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Maximum Percent of Post-Consumer Recycled Polypropylene in an Interior Hard Trim Panel

An Investigation into the Feasibility, Environmental Impact, and Performance of Increasing Post-Consumer Recycled Polypropylene Content in Automotive Interior Components

Master's thesis in Product Development

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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

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Abstract

This study examines the influences PCR PP has on mechanical properties, aesthetics, CO_2 footprint, and the effects from aging. The purpose of the project is to aid Volvo Cars in updating their material composition of hard trim interior panels by recommending a suitable percentage of PCR PP to use. The investigated materials have been 30% PIR PP, 30% PCR PP, 40% PCR PP, 50% PCR PP, 60% PCR PP, and 70% PCR PP with the same amount of additives. To understand this influence, methods such as aging, tensile testing, impact testing, differential scanning calorimetry, perceived quality assessment, and CO_2 footprint calculations were performed. The findings indicate that the mechanical properties are strongly limited by the impact strength, which decreases with the amount of PCR PP. This limits the recommendation for Volvo Cars to 30% PCR PP to be used. Regarding appearance, the perceived quality assessment shows that a switch to the highest material studied, 70% PCR PP, is possible. The tests performed present that aging for 500h and 1000h affects the crystallinity, resulting in varied outcomes for the studied mechanical properties. The CO_2 footprint overall decreases with the amount of PCR PP content. Although, between 30% PIR PP and 30% PCR PP there is an increase in the CO_2 footprint. Further studies should explore the effects on the full components instead of material samples, along with additional tests of the same kind as those conducted to further strengthen the results.

Keywords: PCR, PIR, tensile test, impact strength, crystallinity, DSC, molecular weight, carbon footprint

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Julia Ekener and Agnes Sundström, Gothenburg, May 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

<i>CO₂e</i>	Carbon Dioxide Equivalent
DSC	Differential Scanning Calorimetry
EoL	End-of-Life
GHG	Greenhouse Gas
GU	Gloss Unit
GWP	Global Warming Potential
PCR	Post-Consumer Recycled
PIR	Post-Industrial Recycled
PP	Polypropylene

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1

Introduction

This chapter introduces the project, providing an overview of its background and context. It outlines the key limitations and ethical considerations associated with the project, while also detailing the aims, purpose, and research questions that guide the study.

1.1 Background

Following, the background for the project will be presented. It will describe the current situation and present collaborating companies.

1.1.1 Current situation

Plastic is widely used today across industries such as packaging, construction, and technology due to its versatility, durability, and cost-effectiveness. This widespread use has raised significant environmental, social, and health concerns due to the insufficient waste management and reliance on fossil fuels for production. The levels of production and consumption of today are increasingly recognized as having reached unsustainable levels (Walker & Fequet, 2023).

Half of all plastic produced today is designed for single-use purposes, which implies that it is used once and then wasted. Approximately 98% of single-use plastic products are produced from virgin feedstock, which means that the plastic used is fully newly produced and contains no percent recycled plastic. The production, use and disposal of virgin plastic based on conventional fossil fuel is estimated to represent 19% of the global carbon budget by 2040 (The United Nations Environment Programme, 2025). The use of recycled plastics instead will not only benefit the global carbon budget, but also addressing the depletion of fossil fuel resources by eliminating the need for their use in the production of new plastic materials (Tide Earth, 2024)

At the end of 2017, looking at all plastic waste ever produced, only 10% had been recycled. 76% ended up in landfills and the remaining 14% was incinerated. The inadequate recycling practices lead to the long-term pollution as plastics can persist in ecosystems for centuries. These numbers recognizes the need for improved circular economy and to address the full life cycle of plastics (Grabiell, Gammage, Perry, & Dixon, 2022)

1.1.2 Collaborating Company - Volvo Cars

Volvo Cars, a global automobile manufacturer originating in Sweden, operates six major production facilities around the world and markets its vehicles in more than 100 countries. The company has committed to achieving net zero emissions in their full value chain by 2040. To accomplish this ambitious goal, Volvo Cars must adopt innovative and forward-thinking approaches to sustainability. As many components of their automobiles consist of polymers, which have significant adverse effects on the environment, this is an area where they can develop to reduce their carbon footprint (CO_2 footprint) (Volvo Cars, 2025). Furthermore, the European Union, in 2023, presented a proposal on circularity requirements for vehicle design and end-of-life (EoL) vehicle management. It includes a requirement that each new vehicle include at least 25% of post-consumer recycled (PCR) plastic, and 25% of that material should come from recycled end-of-life vehicles (European Commission, 2023). This may also be a significant motivator for development.

To minimize their CO_2 footprint and follow the regulation that may be implemented, Volvo Cars would like to decrease the amount of virgin polypropylene (PP) in their hard trim panels, shown in Figures 1.1 and 1.2. The hard trim panels consist of: pillars, for example where the seatbelt is located, there are both upper and lower pillars, threshold, and tailgate panel and window frame located in the trunk. Because of safety reasons only lower pillars are made out of recycled material since the upper pillars have airbags inside them. Today their hard trim panels consist of 30% post-industrial recycled (PIR) PP. The goal is to use as high percentage of recycled PP as possible in their hard trim panels while still meeting technical and aesthetic requirements. The materials that will be investigated in this project are PCR PP since that is the change that Volvo Cars aims to implement.

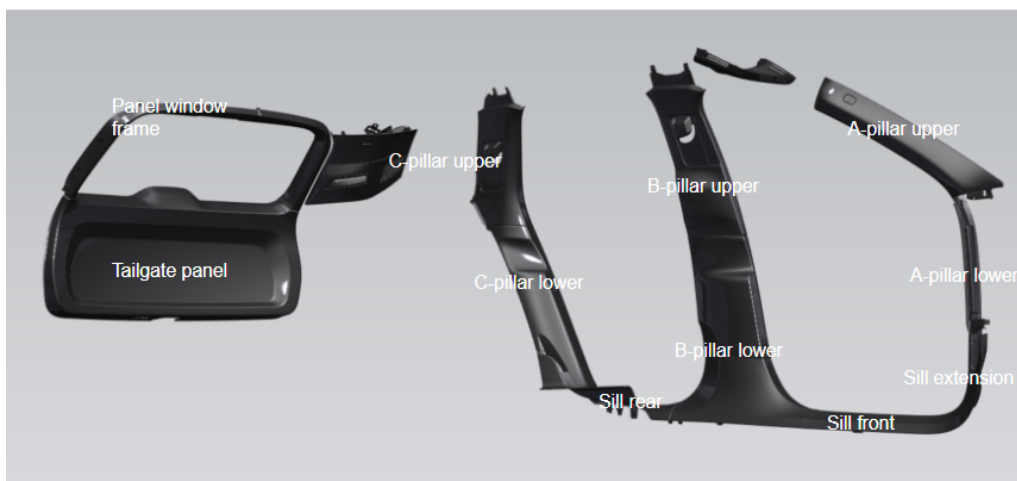


Figure 1.1: The hard trim panels



Figure 1.2: Close-up of one of the hard trim panels, the threshold

1.1.3 Collaborating Companies - Polykemi & Rondo Plast AB

Polykemi is a family-owned company that produces tailor plastic compounds according to the requirements of their costumers. The company does not have a standard product, instead they produce what the customer requests. Their compounds are based on virgin material and/or high-quality recycled raw materials, customized with the help of relevant reinforcing agents and additives. The high-quality recycled raw materials that the company uses come from Rondo. Polykemi has production sites in Sweden, the United States, and China that all use local suppliers. The total production capacity is estimated to be 130 000 tons, with their biggest customer segment being the automotive industry (Axrup, Lindqvist, & Svenmo, 2025), (Polykemi, 2025).

Rondo Plast AB, known as Rondo, is a subsidiary of Polykemi, with a business idea focused on providing recycled technical polymers through grinding, quality assurance, and re-granulation. The company started in 1980. Prior to that, the operations were a division within Polykemi, but the time had come for it to function as an independent company. Initially, the company handled a lot of polyethylene and polystyrene but gradually evolved into a complete plastic recycling company handling all types of plastics. Today, it is one of the most modern plastic recycling companies in Northern Europe, specializing in technical plastics (Axrup et al., 2025), (Rondoplast, 2025).

1.2 Purpose

The purpose of this study is to support Volvo Cars in updating the composition of recycled plastic and virgin material in the production of hard trim interior panels. This study will provide a starting point for future research by identifying an area that offers potential to optimize the percentage of recycled material, rather than providing an exact optimal figure.

1.3 Aim

The aim of this project is to determine the maximum feasible percentage of post-consumer recycled polypropylene that can be utilized in the hard trim interior panels used by Volvo Cars. This without compromising the technical or aesthetic requirements while reducing their CO_2 footprint.

1.4 Research questions

The project will be guided by four research questions. They are the following:

- What is the maximum percentage of PCR PP that can be incorporated into interior hard trim panels while maintaining the same, or increasing, mechanical properties as the currently used material?
- What is the maximum PCR PP limit that can be applied while still meeting the aesthetic requirements for interior hard trim panels?
- How does aging of PCR PP affect the mechanical properties?
- How does the CO_2 footprint of the interior hard trim panels change depending on the amount of recycled content?

1.5 Limitations and Demarcations

The project will be based on one of Volvo Cars' supplier of the PP granules, Polykemi who has provided material samples with different percentages of recycled PP. Moreover it will be based on Polykemi's subsidiary Rondo, who is responsible for upgrading the PCR material to re-granulate for Polykemi to use.

Recycling of plastic and how to use it differs between both countries and companies. Therefore it is most efficient to focus the research on Polykemi's and Rondo's PP granules since that is what Volvo Cars uses today for the panels. The samples were ordered in advance of the project start due to time constraints. Thus, the ordered samples with respective percentages of recycled PP selected by Volvo Cars will be used. The project's own time limit, 21 weeks, implies that the material will not be able to be aged for as long as would be desirable. The aging performed in the project will be 500h and 1000h, which is considered a limitation.

Moreover, the tests and analyzes performed in the study will be based on the dog-bone and plate samples provided. This implies that tests and analyses of the actual components are not included in this project.

Lastly, as mentioned in Section 1.2, the results from the study will not imply an exact percentage of recycled PP that should be implemented in the hard trim interior panels but more of a guidance of what could be used. This will provide support for future research for Volvo Cars and guide their upcoming decision making.

1.6 Social and ethical aspects

In a project of this nature, it is crucial to take into account the societal, ethical, and ecological aspects that may be impacted. This section will touch upon these aspects and some possible affects. An ethical consideration that needs to be considered is related to material sourcing and material production. This includes ensuring that the recycled PP used is ethically sourced and not tied to exploitative labor practices or unregulated waste management systems. This aspect is also considered a societal aspect since it is equally important that the recycled PP does not compromise safety features or release harmful substances in any phase of the life cycle.

Moreover, it is important to present the percentage of recycled content and its environmental benefits honestly in the marketing and communication to avoid any suspicions of greenwashing, meaning a company appearing more sustainable than they are (Cambridge University Press, 2025).

Furthermore, it is essential to develop hard trim interior panels that can themselves be recycled after the vehicle's end of life, to maintain the circular economy principles. This includes ensuring that the PP is of high quality to facilitate recycling, as well as ensuring that the panels can be easily separated from the vehicle during waste management. This aspect can also be considered an ecological aspect since the design to easily separate the panels will contribute to a higher amount of material being recycled and thereby minimizing the landfill waste.

2

Research background

This chapter provides an overview of the essential background information related to the project. It outlines key concepts and relevant topics that inform the project's objectives and context.

2.1 Automotive Interior Hard Trim Panels

Automotive trims are plastic components that can be installed both inside and outside of the vehicle. The inside trims, or interior trims, serve both aesthetic and functional purposes. This since they are designed to elevate the visual appeal of the interior while being functional and providing safety. Moreover, the trims are used to conceal the intricate electrical and mechanical components that manage the vehicle's locks, windows, and other features (Shaisundaram & Vignesh, 2023).

The interior hard trims of cars are manufactured using injection molding. The method implies that thermoplastic resin pellets are melted, injected into a mold, and then cooled back to a solid state in a new shape (Shaisundaram & Vignesh, 2023). Injection molding allows for complex geometries with tight tolerances, offers high repeatability and reliability, and is very efficient (Sybridge, 2023). Hard trims manufactured through injection molding provide various vital functions such as protecting passengers from sharp edges and corners, offer good stability and ductility, are capable of withstanding high temperatures, provide stiffness performance when subjected to load, ensuring a tight fit during assembly, and lastly exhibit good impact resistance (Shaisundaram & Vignesh, 2023).

2.2 Polypropylene as a Material

PP is a type of thermoplastic polymer which implies that the material becomes soft and moldable when heated up, and solidifies again when cooled down. This process is reversible, meaning that the material can be heated, shaped, and cooled multiple times without significantly degrading (Press, 2025). The polymer is derived by combining propylene molecules. Most propylene monomer comes from the steam-cracking process where naphtha, which is a fraction of crude oil, is heated to break it down. In this cracking process propylene is mostly a by-product since the target product is ethylene monomer. Because of this propylene is produced at various ratios depending on the crude oil feedstock. Today many cracking processes contain a propylene plant closely connected to being able to effectively collect the propylene

from the cracking process (Shubhra, Alam, & Quaiyyum, 2011).

The melting point of PP is influenced by several factors, leading to a melting point that is not a fixed value, but rather a range of values. One of the key factors is the molecular weight distribution. PP can consist of molecules of varying lengths (molecular weights). The longer chains can interact more strongly, which may raise the melting point, while the shorter chains may melt at a lower temperature. Moreover, the melting point also depends on the crystallinity, which means the degree of crystallinity in the polymer. Higher crystallinity implies more ordered regions, thus not amorphous, which means higher melting temperatures and vice versa. The factor of additives may also affect the melting point of the material. PP is often not a clear material since it is often mixed with various additives and fillers. These additives, depending on what they are, can both raise or lower the melting point. Furthermore, the processing conditions affects the melting temperate. This since the way the polymer is processed can affect the final structure of the PP. For example, slow cooling often implies higher crystallinity, compared with fast cooling that often results in a more amorphous structure. It is also possible that the PP can crystallize into different structures or polymorphs within the material. This means that different areas of the material may have its own melting point. The typical melting point for PP falls within a range of approximately 160°C to 170°C, depending on the specific characteristics and conditions of the material (Prototyping, 2025).

PP is a highly versatile material with a wide range of properties and characteristics. The properties include (British Plastics Federation, 2025), (RT Prototype, 2025):

- **Semi-rigid** - meaning that it combines both flexibility and stiffness.
- **Translucent** - enables some light to pass through while still maintaining its structural integrity.
- **Good chemical resistance** - can maintain the integrity, strength, and functionality even when exposed to harsh chemicals over time.
- **Tough** - ability to withstand physical stress and impact without easily breaking or deforming.
- **Good fatigue resistance** - endure repeated stress or bending without losing its shape or mechanical properties.
- **Integral hinge property** - it can bend repeatedly without cracking.
- **Good heat resistance** - it can tolerate relatively high temperatures before it begins to deform or lose its functionality.
- **Low water absorption rate** - has a low tendency to absorb water or moisture from its surroundings, meaning it is considered hydrophobic.

