse, Recycle), it becomes evident that these materials can be refurbished and utilized multiple times before eventual recycling, thereby promoting sustainable lifecycle management. This approach not only addresses the environmental challenges posed by PVC waste but also supports resource efficiency and circular economy principles in construction practices.

In conclusion, this thesis outlines a production process for PVC sheet materials suitable for facade applications, effectively repurposing waste that would otherwise be destined for landfill or incineration. This approach not only demonstrates a sustainable reuse of materials but also contributes to reducing environmental impact by extending the lifespan of PVC products in construction.

Further research recommmendation

(1) Circularity design of rPVC panels:
In the context of circularity design, optimizing the heating and cooling rates in the production process plays a crucial role in reducing energy consumption. Additionally, understanding the impact of molds on production parameters is essential. Mold design influences the structural integrity, surface finish, and dimensional accuracy of the final product. Through analysis and adjustment of mold specifications, such as cavity design and cooling channels, the technique can optimize material flow and distribution, leading to improved product performance and production efficiency. Another recommendation is to adop a circular panel design which involves integrating innovative features like embedded connections using plastic-specific mechanisms such as snap fits. These designs facilitate easier assembly and disassembly, promoting reuse and reducing material consumption over the product's lifecycle. Conducting rigorous fire testing and obtaining fire ratings are critical steps in ensuring the safety and suitability of PVC sheet materials for indoor applications.

(2) Exploring various techniques for the restoration of historical sites reveals an intriguing possibility:
The recommendation focuses on the use of plastic as a versatile material capable of in-situ melting and molding into specific forms. Historical restoration projects often demand materials that can withstand substantial loads, resist degradation over time, and be applied without the need for extensive removal from the site. Plastic meets these criteria effectively, offering durability and moldability that traditional materials may struggle to match.

This novel application of plastics in historical restoration not only addresses practical concerns but also introduces innovative solutions to preserve and enhance cultural heritage. By leveraging the properties of plastics, such as their adaptability and structural integrity, restoration efforts can achieve both aesthetic and functional objectives while ensuring long-term sustainability.

(3) Exploring various unsorted wastes that end up in landfill or incineration:
The recommendation primarily addresses the handling of unsorted waste generated by sorting machines, particularly focusing on fractions such as film that often fail the detection by typical sorting technologies like DK350 and DKR310. These sorting machines frequently miss these film fractions, which results in them being grouped into unsorted waste streams. Another waste streams of concern is one which is a mixture of metal and plastic materials - (Coolrec had these waste in the recycling facility). Traditionally, due to the high cost of separating metals from plastics, these mixed waste streams are commonly incinerated to retrieve metals.

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7

Reflection

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

The graduation project topic aligns closely with the Master of Building Technology by bridging the gap between architecture and engineering, with a focus on sustainable design and technical innovation. The thesis, titled Re-P-Tile: Recycling PVC Waste Stream into Architectural Product, explores an experimental approach to repurposing waste into useful architectural materials. This thesis integrates two chairs of the Building Technology master track: the Structural Design and Mechanics chair and the Building Product Innovation chair.

The Structural Design and Mechanics chair offers guidance on experimentation and material engineering, ensuring that the waste materials are transformed into structurally sound and innovative architectural products. Meanwhile, the Building Product Innovation chair provides insights on production processes, fostering innovation and implementing circular design strategies.

The goal of this thesis is to contribute to the growing global challenge of waste management by promoting a circular economy. By transforming PVC waste into viable architectural products, the project aims to reduce environmental impact and create sustainable building materials. This integration of architectural design and engineering principles exemplifies the core objectives of the Building Technology master's program.

2. How did your research influence your design/recommendations and how did the design/recommendations influence your research?

The research and design process were a dynamic and iterative approach. The thesis comprised four parts: the literature review, experimentation, validation and evaluation, and circularity analysis. The literature review involved not only reading current works but also talking to research experts at TU Delft and around the globe. This included factory visits, interviews with lab experts, and discussions with fellow master's students across the faculties of TU Delft. These interactions added value to the literature review, providing crucial insights for the experimentation phase.

Conducting experiments required an in-depth understanding gained from the literature review, ensuring that the practical work was grounded in theoretical knowledge. The validation and analysis stages involved referring back to both the experimentation results and the research to verify findings and draw accurate conclusions. Finally, with circularity design principles in mind, the production and design processes underwent design iterations.