Moreover, the density of PP is 905 kg/m^3 , which is considered relatively low. The lower density makes PP lightweight, which is beneficial for applications where weight reduction is important, such as automotive parts (British Plastics Federation, 2025).

2.3 Post-Consumer and Post-Industrial Recycled material

When recycled plastic is used, it can be either PCR or PIR. Which of them to use depends on a lot of factors such as the required quality, the available feedstock and the price (Alcion, 2025).

PIR refers to plastic discarded from the industry. It is the material that does not make it to the market and can be waste from packaging, scraps, electronic components, and cut-offs from the production process. Since it has not been used as a product the material is often of good quality and can be recycled and reused for the same product or a new (Alcion, 2025). This also means that the waste is clean and without any contamination, making it easier to recycle (Machinery, 2025).

PCR is plastic that has been gathered, sorted, and processed for reuse after it has served its purpose as a consumer product. In other words, it is plastic that has been used by consumers, recycled, and then repurposed to create new products. Examples of household or commercial waste that contribute to PCR plastic include PET bottles and shampoo containers. The advantages of incorporating PCR into manufacturing include that it minimizes plastic waste in landfills and saves natural resources, since it reduces the need to extract and process virgin raw materials. However, a limitation with PCR plastics may imply a reduction in the quality and durability of the material compared to virgin plastic (Alcion, 2025). Furthermore, inconsistent color dispersion may affect the overall color of the desired part which implies an increase of needed additives such as pigment. The increased additives may in turn affect the mechanical properties of the material (Packaging, 2021).

2.4 Mechanical recycling

To reduce the environmental impact and resource inefficiency of plastics, scholars agree that prioritizing recycling over energy recovery and landfilling is essential. In addition to this, efforts should focus on decreasing plastic production, encouraging reuse, and increasing consumer awareness of waste management (Commission, 2023). One way, and the main way, of recycling plastics is through mechanical recycling. This recycling method implies processing of waste into secondary raw material without substantially changing the chemical structure of the material. In the case of plastics this implies that the polymer chains are not chemically disrupted in the recycling process (Royal Society of Chemistry, n.d.), (Shen & Worrell, 2024).

To convert the plastic waste into secondary raw materials five steps are followed. The first step is to sort and separate the waste according to its shape, density, size, color or chemical composition. The collected mix of plastic will typically include various types, particularly if PCR waste. PIR waste on the other hand is usually relatively pure. PCR waste normally contains non-plastic contaminant, such as small metal pieces, wood chips, or labels, which must be removed firstly. To further enhance the material quality the plastics need to be separated into different types, however, this

task is proven very complex. Multiple methods and techniques are used in various combinations to perform this task. Common methods include, (Commission, 2023), (Shen & Worrell, 2024):

- **Eddy current separator** - when an electric current that occurs when changing the magnetic field within a conductor and is used to separate nonferrous metals.
- **Sink-float separation** - when waste is separated based on the specific weight of the material relative to the fluid.
- **Drum separators/screens** - separates materials based on the particle size.
- **Induction sorting** - when the material is sent over a conveyor belt with a series of inductive sensors underneath that has the ability to locate different types of metal.
- **X-ray technology** - can distinguish between different types of material based on density, and near infrared sensors (NIR), that can distinguish between different materials based on the way they reflect light.

The attainable level of purity implies a balance between energy costs and market demands, this leads to that some impurities are inevitable. The maximum achievable purity that can be accomplished when separating mixed plastic waste is around 94-95%. High-quality recycled materials suitable for manufacturing require a purity level of at least 98%. Because of this, further refining is crucial (Commission, 2023), (Shen & Worrell, 2024).

The next step is if the plastic is not processed at the sorting site, in that case it undergoes a baling process where the material is shredded to make transportation easier (Commission, 2023), (Shen & Worrell, 2024).

The third step implies a decontamination process to remove further impurities and contaminants from the plastic. This is done by washing the material. Either cold or hot water, up to 60°C, may be used even though the usage of cold water may result in an increased use of chemicals and mechanical energy. The wastewater from the washing is often treated in-house for reuse. The washed flakes are then dried until they contain less than 0.1% of the total weight of the flakes moisture and are ready for reprocessing (Commission, 2023), (Shen & Worrell, 2024).

The final step includes that the plastic is ground into smaller flakes. The most applied technique for this is extrusion. This technique implies that the material is firstly blended and then injected in the extruder. There it comes in contact with a rotating screw that forces the plastic flakes forward into a heated barren at the desired melt temperature. The pressure causes the plastic beads to gradually mix and melt as they are forced through the barrel. The melt is then degassed to eliminate oils, waxes, and lubricants. Lastly, the molten plastic is pushed through a sieve to filter out impurities, cooled, and pelletized. After extrusion phase the pellets are ready for the final processing where they are used to create the final product (Commission, 2023), (Shen & Worrell, 2024).

Today, mechanical recycling is the top option for recycling of plastics since it has the lowest carbon footprint and is optimal in terms of minimizing overall environmental

impact. A limitation with mechanical recycled plastics is that it tends to continuously degrade in the process and are thus unable to retain quality after one or more recycling loops (Commission, 2023). Moreover is the potential risk of introduction of impurities, frequently due to inadequate sorting practices (Royal Society of Chemistry, n.d.). Furthermore, a central limitation is that mechanical recycling can only handle specific (homogeneous) plastic types and requires thorough pre-sorting and cleaning. A consequence of this is that the method is unsuitable for a significant portion of end-of-life plastics collected (Commission, 2023), (Shen & Worrell, 2024).

Another consequence of mechanical recycling is that it exposes the material to thermo-mechanical and thermo-oxidative conditions. These conditions can trigger a range of degrading reactions such as chain scission, branching, and eventually cross linking. Chain scission refers to the breaking of polymer chains into shorter segments, leading to the formation of low molecular weight chains, and is the most dominant consequence, see Figure 2.1 (Zhang et al., 2024). The shorter molecular chains, or lower molecular weight, will have a lower boiling and melting point compared to the original molecules (Higginbotham, 2020). Lower molecular weight will also make the material respond easier to stress, since it increases mobility of the molecules. Thus, the strength and E-modulus will be reduced with shorter chains. Longer chains lead to more entanglement which makes the material stretch more before rupturing and have higher impact resistance due to more energy needing to break the bonds (Bamberger Amco Polymers, 2024). The degree of degradation is affected by several factors, including extrusion speed, processing time, presence of oxygen, and temperature (Zhang et al., 2024).

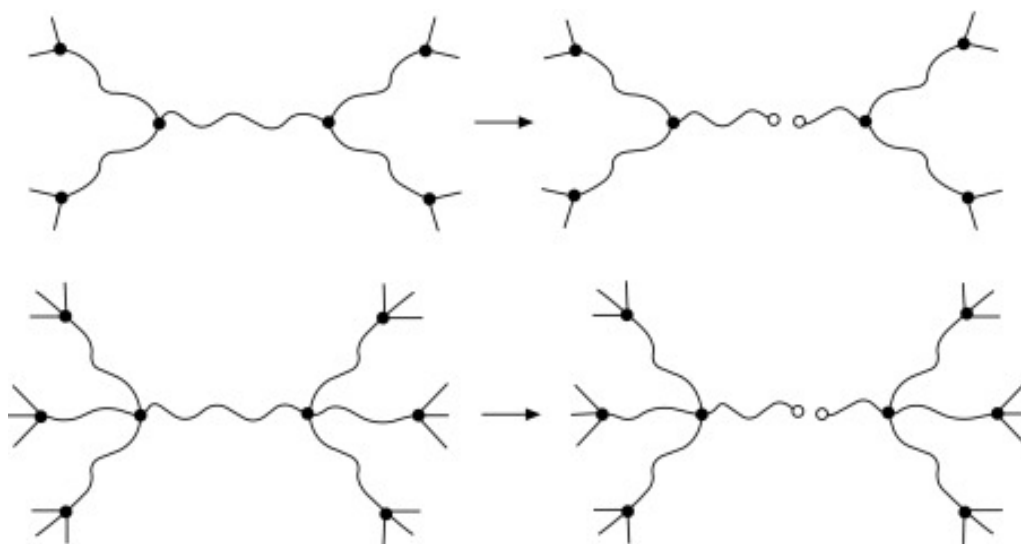


Figure 2.1: Chain scission via (Hollaway, 2013)

2.5 Chemical recycling

Even though plastics are generally recycled mechanically, some plastics can not be recycled this way. The reasons for this may, for example, be because of the charac-

teristics of the material or due to low purity. The low purity may be a consequence of being mixed with other plastics, being composites, being laminated with multiple layers, or containing additives and fillers (Shen & Worrell, 2024). An alternative to mechanical recycling is chemical recycling. The name chemical recycling is an umbrella term that describes a range of different technologies to recycle EoL materials. In common with all different technologies, they include changes in the chemical structure of the material with the intent of producing basic chemicals or feedstock for the chemical industry that can be turned into, in this case, new plastic. Chemical recycling has the capacity to treat more heterogeneous plastic waste streams with certain levels of contamination compared to mechanical recycling, which does not have this potential. However, chemical recycling has other limitations. The high energy intensity of the processes involved makes the method economically challenging, therefore relying profoundly on the demand for recycled feedstock. Furthermore, chemical recycling plants are in need of a stable and continuous supply of feedstock in large enough quantities to remain economically viable. Another issue involves production losses and the resulting changes in yields, which are greatly affected by the quality of the feedstock. In addition, there may be a range of co-products, such as fuels (Commission, 2023).

2.6 Feedstock of Post-Consumer Recycled Plastic

In 2022 Naturvårdsverket did a mapping of plastic flows in Sweden with data collected from 2020. The data is for all types of plastic, not just PP which is the material of interest, but still represents recycling rates in Sweden. From the specific flow of plastic, meaning a specific type of product category that has been separated and not mixed with others, was the total amount of waste 644 000 tons. Packaging (PP plastic) generated the most waste with approximately 320 000 tons. In the mixed flow, plastic made up between 690 000 and 1 million tones. The construction industry generated about 120 000 tons of plastic waste, followed by the automotive and tire industry which contributed with 94 000 tons. These are the largest flows that can be traced back to a product category or source. Of all this plastic waste, approximately 120 000 tons were material-recycled in 2020. More than 1 100 000 tons of the plastic waste went to energy recovery and about 76 000 tons of plastic and rubber waste was used in the cement industry (Naturvårdsverket, 2024).

In 2021 the average plastic waste of a person living in the European Union was 36,1kg. Between 2010 and 2021 the amount of plastic packages generated per person increased by 29% (+8,1kg per person). The total amount of plastic waste in the EU 2021 was 16,13 million tons, of which approximately 6,56 million tons were recycled (Europaparlamentet, 2024).

2.7 Carbon footprint

The CO_2 footprint refers to the total amount of greenhouse gas (GHG) emissions that are produced directly or indirectly by an activity, such as producing a prod-

uct, or accumulated during a product's life cycle. In recent years, it has been used as an indicator of environmental sustainability and can help find hotspots and improvement areas (Scrucca, Barberio, Fantin, Porta, & Barbanera, 2021). The CO_2 footprint is calculated by multiplying the activity data, for example amount of material used, electricity consumed, transportation, with the activity emission factor (Dormer, Finn, Ward, & Cullen, 2013). The emission factor is a value that represent the amount of GHG emitted and can be expressed as a CO_2 equivalent (CO_2e). Since the emissions contributing to global warming are not just carbon dioxide, a CO_2e is used which is a measure of the effect of different GHGs. It converts all GHGs into the equivalent amount of carbon dioxide with the same global warming potential (GWP) (Commission, n.d.-a). The GWP is used to describe how potent a greenhouse gas is based on how long it remains active in the atmosphere. Currently, the GWPs used are calculated over 100 years and carbon dioxide is the reference with a 100 years GWP of 1 (Commission, n.d.-b).

Only using the carbon footprint can be misleading since environmental problems include more than climate change, such as resource use, toxicity impact, and eutrophication. Thus it is important to not only rely on the carbon footprint when evaluating the total environmental impact (Scrucca et al., 2021).

2.8 Tensile test

A tensile test helps to select a material since tensile properties are often included in a requirement list. It determines the material's tensile strength by stretching a sample in a machine until breakage. The sample is often shaped as a dog bone, meaning bigger ends for the machine to grip and a smaller gage that deforms. The primary focus is on creating a stress-strain curve. During the test the force is recorded as a function of the elongation of the sample. That function is then normalized to the dimension of the sample to get the stress-strain curve since then it is independent of the specimens dimensions.

Among the various mechanical tests conducted on thermoplastic polymers, the tensile test is the most poorly understood, with its results frequently misinterpreted and misapplied. Originally adapted from materials exhibiting linear elastic stress-strain behaviors, this test is not always suitable for polymers. Nevertheless, standardized methods like DIN 53457 and ASTM D638 are available for assessing the stress-strain characteristics of polymeric materials (Osswald, Baur, Brinkmann, Oberbach, & Schmachtenberg, 2006).

2.9 Impact test

An impact test is used to evaluate a material's ability to absorb energy during a sudden or impact load. The primary goal is to assess a material's toughness (Callister & Rethwisch, 2017).

Using the absorbed energy the impact strength can be calculated. According to the

ISO 179-1:2023(E) for an unnotched sample the impact strength is calculated as:

$$a_{cU} = \left(\frac{W_c}{h \cdot b} \right) \times 10^3 \quad (2.1)$$

Where W_c is the corrected energy, in joules, absorbed by breaking the test specimen, h is the thickness, in millimeters, of the test specimen, and b is the width, in millimeters, of the test specimen.

2.10 Differential Scanning Calorimetry

Differential scanning calorimetry (DSC), is an efficient analytical tool used to identify and characterize the physical properties of a polymer. Properties such as melting temperatures, crystallization, mesomorphic transition temperatures, meaning the temperatures at which a material transitions between different structural phases, can be determined using this method (RISE, 2025), (Schick, 2009).

The percentage of crystallinity of the material analyzed by DSC is calculated using the following formula (NETZSCH Analyzing & Testing, 2025):

$$\text{Crystallinity (\%)} = \left(\frac{\Delta H_m - \Delta H_c}{\Delta H_m^0} \right) \times 100 \quad (2.2)$$

Where ΔH_m is the measured melting enthalpy, ΔH_c is the cold crystallization enthalpy (if present), and ΔH_m^0 is the melting enthalpy of a 100% crystalline polymer. The value for ΔH_m^0 is the same for each type of material and can therefore be found in literature, for PP the value is 207 J/g. The subtraction that occurs in the numerator, $\Delta H_m - \Delta H_c$, takes the enthalpy area of the melt and subtracts the enthalpy area of the post-crystallization or cold-crystallization, that can be calculated from the DSC-diagram. The result of the calculation gives the crystallinity as a percentage. The amorphous content can be determined by subtracting the crystallinity percentage from 100 (NETZSCH Analyzing & Testing, 2025).

Amorphous materials are defined by a short-range order, with atoms bonded in random and disordered spatial arrangements. The reason for this structure are factors that do not allow the formation of a regular arrangement, usually by a rapid solidification method (Xu & Xu, 2017), (Tanzi, Farè, & Candiani, 2019). Some materials, especially many polymers, can have macromolecules that are efficiently packed in some regions, that produces a higher degree of long-range order, while other regions have a short-range order. This implies that some regions may be crystalline while others are amorphous. Materials with this structure are called semicrystalline materials. In materials that have an amorphous structure the molecules are bonded together by weak bonds, this implies lower mechanical properties compared to materials with a crystalline structure (Tanzi et al., 2019). Because of the more ordered and packed structure in a crystalline material, it will affect the ability to deform. Thus, an increase in crystallinity will lead to a greater stiffness and a higher melting temperature. It also implies reduced ductility, since more order will limit the movement of molecular chains, which makes it more brittle (Chanda, 2013). The

molecular weight will also affect the crystallinity, shorter chains can form crystals more easily and faster since they are not as entangled as longer chains tend to be. However, a material with a lower molecular weight can be weaker in strength even if they have a higher degree of crystallinity (Whisnant, 2022). The crystallite size can also effect the mechanical properties of the material (Whisnant, 2023). Crystallites can make the material less prone to crazing and shear yielding, these are mechanical properties that help to absorb energy (Ludwig & Davidenkov, 2003). Factors that affect the crystalline structure and degree of crystallinity is, for instance, the processing conditions and cooling rates (Strasser & Hanss, 2023).

2.11 Aging of material

To determine how components and materials will change over time, the method aging or artificial aging is used. This method implies that the material or component is exposed to a condition, such as radiation, heat, or chemicals, during a determined period of time to simulate real life aging. The determined time period that a component or material should be exposed to the relevant condition depends on factors such as what material/component it is, in what environment the material/component is expected to be used in, or how the material/component is expected to be used. The advantage with artificial aging is the possibility to accelerate the aging process and get results faster compared to having to age the material or component naturally which might take years (Izdebska, 2016).

When aging is carried out with heat, it is performed in a chamber with a constant temperature where the material is placed. The heat will cause thermal degradation, which in the case of a polymer implies a change in the structure due to shortening of its chain. Thermal degradation can occur in the whole volume of the polymeric material and will affect the properties of it. Thus it is important to understand what influence aging and degradation have when choosing and sourcing a material, not only for the main use, but also for storage of the material and recycling (Izdebska, 2016).

Furthermore, the crystallization will also be affected by the heat. A temperature closer to the melting temperature during a longer time period will enable more movement of the polymer chains. They can fold into a more structured order, and an increase in crystallinity will occur (Nurazzi et al., 2023).

2.12 Perceived quality

Perceived quality (PQ) refers to the impression the customer gets of a product, service, brand, or business derived through sight, sound, touch, and scent (Roffey, n.d.). Having the term "perceived" in its name suggest a factor of subjectivity, but it is not fully subjective or objective. Though PQ is how and what the customer feels about a product, which will be person depending. A first impression and opinion is formed within minutes and determines if a customer trust a product, if it is of high quality or not. What is evaluated is often not tied to actual reliability, such as

2. Research background

strength, durability. Therefore it is important to consider PQ so that the customer will accept the product, but also develop them to be reliable (Solin & Curry, 2023).

At Volvo Cars perceived quality on interior plastic components is done by analyzing the color and gloss of the material. This implies both visual observation and measuring of the material and comparing with a master (the reference). The visual observation is performed in a light booth that illuminates a predetermined amount of light. In the booth the component is observed from different angles next to the master. The color, gloss, embossing (surface), and defects are of interest. Since the assessment is done by humans there is a risk that the result is subjective. Therefore, it is always done by at least two people, and if they disagree a third party is brought in. Measurements are also conducted to compare with the visual outcome; however, greater emphasis is placed on visual assessment, as it reflects what the customer will ultimately perceive. This implies that if a material passes visual assessment but measurements indicate it falls outside the specified tolerances, it will still be considered acceptable (Jacobsson & Ljungholm, 2025).

Measured parameters are color and gloss, which is done using a spectrophotometer tool and a glossmeter respectively. A spectrophotometer illuminates the sample with a controlled light source and measures how the sample interact with the light. A solid sample will absorb some of the wavelengths from the light and reflect some. The reflected light hits a detector that measures the intensity of specific wavelengths of the visible spectrum. For example, if a sample absorbs all light over visible ranges and reflects none of visible wavelengths, it will appear black (X-Rite, 2022). Since there are many parameters that affect how colors are perceived by human eyes, the International Commission on Illumination (CIE) has created a model that standardized and simplifies color communication. It is called L^*a^*b or CIELAB, and uses a color space, see Figure 2.2, to distinguish color differences with three values: L, a; and b.

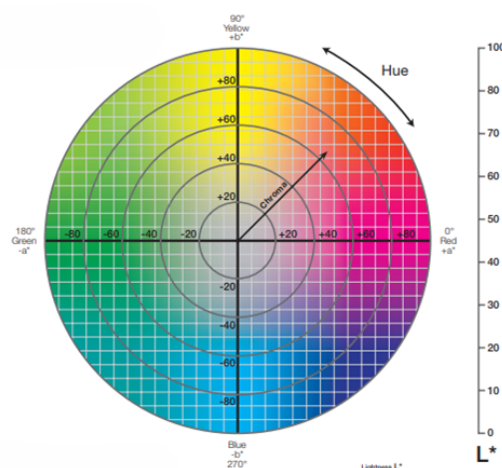


Figure 2.2: Color space used in PQ via (Mouw, 2018)

"L" stands for lightness; "a" represents the green-red axis, and "b" the blue-yellow axis, and these are the values the spectrophotometer measures. The master is set at

the origin of the circle which the measurements are compared to, giving the values: ΔL , Δa , and Δb (Datacolor, 2023).

The gloss, or specular reflection, of the material is measured with a glossmeter. It projects a beam of light at a fixed intensity and angle. The amount of reflected light at the same but opposite angle is measured by a detector. The result is given in Gloss Units (GU) which is a scale ranging from 0 to 100, where 0 is perfectly matte and 100 is glossy. It is based on a reference that is a highly polished black glass standard with a defined 100GU at the specified angle (Instruments, 2025).

2.13 Polykemi's and Rondo's functions and processes

A primary part of Polykemi's industry implies working with recycled material. This means that Polykemi is not the original source of the material that they use. Instead, they obtain and purchase recycled material. As a result, it becomes crucial to know the origin of the recycled material and prioritize traceability. The purpose of this is to understand its previous use, identify the raw material, and verify that the material is in fact recycled. To do this Polykemi has to work closely with their sources and rely on their trustworthiness. As a result, they mainly source recycled material from manufacturing companies in the form of PIR material, as they can trace the raw material throughout the entire production process, and less from recycling companies where the origin is less traceable. Comprehending the origin of the material is easier to do with PIR material due to the fact that it is mainly bought directly from manufacturing companies that handle the material from raw material. Sources of PIR material can include, for example, packaging, spills, and nonwoven fabrics. The traceability with PCR on the other hand is more difficult. The reason for this is that the origin of the material is most often unknown. Sources of PCR material can, for example, come from communal recycling (chairs, plastic crates, toys etc.) and household recycling (food packaging, bottles, bags etc.), but can also be marine ropes and ship's ropes (Axrup et al., 2025).

Polykemi's PCR material is delivered to them from their subsidiary Rondo, who handles the upgrading of the sourced recycled material. This implies to upgrade sourced recycled material of inadequate quality into better quality. Polykemi receives re-granulated PCR without contamination such as heavy metals, paper remnants, or wood chips. Before arriving to Polykemi and Rondo the material has undergone many processes such as being collected, sorted and washed. These processes are not usually being handled by the same operators, thus the traceability and origin is difficult to determine. The long process and many steps to obtain the PCR material require a well-built infrastructure that makes the PCR material more expensive than the PIR material. The many steps of the process also lead to a higher CO_2e compared to the respective PIR material. This is the reason why PCR is currently not used as widely. At Polykemi PCR material is only used when requested by the customers (Axrup et al., 2025).

The process of Polykemi being able to deliver PP components consisting of recycled material begins at Rondo. The PCR PP arrives to Rondo mixed and shredded, ahead of this it has already been washed, see Figure 2.3. Despite the fact that the material has been washed it is in the majority of cases still dirty and contaminated, for example containing traces of metal, paper remnants or wood chips. To determine if this is the case, lab tests on the received PCR PP is performed. These test include for example an XRF-test, or X-ray Fluorescence, that determines if there is any contamination, mainly heavy metals, in the material.



Figure 2.3: The shredded PCR PP that arrives to Rondo

To remove dirt and contamination the material is filtered through an erema extruder machine. This machine uses a laser filter to remove any impurities and then granulates the material, see Figures 2.4, 2.5, 2.6, 2.7. Following this step, additional lab tests are performed, where the now filtered granulates, are again examined to see if they contain dirt or impurities. Other mandatory lab tests are melting index, fluidity, and mechanical properties to ensure that the quality is sufficient. After these tests, the material is labeled according to its quality. After labeling, the granulate is ready to be sent to Polykemi for production of the requested final material-compound (Axrup et al., 2025).



Figure 2.4: The erema extruder machine that removes contamination



Figure 2.5: The extruded contamination by the erema machine



Figure 2.6: The granules created by the erema machine



Figure 2.7: Closeup of the granules

The granulate arrives at Polykemi from Rondo. Polykemi's task is then to create a material compound that is requested by the customer. This compound is made by mixing granulate from suppliers and qualities to obtain the desired properties. Other additives such as pigment and fiberglass are also added, depending on the customer's requirement. Virgin material is also added to the compound to stabilize

it and obtain better quality, but also to facilitate the coloring of the material. Since the PCR material contains a mix of colors, additional pigment is required to receive the desired color. To ease the coloring some virgin material may therefore be added since it is easier to color. When the desired mix is completed, the compound is then put in an extruding machine that uses two screws and heats the mixture to 245-250°C where it is extruded into long spaghetti-like strings, see Figures 2.8 and 2.9. They are then immediately cooled down in water and dried. Finally, they are cut into new granulates and packaged, ready to be sent to customers (Axrup et al., 2025).



Figure 2.8: The spaghetti-like strings cooling down in water right after being extruded



Figure 2.9: The spaghetti-like strings drying and on their way to be cut into granules

Regarding the available feedstock of PCR PP it is good and sufficient according to Polykemi. Furthermore Polykemi states that they are able to produce upgraded PCR PP of good and consistent quality even if the source of material varies (Axrup et al., 2025).

2.14 Sample Production Details

In this project, the material samples that have been analyzed and tested have been provided by Volvo Cars' supplier Polykemi. The samples were produced using the method mentioned in Section 2.13. On the request of Volvo Cars', they delivered six variants of plastic to investigate, all with a different percentage of recycled plastic in them. All samples were made with the same amount of additives and color pigments for charcoal solid. The additives were 17% of talc, UV, impact resistance, and scratch resistance. The different variants were as follows:

- 30% PIR PP, 45% virgin material, additives
- 30% PCR PP, 45% virgin material, additives
- 40% PCR PP, 35% virgin material, additives
- 50% PCR PP, 25% virgin material, additives
- 60% PCR PP, 15% virgin material, additives
- 70% PCR PP, 5% virgin material, additives

An amount of 35 dogbones of each percentage and a number of 10 plates of each percentage were provided. They were produced using injection molding with the following settings:

Dogbones:

Injection molding: Arburg 470C screw Ø 35mm

Clamping force: 50 ton

Temperature profile cylinder: 230 – 230 – 230 – 220 – 200 – 40

Temperature tool: 40°C

Plates:

Injection molding: Arburg 420C screw Ø 30mm

Clamping force: 100 ton

Temperature profile cylinder: 240 – 240 – 235 – 235 – 230 – 40

Temperature tool: 50°C

3

Methods

This chapter outlines the methods utilized in the project, detailing the procedures and techniques used. It also provides a rationale for the selection of these methods, explaining their relevance and suitability for addressing the research objectives.

3.1 Literature review

The project commenced with a literature review to establish a broader perspective regarding the background for the project and acquire knowledge on relevant subjects such as PP as a material, different recycling methods, the tests that was to be performed in the project etc. The literature review was performed by brainstorming relevant and important subjects to understand and examine. When the preliminary list was completed the research began by searching for literature and sources related to the subjects. Search engines used for this task were Google, Google Scholar and Chalmers Library. The result of the literature review can be found in the research background, see Chapter 2.

3.2 Interviews and study visits

Interviews were held with personnel at Volvo Cars, Polykemi and Rondo. The aim with the interviews was to collect information on how processes are performed and gain more understanding regarding the subject. The main study visit was made to Polykemi and Rondo located in Ystad where an interview with Johan Svenmo, Patrik Axrup, and Patrik Lindqvist was held. At Volvo Cars interviews were conducted with Hanna Ljungholm and Inger Jacobsson from the PQ department. The interviews that were conducted were unstructured to allow the respondent to speak freely and elaborate on their thoughts. In an unstructured interview, the questions and in which order they are asked do not have to be set before. It is a flexible way of interviewing adapting the conversation to the situation and following interesting threads that emerge during the interview (George, 2022a). They are usually used for qualitative data, meaning non-numerical (George, 2022b). Questions were prepared beforehand but were asked as deemed appropriate. They were recorded and notes were also taken during the meeting. Since most of the information from the interviews was used as background information, no transcription was done. Instead, a summary of the notes was done which can be found in the Appendix A.

3.3 Aging

To determine if and how the materials would be affected by time, aging was carried out, see Figure 3.1. 20 samples of each percentage were aged in 80°C without humidity, ten samples for 500h, and ten samples for 1000h. 1000h corresponds to 3 years in hot market, mentioned in Figure 3.1. If following Volvo Cars' standards, see Figure 3.2, the samples should be aging in 75°C, but in this case 80° C was used instead, as an oven with that temperature was available during the short time span of this project. The aging was performed without no humidity because PP is a hydrophobic material, see section 2.2.

2.1.29 Long Term Heat

Applicable area:

All components according to job split.

Purpose:

Determine how components will handle long time heat influence. Logged part temperature at APG in Arizona at 45°C ambient temperature, T(45°C)-5°C, can be seen in the table below. Corresponding to approx. 3 years in hot markets.

Test method:

The tests refer to complete parts assembled as in a vehicle. Oven ageing with air circulation according to **SS-ISO 188:2011** (3-10 times/hour).