This back-and-forth methodology ensured a robust and comprehensive study, where each phase informed and refined the others. The iterative nature of the research allowed for continuous improvement and adaptation, ultimately leading to a well-rounded material development.

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

The graduation thesis focused on involving experts who had extensive knowledge about similar materials, addressing a gap in the literature specifically related to PVC. Collaborating with fellow master's students working on related projects provided valuable interdisciplinary insights that would have been difficult to acquire through a purely theoretical approach. Conversations with these students and experts gave way to innovative ideas on optimizing production processes. Input from industry professionals offered important cost estimation insights, while the practical experience of material experts majorly helped the experimental phase. These experts, having hands-on experience with other plastics, provided practical guidance that helped the experimentation process.

The thesis placed a major emphasis on the experimentation phase, as the core idea was inspired by the properties and applications of other materials, but its application to PVC was innovative approach. This hands-on approach was essential because existing literature on PVC was insufficient. Through experimentation, the thesis aimed to discover new insights and validate theoretical concepts in a practical context.

By balancing expert knowledge and interdisciplinary collaboration, the research not only filled a significant gap in existing literature but also provided practical solutions and optimizations for working with PVC.

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

Academically, the project fills a significant gap in knowledge about PVC applications, offering new insights and understanding. By integrating knowledge from different fields- material science, product design and engineering, the project highlights the importance of collaborative efforts in solving complex problems, enriching collaborative academic methods. The experimental techniques and practical validation processes introduced can be used in other material studies like PVC, improving research practices.

Societally, the project provides practical applications for industries using PVC, offering optimized production processes and cost-effective solutions. These improvements can lead to more efficient manufacturing practices, reducing production costs and carbon emissions. By focusing on circularity analysis and sustainable design principles, the research aligns with broader societal goals of environmental responsibility and sustainability. Promoting environmentally friendly practices, the project contributes to global efforts towards efficient waste management, sustainable resource management and reducing environmental impact.

The methodologies and insights can be applied to other materials, making the research relevant and useful across various fields of material science and engineering. The project also opens new avenues for future research, encouraging further exploration of application locations and product forms.

5. How do you assess the value of the transferability of your project results?

The methodology used, which combines theory with practical experiments, can be applied to other studies. This approach, involving different experts' perspectives, can help solve various problems in material science and engineering that are not covered in existing literature. The techniques we developed for testing and validating results can also be applied to other plastic-like materials, making the research useful in many contexts. The thesis paves the way at the plastic resin selection checkpoint, allowing others to choose different resins and tailor their research differently by following the same methodology. The focus on sustainability and circularity principles is another area where the project's results can be transferred. If implemented, the research can add significant value to the industry.

Academically, the interdisciplinary approach and innovative methods can be integrated into graduation studios, helping students and researchers develop practical skills and a comprehensive understanding across disciplines, which is crucial for developing new products. This serves as a model for teamwork and collaboration. The project's findings also pave the way for future research, encouraging the exploration of new applications for PVC and other materials. This hands-on approach to research fosters innovation and continuous improvement.

The project's emphasis on sustainability and circularity principles means that its methodologies can be used to assess and improve the environmental impact of various materials and products, helping different sectors adopt more eco-friendly practices. This contributes to global efforts in resource management and reducing environmental harm.

8

Appendix

8.1 XRF results of the window sample

Materials Science and Engineering
TUDelft, Faculty of 3mE
Mekelweg 2
2628 CD Delft, The Netherlands
Tel:015-2789459
Email: R.W.A.Hendrikx@tudelft.nl
X- ray diffraction facilities

Experimental conditions:

For XRF analysis the measurements were performed with a Panalytical Axios Max WD-XRF spectrometer and data evaluation was done with SuperQ5.0i/Omnian software. 18/12/2015 09:37:03

3/18/2024 11:59:59 AM

PANalytical

Quantification of sample Telesilla, "PVC window, pellet", 18mar24

Sum before normalization: 74.8 wt%

Normalised to: 100.0 wt%

Sample type: Solid

Correction applied for medium: No

Correction applied for film: No

Results database: omnian 4kw 20mm

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Cl	84.758	0.1
2	Ca	5.822	0.08
3	Ti	5.039	0.07
4	Pb	3.333	0.05
5	Si	0.351	0.02
6	P	0.138	0.01
7	Na	0.128	0.01
8	Al	0.118	0.01
9	Mg	0.111	0.01
10	Zn	0.065	0.008
11	Cd	0.057	0.007
12	S	0.031	0.005
13	Fe	0.03	0.005
14	Sr	0.011	0.003
15	Zr	0.008	0.003