Temperature/time zones

Figure 3.1: Description and purpose of aging at Volvo Cars

- 95°C ± 2°C/1000h applicable to horizontal part of steering wheel area (also area that can become horizontal when turning the wheel, eg steering wheel housing and deco)
- 90 ± 2°C/1000h, applicable to: instrument panel (IP) area close to windscreen, upper top cover area, lower top cover area, textile seat and door panel insert upholstery, plastic components on rear seat back rest adjacent to parcel shelf. Wood deco parts on IP and Tunnel Console.
- 85 ± 2°C/1000h, applicable to: steering wheel area (other than as described in b) II), roof lining area, A and C/D (Sedan models) pillar panel areas. . Upper part of tunnel console (incl. gear shift lever complete).
- 75 ± 2°C/1000h, applicable to: IP lower panel area, upper and lower door panel area, floor upholstery and plastic components; luggage compartment upholstery and plastic components and load floor.
- 75 ± 2°C/1000h, applicable to leather and tri cot plastic seat upholstery.

Figure 3.2: Highlighted part shows the temperature these samples should be aging in

The samples were put into bags of ten and marked with their respective percentage and for how long they would be aged, see Figure 3.4. All the bags were then spread out on the floor of a car that also would be aged for the same amount of time and the same temperature, see Figures 3.3, 3.4, and 3.5. The car, with the samples placed on the floor, was then driven into a big "oven" in the form of a container with an inner temperature of 80° C. Before the aging began the samples were taken out of their respective bags and spread out upon it on the car floor. After three weeks, meaning 500h, the first samples were removed from the oven and after six weeks, meaning 1000h, the rest were collected.



Figure 3.3: Bags filled with samples placed on the car floor



Figure 3.4: Close-up of the bags placed on the car floor



Figure 3.5: Samples spread out on the car floor during aging

3.4 Tensile tests

Tensile tests were carried out in order to be able to measure the mechanical properties of the materials. All tensile tests were performed at room temperature in the material lab at Volvo Cars. A tensile testing machine by the brand Zwick Roell was used. Five samples were used for each aging point, thus 15 in sum, for one material, and 90 samples in total were tested.

Before the tests could be performed the test specimens were marked with two reflexive points with a distance of 80mm using a machine, see Figure 3.6 and 3.7. The points are marked for two cameras to be able to measure the distance during the elasticity phase.

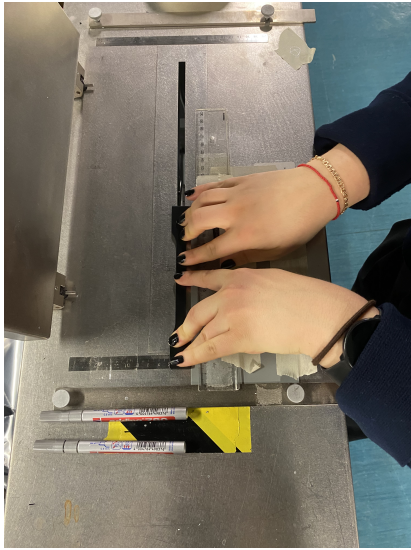


Figure 3.6: Putting on the reflexive points



Figure 3.7: Test specimen with reflexive dots

The width and thickness of the rectangular middle part of the samples was measured and then entered in the machine program called TestXpert. The sample is first locked at the top, then the machine resets the force to 0 newton in the specimen, and then the bottom part of the sample is secured. A distance of 115mm was established between the locking points in the machine. The test started with that the two cameras located the marked reflexive points, thereafter the machine began to apply a force and drag until the sample broke, see Figures 3.8 and 3.9.

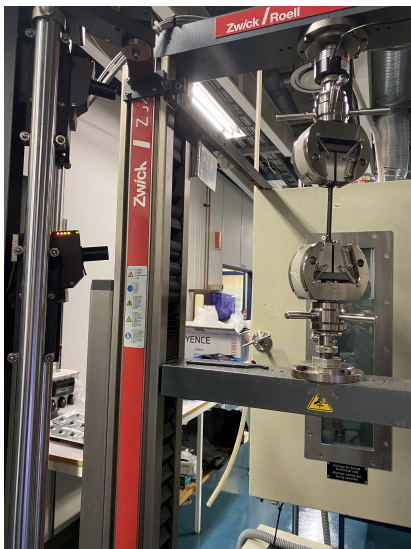


Figure 3.8: Cameras locating the reflexive points



Figure 3.9: Test specimen during tensile test

After the elastic phase the cameras stopped measuring the distance and from it was based on the lower beam in the machine. TestXpert produced a stress-strain curve for each test and a list of other measurements. Among these measurements

E-modulus, stress at yield point, strain at yield point, and strain at breakage were deemed necessary to further analyze. The E-modulus calculated by the program was determined using the secants method. For the secants method the beginning of the tensile modulus determination was set to 0,1% strain and the end to 0,15% strain. In this case, the ultimate tensile strength, meaning the maximum stress, and the yield stress had the same value, therefore, only one had to be evaluated. The values were averaged and visualized in bar charts for easier comparison, see Section 4.1 for all results. After the first tests of the unaged material were performed, it was discovered that what was thought to be 30% PCR PP was actually 30% PIR PP due to a miscommunication the supplier. The data was still used in the analysis since it had been obtained, but for further tests only five samples were used, as for the other material. Thus, the result for the unaged 30% PIR PP consists of the result from ten samples.

3.5 Impact tests

The execution of the impact tests was carried out with ISO 179-1:2023(E) as a guideline. The only part that deviated from the standard is that the absorbed energy, W , by the machine should be in the range of 10% to 80% of the available energy at impact, in this case meaning between 0,75 J and 6,0 J. To fulfill this the machine needs to be calibrated carefully, which requires many additional samples to perform impact tests on. The reason why this could not be achieved in the project was simply that there were not enough samples to calibrate the machine sufficiently. This led to the fact that 20, of the total 90, impacts tests had values greater than 80% of the available energy at impact. According to Kai Kallio, Material Specialist at Volvo Cars, who helped with the execution of the impacts tests, this is from Volvo Cars' perspective, acceptable since the ISO standard is typically used as a guideline rather than strict rules. However, it is a potential source of error that should be considered when analyzing the results.

The initial step of the impact testing involved conditioning the samples by placing them in a conditioning room with the following parameters: $23^{\circ}\text{C} \pm 2^{\circ}$ and $50\% \pm 5\%$ humidity. The samples were placed in the conditioning room for approximately 22h, see Figure 3.10.

Before actual testing could be carried out, the machine needed to be calibrated. This was done by performing impact tests on some unaged 30% PCR PP samples and changing the size of the gap where the samples lay in the machine, depending on the absorbed energy of the tests used for calibrating. The bigger the size of the gap the lower the absorbed energy, since the supports of the specimens moves further apart. The goal was to get an absorbed energy around 5 J, meaning approximately 71% of the allowed absorbed energy, since the hypothesis was that the unaged 30% PCR PP samples were thought to be on the tougher side. This would imply that the other samples would hopefully be in the allowed range as well. The allowed range is, according to ISO 179-1:2023(E), between 10% and 80% of the available energy at impact. The size of the gap that ended up being used for the testing was 31,55 mm.

3. Methods

Ideally, the machine calibration would include testing on all of the different samples to make sure that all would be in the allowed range. Unfortunately, there were not enough extra samples available apart from unaged 30% PCR PP samples, which is why these were used. This led to the machine being not perfectly calibrated.

The next step included cutting of the bigger end parts of the samples to be able to place the sample straight later on in the impact testing machine. The cutting was done with a cutter, see Figure 3.11, and the result after the cutting is shown in Figure 3.12.



Figure 3.10: Conditioning the samples

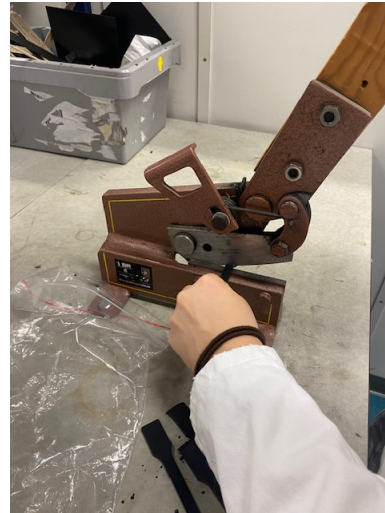


Figure 3.11: Cutting the samples into the correct size

The length of the cut samples does not have to be exactly the same for every sample according to ISO 179-1:2023(E). When calculating the impact strength, the ISO standard only takes into account thickness and width. The next step was to perform the actual impact tests. This was carried out by placing and aligning the cut samples in the machine, see Figure 3.13.



Figure 3.12: How the samples were cut



Figure 3.13: A sample ready for impact testing in the machine

Then the testing could start, all tests were performed at room temperature. Two buttons were pressed at the same time, which caused the pendulum in the machine, see Figure 3.14, drop and hit the sample placed at the bottom. Thereafter it was observed if the sample broke completely, hinge broke, partial broke, or did not break at all. Moreover, the absorbed energy shown at the top of the machine on the display, see Figure 3.15, was noted.

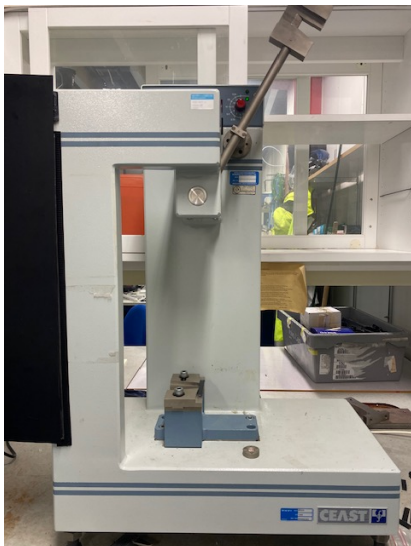


Figure 3.14: The impact test machine



Figure 3.15: The result shown by the machine after a test

This was repeated 15 times for each material, five samples for each aging point, in total 90 tests. When all impact tests were performed and all results were noted, the impact strength calculations could be performed. The Charpy impact strength

of unnotched specimens, a_{cU} , expressed in kilojoules per square meter, is calculated with the following formula:

$$a_{cU} = \frac{W_c}{h \cdot b} \times 10^3 \quad (3.1)$$

where W_c is the energy, in joules, absorbed by breaking the test specimen, h is the thickness, in millimeters, of the test specimen, and b is the width, in millimeters, of the test specimen.

3.6 Differential Scanning Calorimetry

To perform the DSC test, small samples were cut from the original dog bone samples, each containing different percentages of PCR PP. To be able to perform the test the samples needed to weigh between 5-10 mg. They were carefully cut with knives and weighed to ensure that the weight was within the required range, see Figure 3.16. Once verified, the samples were placed in the small DSC pan to confirm they fit properly, see Figure 3.17. Two samples were cut from each percentage of the unaged material and two samples each of 40% and 70% PCR PP that had been aged for 500h, a total of 16 samples. The reason for why aged 40% and 70% PCR PP was selected was to examine the two tests with the greatest difference regarding recycled content and to examine if aging affected the DSC result. The 30% PIR PP material aged for 500h would have given a greater difference in recycled content, but since this was the reference sample and not a material of interest in this project, the aged 40% PCR PP was used instead. The reason why the aged 30% PCR PP was not examined is because it was not done aging at the point for the DSC test. However, using the 40% PCR PP and 70% PCR PP was sufficient enough for the purpose of investigating if and how aging affected the crystallinity.



Figure 3.16: Cutting out the small samples

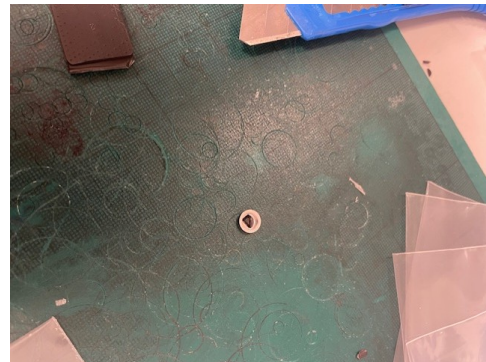


Figure 3.17: Making sure the samples fit in the pan

The samples were then prepared for testing. It started with a pan that was placed on a scale that was then tared so that the sample could be placed there and weighed again, see Figure 3.18. A hole was punched into the lid using a needle to prevent pressure from building up in the pan during the test, see Figure 3.19.



Figure 3.18: Weighing the samples



Figure 3.19: Making a hole in the DSC-pan lid

The lid was then placed on the pan, see Figure 3.20, and then placed in a tool that sealed them together by pressing down the lid, see Figure 3.19.



Figure 3.20: Placing the lid on the pan with the sample in



Figure 3.21: Pressing the lid and pan together

The prepared sample could then be placed in the DSC-machine, see Figure 3.22. In the computer program, called STAR, the respective weight of the samples and placement of the pan in the machine were entered to keep track of the different samples.

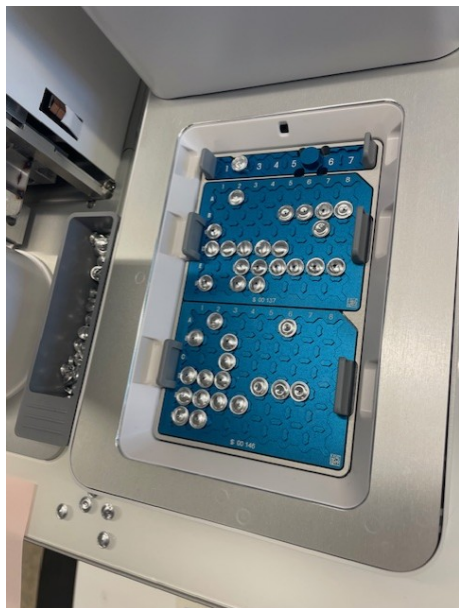


Figure 3.22: Placing the pans in the machine



Figure 3.23: The machine performing the DSC-test

The machine had been programmed to first melt the material, going from -50°C to 200°C , then down to -50°C to once again be heated up to 200°C and melt the material a second time. These temperatures are based on the melting point and the glass transition temperature that PP has. In the machine the temperature changed with $10^{\circ}\text{C}/\text{minute}$. In addition, $50\text{ml nitrogen}/\text{min}$ was pumped into the surrounding environment in the machine prevent the material from reacting with its surroundings. The 16 tests lasted approximately 20h altogether. When one test was performed, the machine automatically performed a new test on the next sample, see Figure 3.23. Afterwards a graph for each sample was given showing the heating and cooling process in three separate curves, see Figure 2.10.

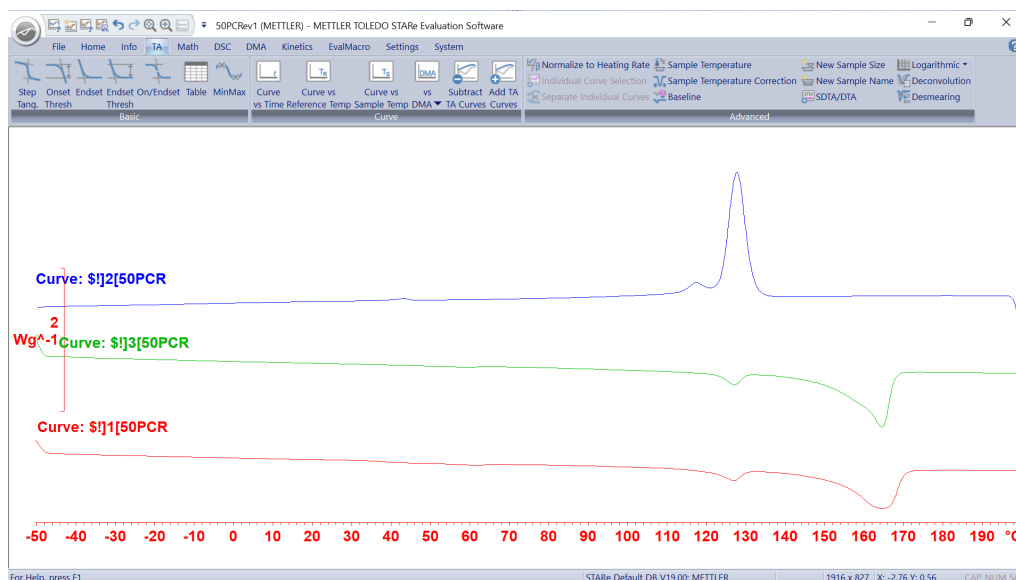


Figure 3.24: Example of graphs from the DSC-test for 50% PCR PP

Using STARe Evaluation software the enthalpy could be calculated for the heating curves, see curve 1 (red) and curve 3 (green) in Figure 2.10, by doing integration. Curve 2 (blue) was not used because it shows the cooling stage of the process which is not of interest. From the first heating curve, the crystallinity can be calculated on the basis of thermal history and how the material has been processed, such as using injection molding. In the second heating curve, all previous processing and its influence are removed, and the pure material can be analyzed (BARLOG Plastics GmbH, n.d.). Since the material in the final component is made by injection molding, the crystallinity in the first curve is more accurately represented. Therefore, only the crystallinity from the first curve will be analyzed.

Notice that there is a big peak on each graph with a smaller peak on the left. A peak represents that the material melts. The enthalpy, and in turn the crystallinity, was calculated separately for both peaks together, only the big peak, and only the small peak. There was no clear smaller peak for 30% PIR PP and thus the crystallinity could only be calculated for the big peak. Since two tests were performed for each material, the average was taken of them and then visualized in bar charts. Furthermore, the peak temperature, meaning the melting temperature, was also illustrated, see Section 4.3 for results.

3.7 Perceived Quality

Perceived quality tests were carried out to determine the perceived quality factors of the recycled PP samples. The first test performed was to visually investigate the samples against the master, also called the reference material, in a light booth. In this case the master was a PP plate with the identification number 9123691, with a uni grain surface, in the color charcoal-solid and the value 1,9 in GU. The light-settings of the light-booth was set to D65, 6500 Kelvin and 1329 lux, this was to

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represent the environment of daylight. The samples, one at a time, together with the master, were then placed in the light booth beside each other to visually investigate the differences regarding color, gloss, embossing and defects, see Figure 3.25 and 3.26. The tests were performed by the two experienced perceived quality operators Hanna Ljungholm and Inger Jacobsson.

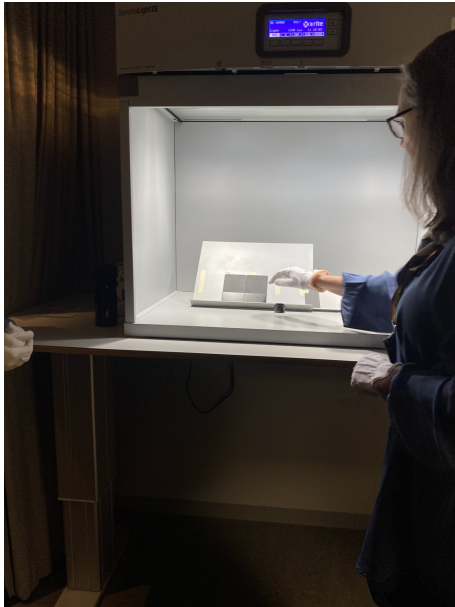


Figure 3.25: Samples in Spectralight



Figure 3.26: Samples in Spectralight

The next test included measuring the color of the samples. This was done using a spectrophotometer, see Figure 3.27. When using this tool, different nozzles can be used to determine how much light should be allowed in during the test. In this case the tool was set to the light-setting D65 with a specular component included (SCI), this to represent the environment of daylight. The test begun by measuring the master and setting its measurements to represent the origin. Thereafter, the samples were measured one by one and their differences were compared with the set origin. Three measuring points were taken for each sample. The tests were performed simply by pressing the nozzle of the spectrophotometer against the sample and taking the measurement, see Figure 3.29. The results were given in delta L, a and b. The color and light tolerances for dark interior colors, as appropriate for the samples in these tests, are as follows:

- ΔL (Lightness): Tolerance ± 0.5
- Δa and Δb (Color components in the a- and b-axes): Tolerance ± 0.2



Figure 3.27: The Spectrophotometer tool used to measure the color of the material



Figure 3.28: Different nozzles for the tool that decides how much light should be let in



Figure 3.29: The Spectrophotometer in use

The last test was to measure the gloss of the samples. This was performed using a Glossmeter, see Figure 3.30. The test began by firstly measuring the GU of the master, which in this case was measured to 1,9. After that, the samples' GU were measured one by one and noted, also taking three measuring points for each sample. The tests are executed by simply pressing the Glossmeter on the sample and taking the measurement, see Figure 3.31. The gloss tolerance for dark interior colors, as appropriate for the samples in these tests, is $\pm 0,3$.



Figure 3.30: The Glossmeter tool

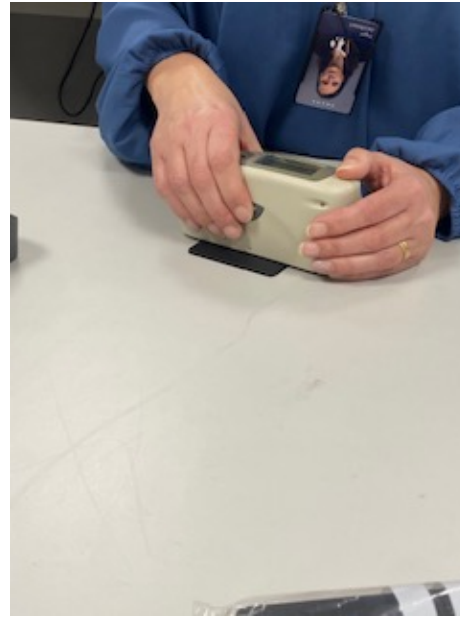


Figure 3.31: The Glossmeter in use

Using the three measuring points for each parameter, an average was calculated to compare with the reference and create bar charts. These can be seen in Section 4.4.

3.8 Calculation of Carbon footprint

The CO_2 footprint calculations are based on CO_2e data supplied by Polykemi. The values are based on Cradle-to-gate ISO 14044:2016, background data Ecoinvent 3.9 evaluated with Environmental Footprint 3.1. Moreover, the values are based on the samples provided and used in the project, which in turn come from a PCR PP source in Sweden with washing in Sweden. However, the PCR PP provider has not yet fully completed their LCA which implies that the provided CO_2e values may be considered indicative at present. If future sourcing were to come from other countries, these values would most likely be higher considering the additional need for transport and the energy type used when washing (Axrup et al., 2025).

The CO_2e values used in the calculations are the following (Axrup et al., 2025):

- 30% PIR PP: 1,55 kg CO_2e /kg
- 30% PCR PP: 1,63 kg CO_2e /kg
- 40% PCR PP: 1,44 kg CO_2e /kg
- 50% PCR PP: 1,24 kg CO_2e /kg
- 60% PCR PP: 0,90 kg CO_2e /kg
- 70% PCR PP: 0,85 kg CO_2e /kg
- Virgin PP material: 2,16 kg CO_2e /kg

The weights used in the calculations are presented in Table 3.1 and were provided by Emma Johansson (personal communication, April 3, 2025), a developer at Volvo

Cars. They are based on a car of the size of Volvo Cars' XC40, which approximately weighs 1 800kg (Volvo Car Sverige AB, 2020). Only parts consisting of the used material, recycled PP, are used in the calculations, these values are written in bold.

Table 3.1: The part weights of the hard trim interior panels

Part:	Amount of part:	Material:	Weight/part (g):	Total weight (g):
A pillar upper	2	Textile covered PC/ABS	382	764
A pillar lower	2	Recycled PP	77	154
B pillar upper	2	Virgin material	794	1588
B pillar lower	2	Recycled PP	553	1106
C pillar upper	2	Virgin material	484	968
C pillar lower	2	Virgin material (in some cars recycled PP)	639	1278
Belt outlet	2	PC/ABS	137	274
Sill front	2	Recycled PP	228	456
Sill extension left	1	Recycled PP	256	256
Sill extension right	1	Recycled PP	278	278
Sill rear	2	Recycled PP	292	584
Brackets sill rear	2	Fiberglass reinforced PP (recycled PP)	22	44
IC ramp	2	Fiberglass reinforced PP (recycled PP)	164	328
Bracket D pillar	2	Fiberglass reinforced PP (recycled PP)	138	276
Tail gate panel	1	Recycled PP	2112	2112
Panel window front left	1	Recycled PP	471	471
Panel window front right	1	Recycled PP	365	365

Figure 3.32 shows the parts in Table 3.1.

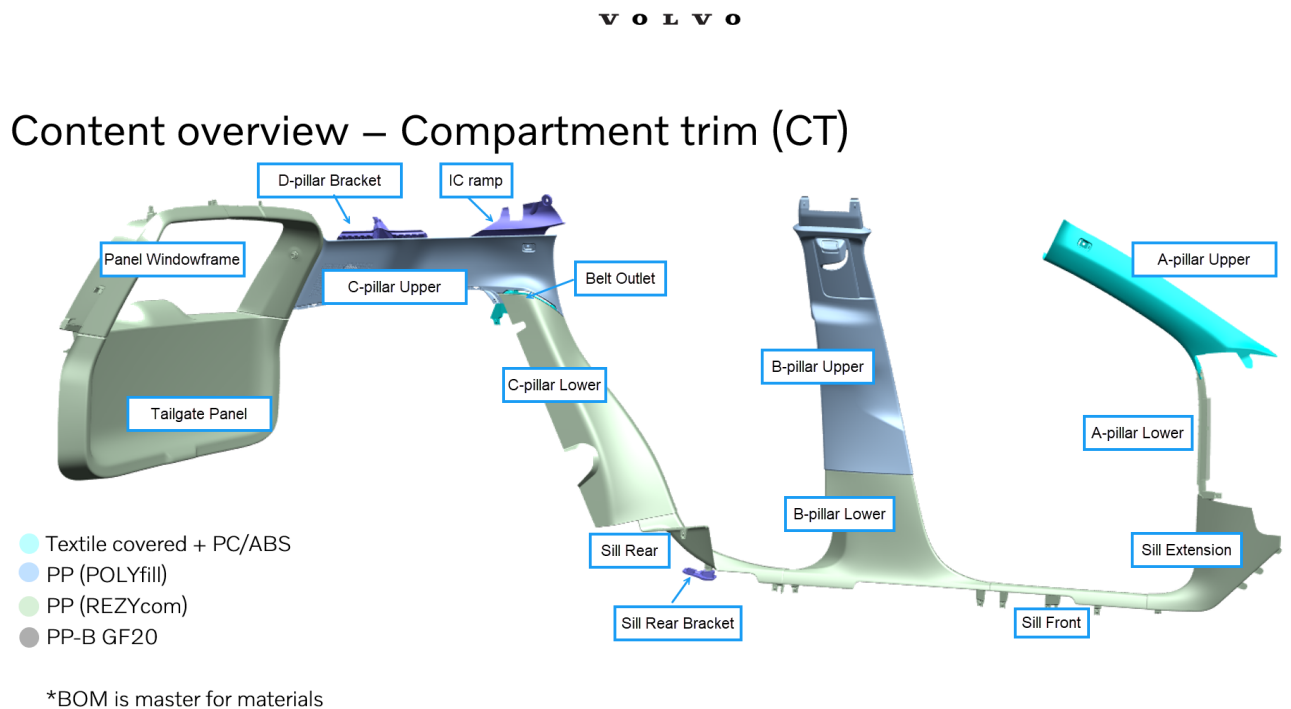


Figure 3.32: The hard trim panel parts with their separate names

The CO_2e calculations consisted of adding all the weights of the parts consisting of the material used, recycled PP, which gives the total weight of the parts with the relevant material. Thereafter the total CO_2e was calculated by multiplying the total weight together with each of the CO_2e values for the different types of

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recycled PP. When the values were given, they were also converted to the carbon footprint of a 33cl aluminum can of Coca Cola to put the value in perspective (CO2 Everything, n.d.). An approximation of 200 000 cars produced a year was used in the calculations, this is based on the size of Volvo Cars' factory in Torslanda (Volvo Car Sverige AB, 2024).

4

Results

This chapter presents the results obtained from the various tests conducted during the project. It provides a descriptive overview of the findings, highlighting key data and observations.

4.1 Tensile tests

The performed tensile tests results is presented in stress-strain curves and a list of measured parameters, see Appendix A.2. The following parameters were used to illustrate the trends in mechanical properties in bar charts:

- E_t [MPa] - E-modulus
- σ_Y [MPa] - Stress at yield point
- $\varepsilon_Y(\text{corrected})$ [%] - Strain (elongation) at yield point, corrected means it has been adjusted to better reflect the actual deformation
- ε_B [%] - Strain at breakage point

Note that in the bar charts, the bars representing unaged 30% PIR PP, consist of a mean value calculated from ten test results instead of five, as for the rest. This is due to a misunderstanding that the unaged 30% PIR PP was initially thought to be unaged 30% PCR PP.

The bar charts for the E-modulus, stress at yield point, strain at yield point and strain at breakage can be seen in Figures 4.1 - 4.4. The error bars represent the range between the lowest and highest values.