Presence of lead

8.2 XRF results of the pipe sample

3/18/2024 12:38:15 PM

PANalytical

Quantification of sample Telesilla, "PVC pipe, pellet", 18mar24

Sum before normalization: 72.7 wt%

Normalised to: 100.0 wt%

Sample type: Solid

Correction applied for medium: No

Correction applied for film: No

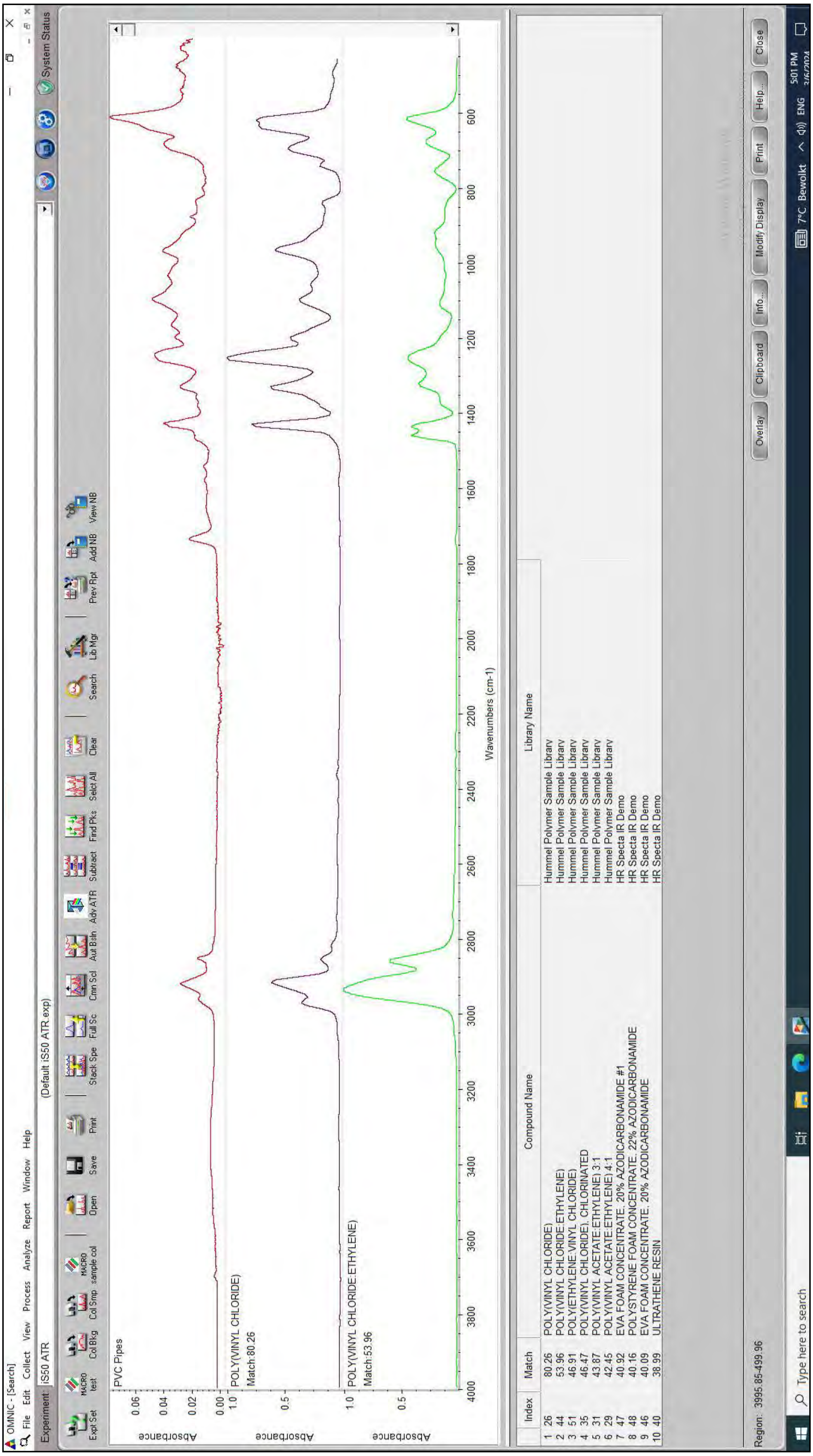
Results database: omnian 4kw 20mm

Results database in: c:\panalytical\superq\userdata

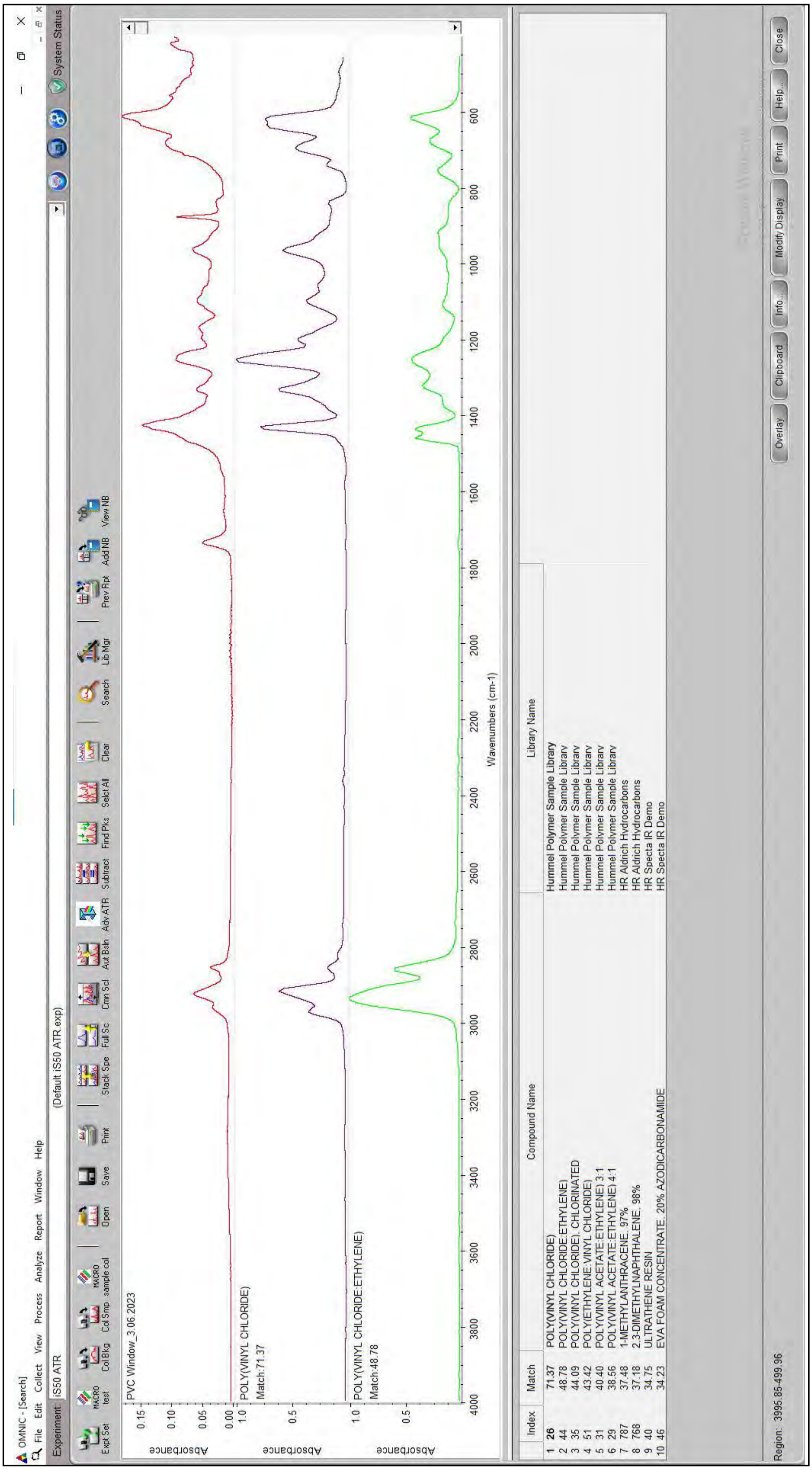
	Compound Name	Conc. (wt%)	Absolute Error (wt%)	
1	Cl	83.489	0.1	
2	Ca	13.838	0.1	
3	Ti	1.122	0.03	
4	Pb	0.602	0.02	*Presence of lead*
5	Si	0.265	0.02	
6	Zn	0.219	0.01	
7	Al	0.158	0.01	
8	Na	0.128	0.01	
9	Mg	0.058	0.007	
10	Fe	0.055	0.007	
11	P	0.034	0.006	
12	S	0.018	0.004	
13	Sr	0.016	0.004	

Use of our XRD or XRF analysis:
In a publication: 'PersonX at the Department of Materials Science and Engineering of the Delft University of Technology is acknowledged for the X-ray analysis. If it is an important part of the publication: a co-authorship is preferred. It is useful to involve us in the preparation of any presentation!