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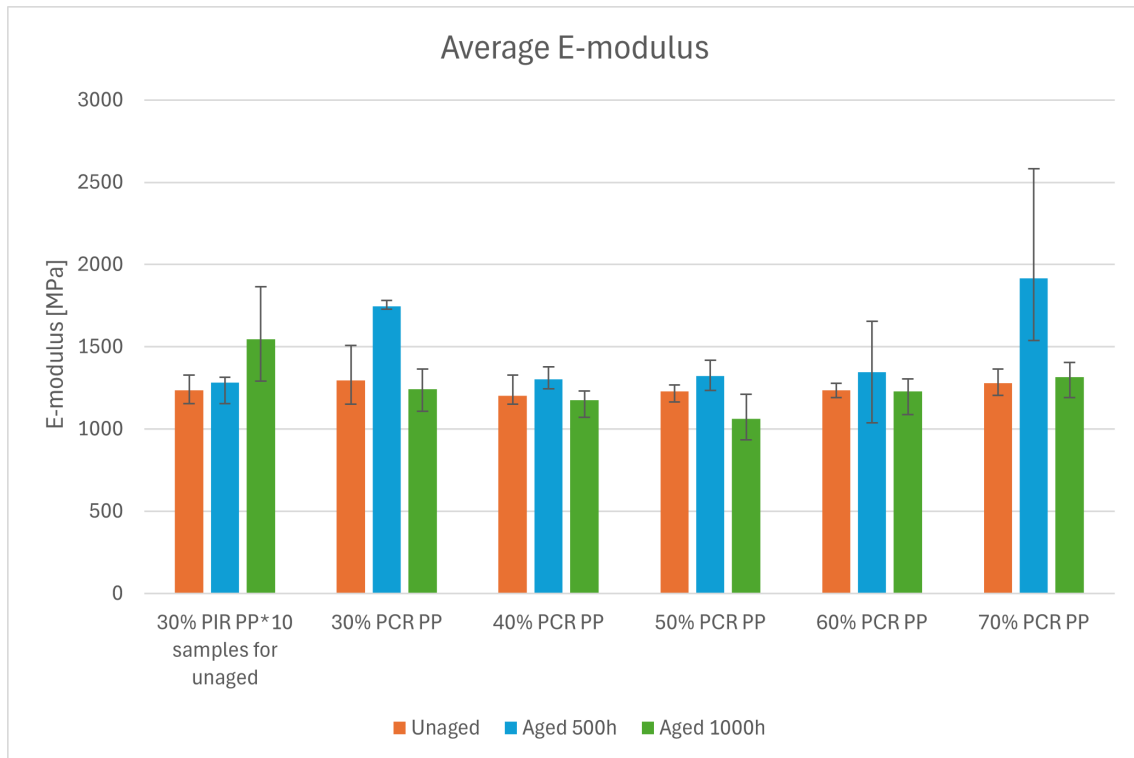


Figure 4.1: The average E-modulus

The E-modulus has a, in general, balanced trend. Exceptions are 30% PIR PP aged 1000h, 30% PCR PP aged 500h, 50% PCR PP aged 1000h, and 70% PCR PP aged 500h which all show different amounts of variance.



Figure 4.2: The average stress at yield point

The stress at yield point have an overall increasing trend, both between material groups and within material groups. The material groups 30% PIR PP and 30% PCR PP are the only exceptions.

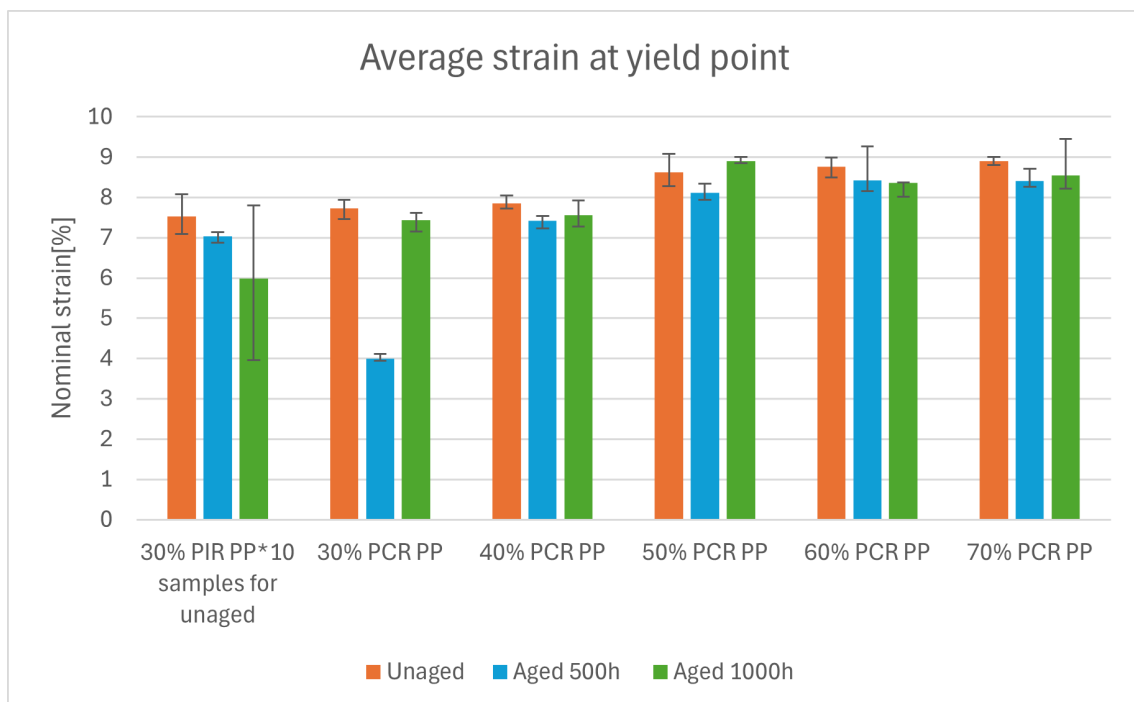


Figure 4.3: The average strain at yield point

The strain at yield point shows signs of a uniform trend, with exceptions of 30% PIR PP aged 1000h and 30% PCR PP aged 500h. The trend within each material group is that the strain at yield point decreases between unaged and aged 500h.

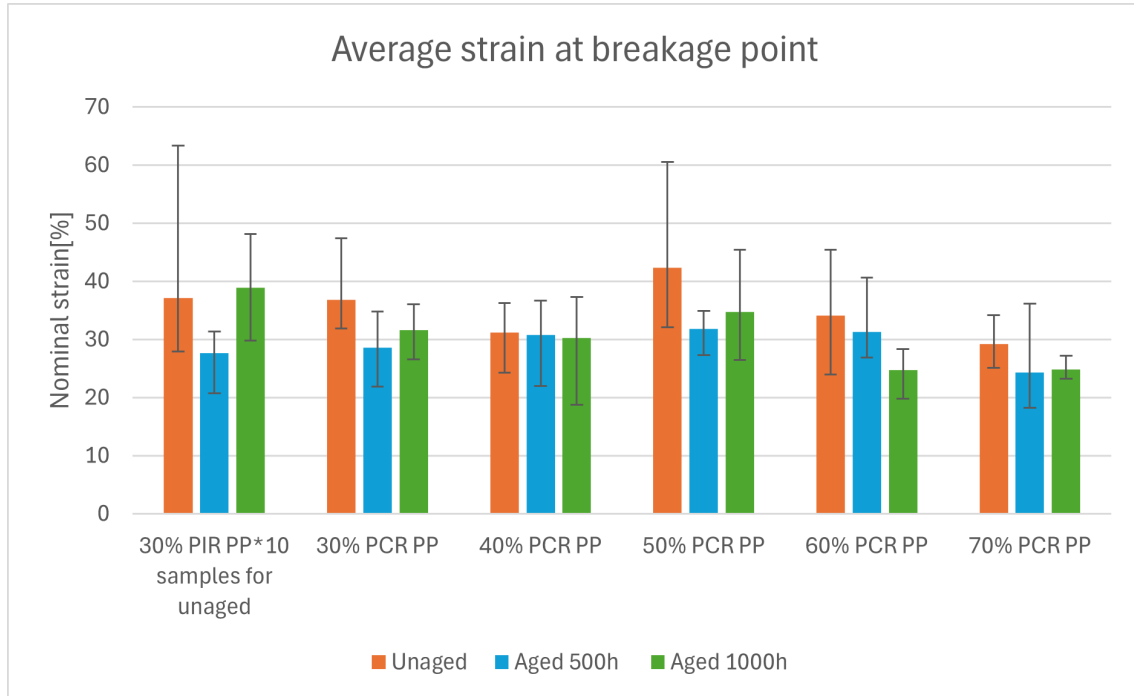


Figure 4.4: The average strain breakage point

Strain at breakage point has a wide distribution of test results both between material groups and within the material groups. Moreover, the error bars presented show a wide spread. The largest error bar presented is for the unaged 30% PIR PP that ranges between approximately 70%-168% of the mean average value.

4.2 Impact tests

Figure 4.5 shows the bar chart that represents the result of the impact tests where the different bars illustrate the average impact strength in KJ/m^3 for the respective materials and aged materials.

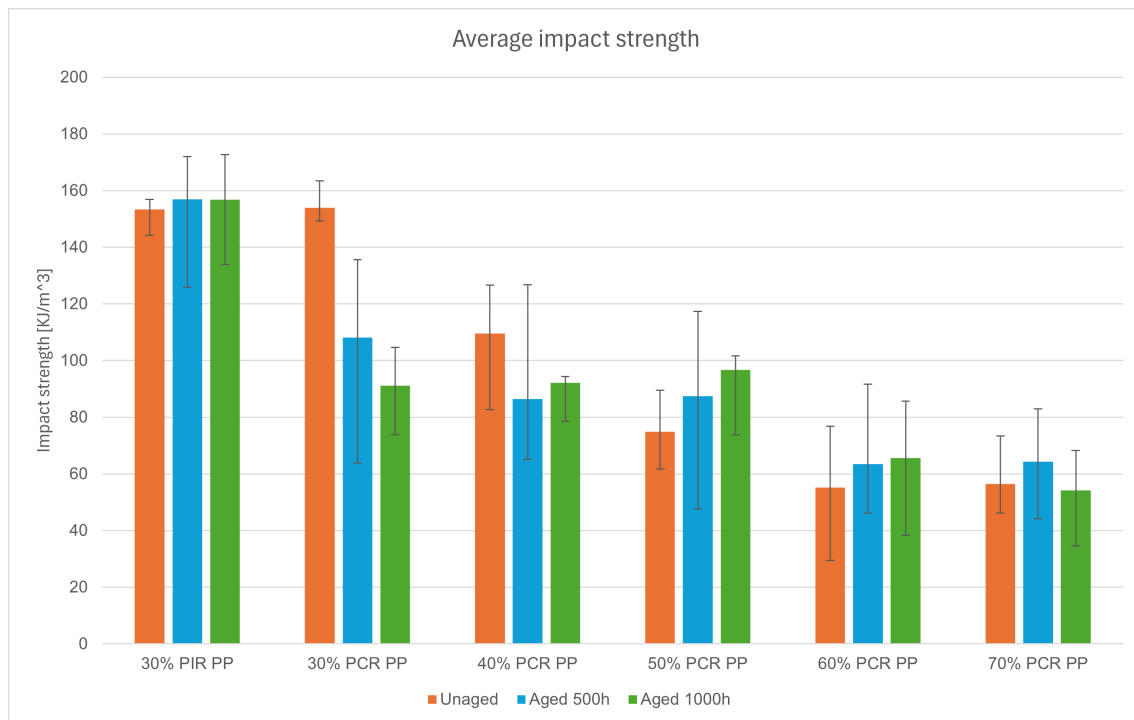


Figure 4.5: The average impact strength for the tested materials

The impact strength presents an overall declining trend between the material groups. Within the material groups the result is mixed. Furthermore, the bar chart shows a wide distribution of error bars.

4.3 Differential Scanning Calorimetry tests

Following are the results of the DSC tests, both the degree of crystallinity and the peak temperature, presented in bar charts. The results for the total crystallinity and observed peak temperature can be seen in Figures 4.6 and 4.7, the crystallinity and observed peak temperature of the big peak in Figures 4.8 and 4.9, and the crystallinity and observed peak temperature of the small peak in Figures 4.10 and 4.11. Note that for 30% PIR PP there was no clear smaller peak and is thus left empty in the bar chart. Also observe that for the temperature charts the Y-axis does not begin at 0, this to facilitate comparison.

The complete list with values obtained from the DSC tests used to calculate the crystallinity is shown in the Appendix A.3.

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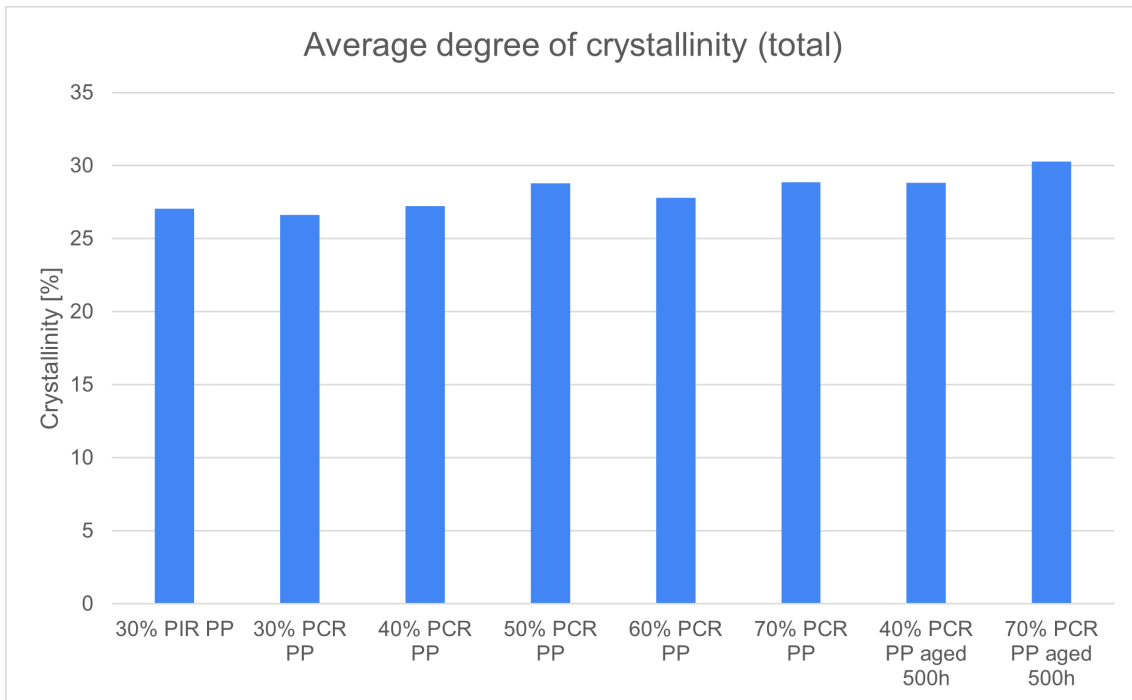


Figure 4.6: The total average crystallinity

The total average crystallinity can be seen in Figure 4.6, where a trend of increase can be observed.

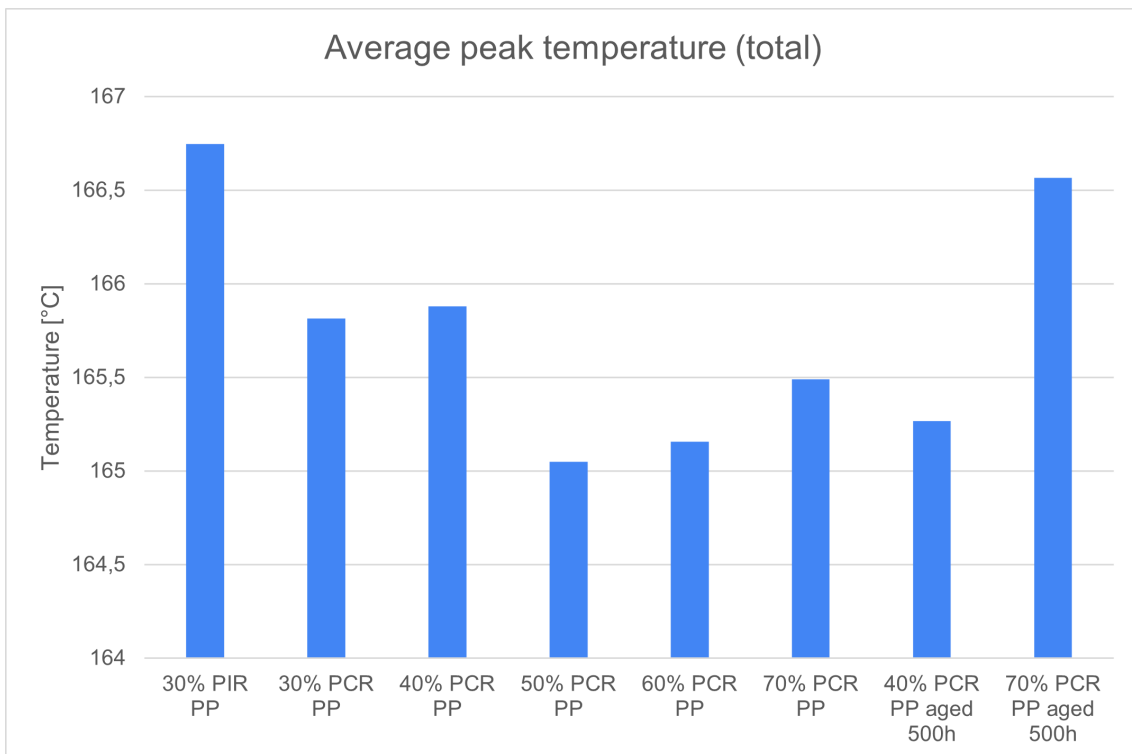


Figure 4.7: The total average peak temperature

The total average peak temperature has a varying result with no clear observed

trend as can be seen in Figure 4.7.

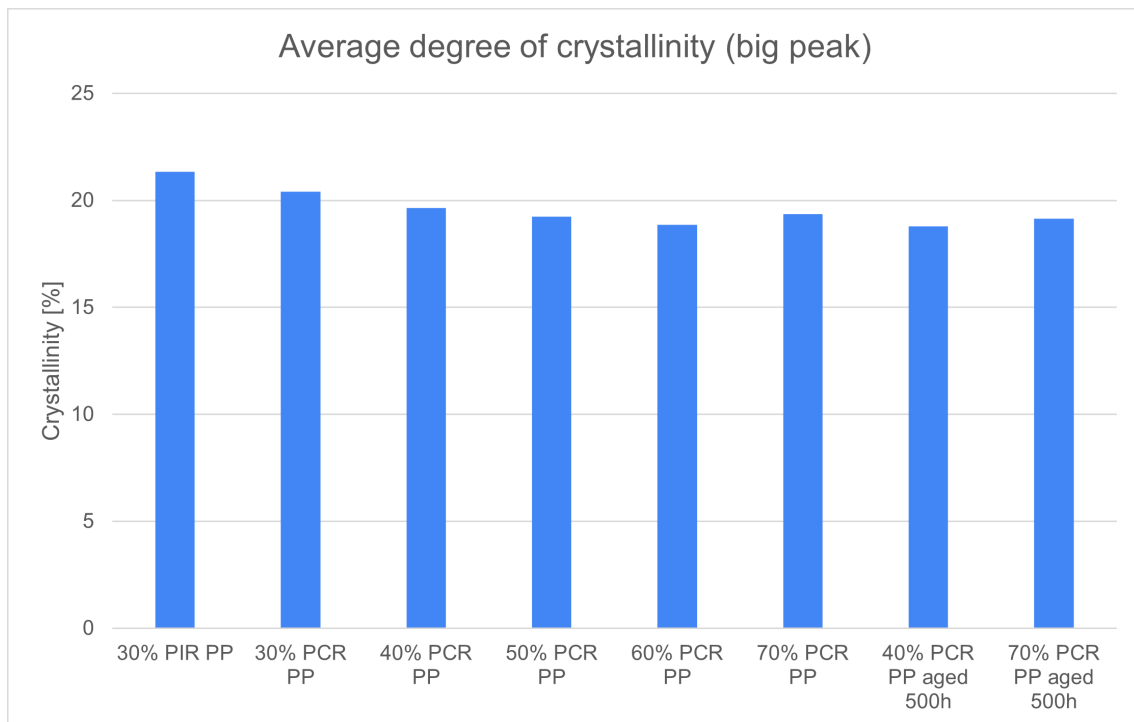


Figure 4.8: The average crystallinity of the big peak

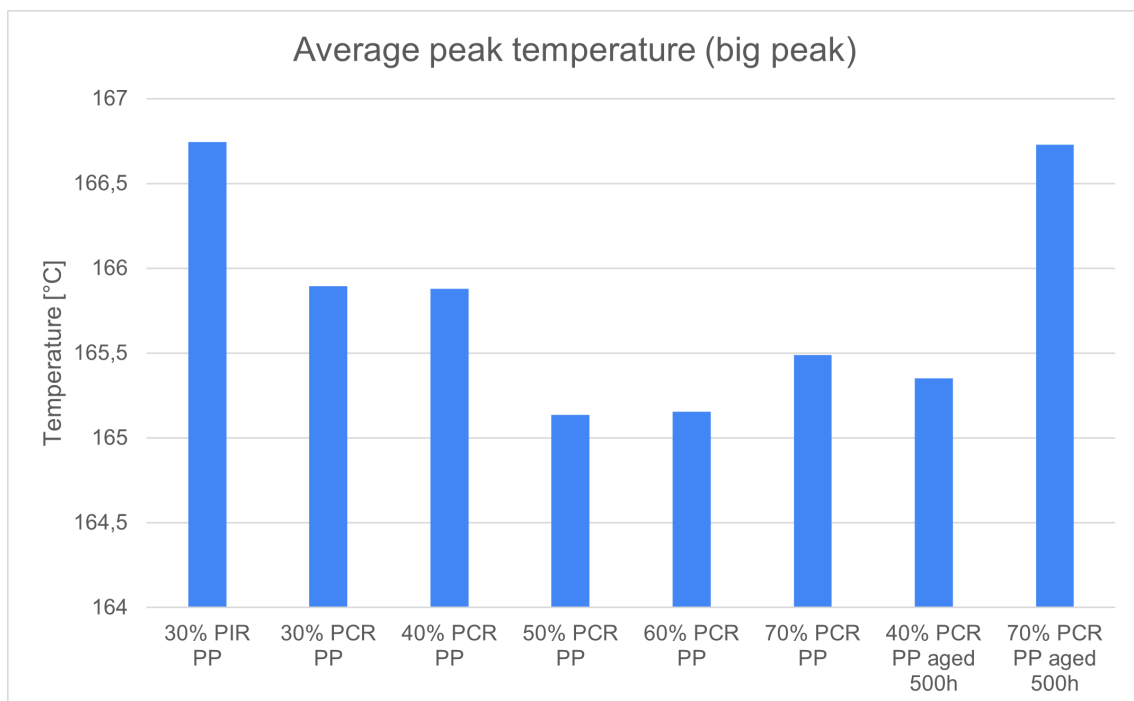


Figure 4.9: The average peak temperature of the big peak

Figures 4.8 and 4.9 present the average crystallinity of the big peak and the average peak temperature for the big peak. It shows that the average crystallinity has a

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decreasing trend and that the average peak temperature has a diverse result with no clear trend.

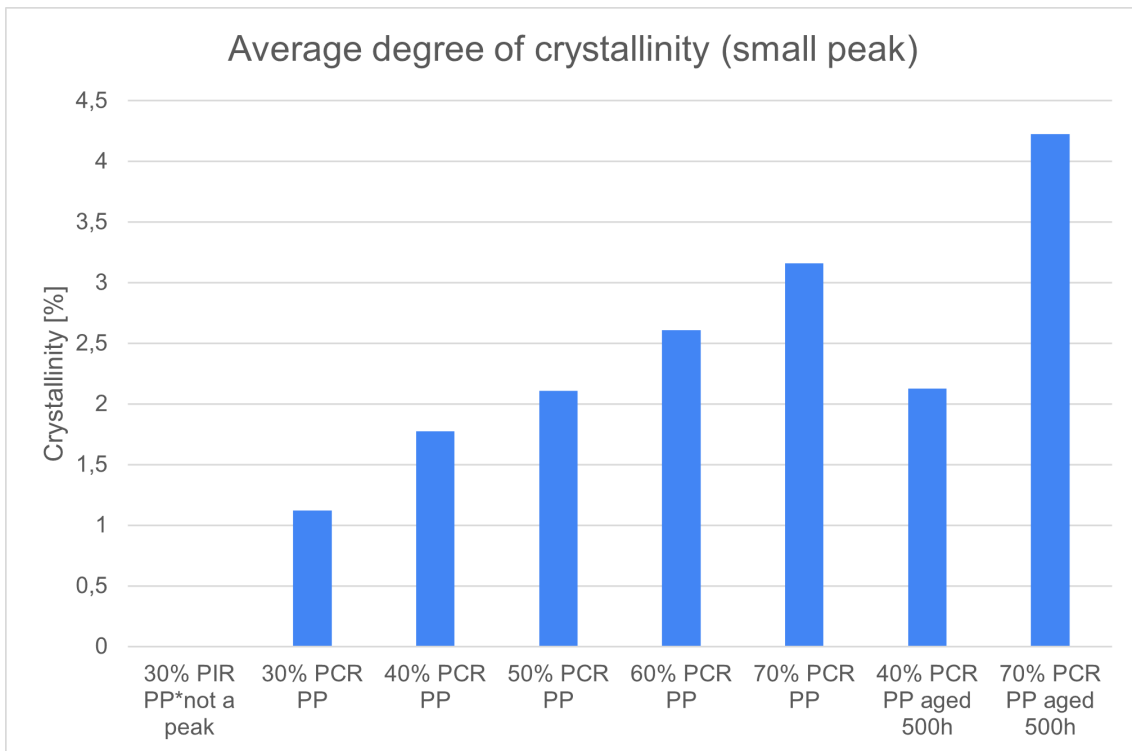


Figure 4.10: The average crystallinity of the small peak

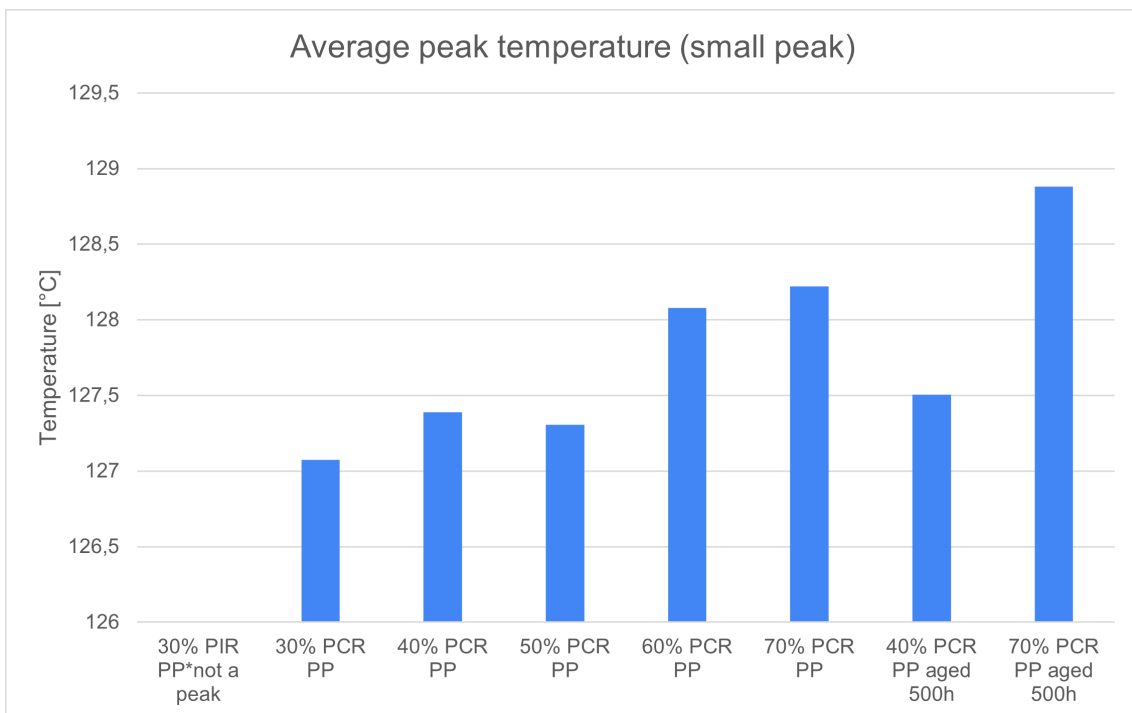


Figure 4.11: The average peak temperature of the small peak

Figures 4.10 and 4.11 present the average crystallinity of the small peak and the average peak temperature for the small peak. It can be seen that the average crystallinity is increasing, and the average peak temperature has a varying result, where no clear trend can be observed.