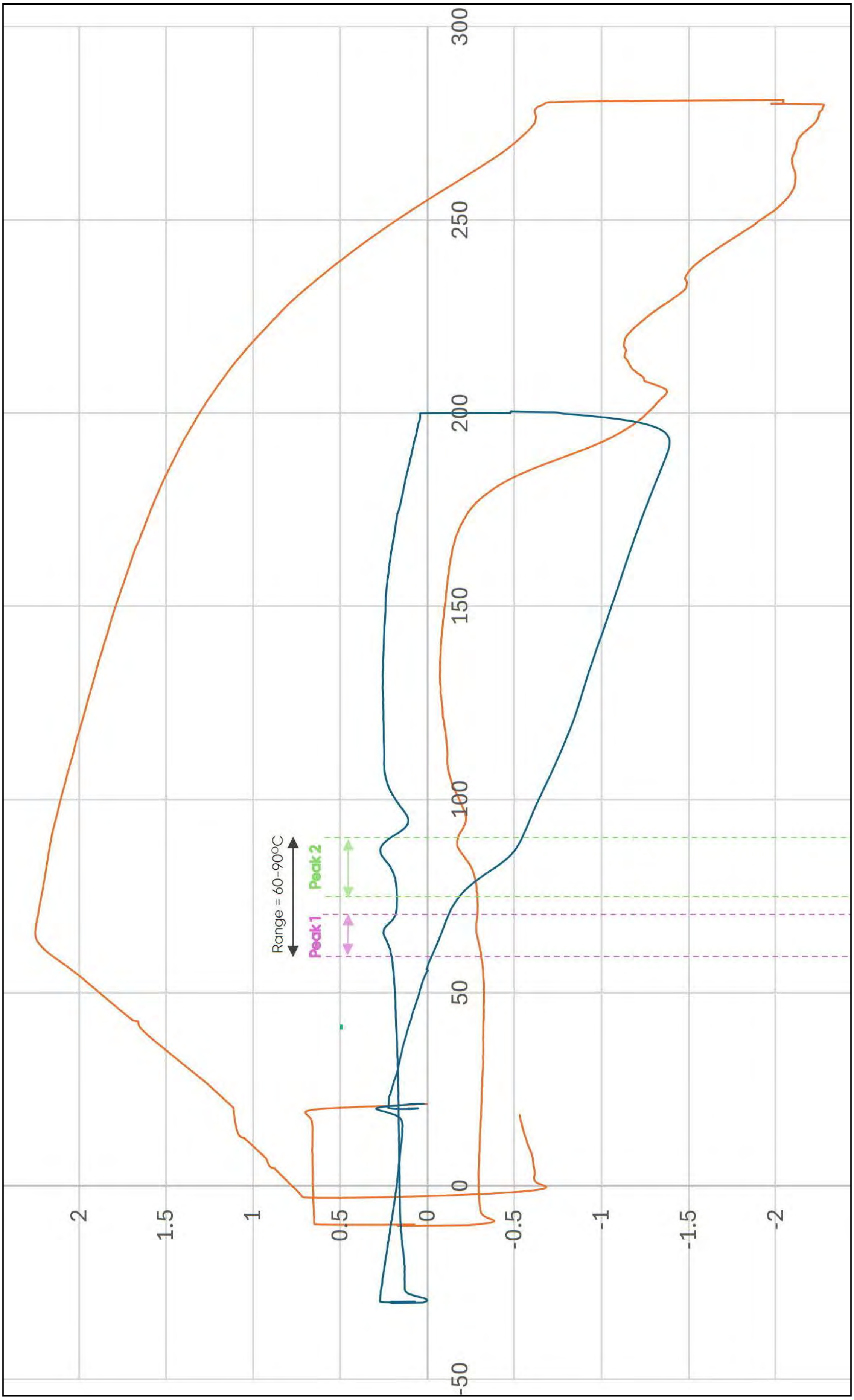
8.3 FT-IR results of the pipe sample



8.4 FT-IR results of the window sample



8.5 DSC results of the pipe vs window sample



8.6 DSC results of the different colours of pipe sample