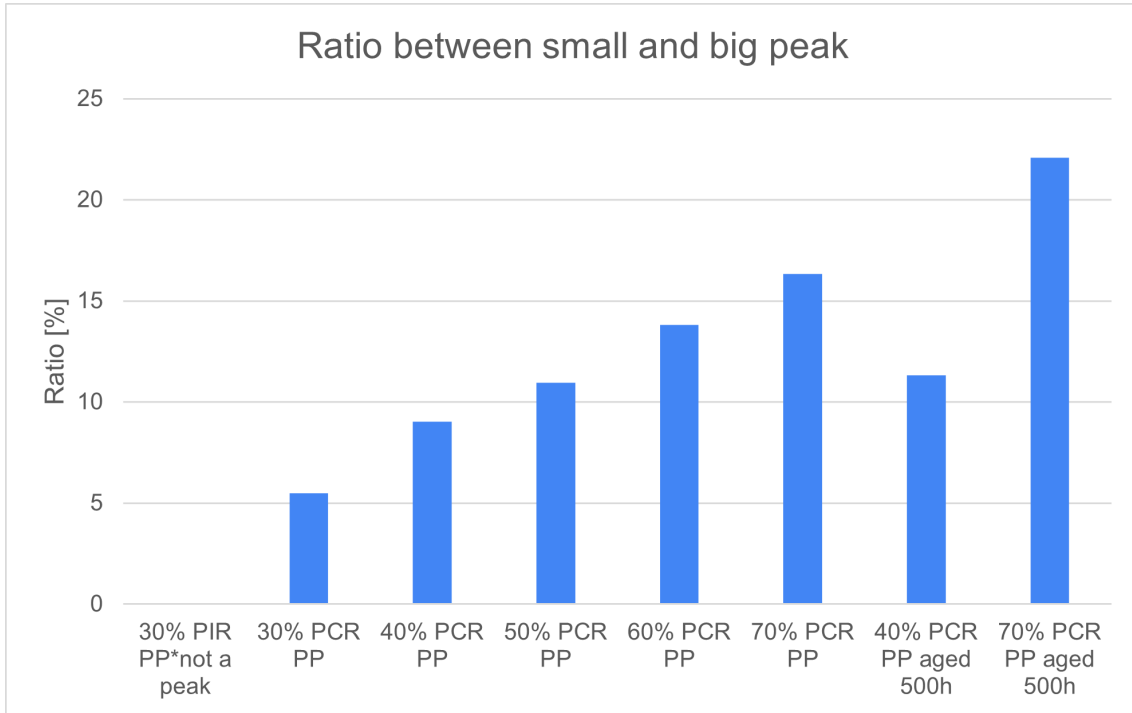


Figure 4.12: The ratio in crystallinity between the small peak and the big peak

The bar graph, seen in Figure 4.12, shows the ratio between the small and big peaks. The bars represent the number of percentages that the size of the small peak represents of the big peak.

4.4 Perceived Quality assessment

The results of the visual assessment can be seen below in Table 4.1.

Table 4.1: Results of the visual assessment

Sample:	Color	Gloss	Embossing	Defect
30% PIR PP	Slightly light but ok	Ok	Ok	Flashes, not ok
30% PCR PP	Slightly light but ok	Slightly glossy but ok	Ok	-
40% PCR PP	Slightly light, slightly blue but ok	Slightly glossy but ok	Ok	Flashes, not ok
50% PCR PP	Borderline, slightly light and slightly blue but ok	Slightly glossy but ok	Ok	Flashes, not ok
60% PCR PP	Borderline but ok	Slightly glossy but ok	Ok	Flashes, not ok
70% PCR PP	Borderline but ok	Slightly glossy but ok	Ok	Flashes, not ok

All samples were approved by visual assessment, even though there are defects in the form of flashes that are not ok. The flashes were a little bit of extra material on the sides as a result of the production of the plate, this may therefore not be the case for the final component. If that were to be the case on the final component, then that would need to be addressed.

4. Results

In table 4.2 the measured values from the color and gloss assessment are presented and in table 4.3 and table 4.4 they are compared with the reference.

Table 4.2: Results of the color measurements

Sample	Color			Gloss
	ΔL	Δa	Δb	GU
30% PIR PP	1,15	-0,12	-0,26	1,90
	1,18	-0,12	-0,23	1,90
	1,28	-0,12	-0,26	1,80
Average	1,20	-0,12	-0,25	1,87
30% PCR PP	1,09	-0,10	-0,04	1,80
	1,02	-0,09	-0,03	1,90
	1,10	-0,10	-0,04	1,80
Average	1,07	-0,10	-0,04	1,83
40% PCR PP	1,52	-0,13	-0,20	1,80
	1,48	-0,13	-0,19	1,80
	1,50	-0,12	-0,18	1,80
Average	1,50	-0,13	-0,19	1,80
50% PCR PP	1,79	-0,15	-0,27	1,90
	1,76	-0,14	-0,25	1,90
	1,74	-0,13	-0,23	1,80
Average	1,76	-0,14	-0,25	1,87
60% PCR PP	1,86	-0,14	-0,27	1,80
	1,76	-0,15	-0,27	1,80
	1,77	-0,13	-0,21	1,80
Average	1,80	-0,14	-0,25	1,80
70% PCR PP	1,86	-0,16	-0,22	1,90
	1,90	-0,16	-0,22	1,90
	1,88	-0,15	-0,22	1,90
Average	1,88	-0,16	-0,22	1,90

Table 4.3: Results of the color measurement compared to the reference and the approved tolerance

Color							
Sample:	Reference	ΔL	Tolerance	Δa	Tolerance	Δb	Tolerance
30PIR	0	1,20	$\pm 0,5$	-0,12	$\pm 0,2$	-0,25	$\pm 0,2$
30PCR	0	1,07	$\pm 0,5$	-0,10	$\pm 0,2$	-0,04	$\pm 0,2$
40PCR	0	1,50	$\pm 0,5$	-0,13	$\pm 0,2$	-0,19	$\pm 0,2$
50PCR	0	1,76	$\pm 0,5$	-0,14	$\pm 0,2$	-0,25	$\pm 0,2$
60PCR	0	1,80	$\pm 0,5$	-0,14	$\pm 0,2$	-0,25	$\pm 0,2$
70PCR	0	1,88	$\pm 0,5$	-0,16	$\pm 0,2$	-0,22	$\pm 0,2$

Table 4.4: Results from the gloss measurement compared to the reference and the approved tolerance

Gloss			
Sample:	GU	Reference	Tolerance
30% PIR PP	1,87	1,9	$\pm 0,3$
30% PCR PP	1,83	1,9	$\pm 0,3$
40% PCR PP	1,80	1,9	$\pm 0,3$
50% PCR PP	1,87	1,9	$\pm 0,3$
60% PCR PP	1,80	1,9	$\pm 0,3$
70% PCR PP	1,90	1,9	$\pm 0,3$

When comparing the results from the color measurements to the reference, they are outside the tolerance. The measuring of the gloss is within the tolerance.

4.5 Carbon footprint calculations

Using Table 3.1 the total weight of the relevant parts was calculated to be 5,782kg. Using this total weight, the CO_2e for the different categories was calculated and is shown in Table 4.5. The value in column "Yearly (200 000 cars) CO_2e " in the table is translated into the corresponding amount of Coca Cola cans to easier comprehend the values.

Table 4.5: CO_2e values for the different materials

Material	CO_2e/kg	Total CO_2e	Yearly (200 000 cars) CO_2e	Amount of Coca Cola cans
30% PIR PP	1,55	8,96	1 792 420	10 543 647
30% PCR PP	1,63	9,42	1 884 932	11 087 835
40% PCR PP	1,44	8,33	1 665 216	9 795 388
50% PCR PP	1,24	7,17	1 433 936	8 434 917
60% PCR PP	0,90	5,20	1 040 760	6 122 117
70% PCR PP	0,85	4,91	982 940	5 782 000
Virgin PP	2,16	12,49	2 497 824	14 693 082

Shown in Table 4.5 the CO_2e is the highest for virgin PP. Moreover, there is a decrease of CO_2e with more PCR content. However, the CO_2e for 30% PIR PP is lower than the value for 30% PCR PP.

5

Discussion

This chapter explores and interprets the results in relation to the research questions. The discussion also highlights any patterns, implications, and potential limitations identified during the project. Additionally, it suggests potential directions for future research.

5.1 Potential sources of error

During the testing of the materials, there have been a couple of potential sources of error that could affect the results. Being aware of these is important when analyzing the results and if replicating the study and/or continuing it. The first potential error could be the number of samples that were used for each test. Since the material had already been ordered prior to the study, there was a limited number of samples to work with, five samples for each test and for each point of aging. A higher number for each test could have given a more secure result and less distribution. Calibrating the impact test machine would also ideally require a greater number of samples, as mentioned in Section 3.5. If more material from Polykemi had not been acquired during the project, the initial amount of samples would not have been enough. Since the additional material was acquired late in the project, these samples unfortunately did not have the time to age, which led to a shortage of aged samples.

When aging the materials they were placed on the floor of a car, as mentioned in Section 3.3. This meant that one side of each sample was not in contact with the hot air. To avoid this, aging by hanging the samples, so that all sides are exposed to hot air, could have given a different result with a greater difference between the aged materials and thus more accuracy. This knowledge was gained after the commencement of the aging. However, it is possible that because the materials aged for a longer time period, the sides of the samples were still sufficiently in contact with the hot air. But the effects were not investigated further, and therefore the consequences are unknown.

When doing the impact tests conditioning was carried out on the samples first. The conditioning step was not performed for the tensile tests. Having done conditioning to all samples before the tests would give them more equal conditions and a more fair comparison. This was not done because the method was not known at the time the tests were performed.

In conclusion, many of the mentioned potential sources of error could have been

prevented by a more thorough test plan prior to starting the tests. Consulting more experts to get a clearer picture of what needed to be done together with investigating related ISO standards could have been done.

5.2 Material tests

Below follows a discussion regarding the test results and how to interpret them. Furthermore, it is explained if the actual result corresponds to the expected result from theory.

5.2.1 Evaluation of DSC tests

Figure 4.6 illustrates the total crystallinity of the different groups of materials used in the project. It shows that the total crystallinity is overall considered equal but that it gradually increases slightly with more recycled content. Moreover, all samples are approximately almost 30% crystalline, which implies that 70% of the material is amorphous.

As mentioned in Section 2.11, the crystallinity increases with aging. This shows proof in Figure 4.6 where the bars for 40% and 70% PCR PP aged 500h are higher than the bars with the same material, but unaged.

Furthermore, Figures 4.8 and 4.10 reveal the crystallinity of the so-called big and small peaks that constitute the total crystallinity shown in Figure 4.6. Figure 4.12 presents the ratio between the small and big peaks where it can be seen that the size of the small peak varies approximately between the range of 0,6%-2,5% of the size of the big peak. Interestingly, Figure 4.8 expose that if the small peak is excluded from the total crystallinity, the crystallinity would instead decrease with more recycled content. This demonstrates that the crystallinity of the content of the small peak compensates for the crystallinity of the big peak which results in a gradually increase of total crystallinity.

The DSC-tests reveal that there is a so-called small peak that melts before the main big peak. Figures 4.9 and 4.11 present the melting temperature of the respective peaks. These figures clarifies that the big peak has a considerably higher melting point, for example, the melting point between the peaks for 30% PCR PP differs almost 40°C. This proves that the material is not homogeneous. The small peak could portray the additives, but since all of the tested materials contain the same amount of additives there should be no size differences between the small peaks of all materials in that case. Furthermore, the DSC-test results for 30% PIR PP should then also include a small peak which it does not. This implies that the small peak is the result of something that the PIR PP does not include. Moreover, Figure 4.11 reveals that the small peaks in fact have melting temperatures, this proves that the small peaks are not due to some remains of dirt from the recycled content either. The explanation behind the small curves could, therefore, depend on the material structure resulting from recycling. As mentioned in Section 2.4, the material degrades when mechanically recycled by chain scission, forming low molecular weight

chains. These shorter molecular chains will have lower melting points, which is what can be seen when analyzing Figures 4.9 and 4.11. To strengthen this theory further it can be seen that the crystallinity for the small peak increases with the recycled content. This implies that the size of the small peak increases with the recycled content as well since the crystallinity is calculated by integration, as mentioned in Section 3.6. This would imply that the amount of short molecular chains increases with the recycled content, which is reasonable since the greater the amount of recycled content, the higher the concentration of shorter molecular chains. Moreover, Section 2.10 explains that the shorter molecular chains tend to crystallize easier, which further strengthens the theory.

5.2.2 E-modulus

Figure 4.1 illustrates a bar chart of the average E-modulus for the tested materials. It shows an overall uniform result with relatively small error bars. The error bars range within approximately 89%-110% of the average E-modulus value, on the majority of samples. Exceptions are for 30% PIR PP aged 1000h and 70% PCR PP aged 500h that both have greater error bars and stand out from the overall uniform length of the bars. In addition, 30% PCR PP aged 500h and 50% PCR PP aged 1000h stand out from the overall length of the bars, while unaged 30% PCR PP and 60% PCR PP aged 500h shows greater error bars than the majority. Furthermore, the trend within the material groups, except for 30% PIR PP, is that the materials that has aged 500h has the highest E-modulus.

As mentioned in Section 2.10, the stiffness of a material is connected to the crystallinity. Thus, a consistent result of the E-modulus could be explained by the homogeneous total crystallinity, presented in Figure 4.6. However, this relationship between stiffness and crystallinity would imply that a more aged material should have a higher E-modulus because aging a material increases the crystallinity. However, this is not the case. The bar chart shows a decrease between materials aged 500h and aged 1000h, although small, it can be considered an unexpected result. The explanation behind these can depend on many factors. An answer may be found in that even though the crystallinity increases with aging, the increase in this case is small, which can be seen in Figure 4.6. In addition, the samples were aged 500h and 1000h. It is possible that aging for a longer time period might have given, other results, such as an increasing E-modulus.

5.2.3 Stress at Yield Point

Figure 4.2 represents the average stress at yield for the tests. Stress at yield point is the so-called ultimate tensile strength, meaning the maximum stress that the sample has been subjected to. The figure displays that there is an overall increasing trend in stress both between and within material groups. Exceptions are 30% PIR PP, where there is only an increase within the material group, and 30% PCR PP where the material aged 500h stands out and has a bar taller than the same material aged 1000h.

The overall increase presented could be explained by the degree of crystallinity. As mentioned in Section 2.10, a higher crystallinity reduces the movement of the molecular chains, thus more energy is needed for the material to deform. An increase in the crystallinity of the tested material can be seen in Figure 4.6. The increase in stress at yield point with aging and the increase in recycled content could therefore be affected by the increase in crystallinity. However, the degree of crystallinity cannot explain the drop in stress from 30% PIR PP to 30% PCR PP since their degree of crystallinity is practically the same. Due to this unexplainable drop, it is probable that the result is also affected by the length of the molecular chains. As explained in Section 2.4, the chain length of the molecular chains is shortened during mechanical recycling. This implies that the higher the amount of recycled content, the higher the concentration of short molecules. Furthermore, this implies that shorter molecules respond more easily to stress because shorter chains increase the mobility of the molecules. However, if the stress at yield point results are heavily dependent on the size of the molecular chains, then the stress would decrease with increasing recycled content, which is not the case. Because of this, it is reasonable to assume that the results are affected by both crystallinity and length of molecular chains.

5.2.4 Strain at Yield Point

The results on the strain at yield point are presented in Figure 4.3. Overall, the lengths of the bars are somewhat consistent with small respective error bars that range between approximately 96%-111% of the average strain at yield point. The most noticeable exceptions are 30% PIR PP aged 1000h, which both has an obviously bigger error bar and an apparent shorter bar, and 30% PCR PP aged 500h that has an even more apparent shorter bar. Furthermore, there is a slight increasing trend between the material groups and a decreasing trend within each material group.

The strain at the yield point indicates the extent of elastic deformation that a material undergoes before the onset of permanent deformation. As mentioned in Section 2.10, a higher degree of crystallinity reduces the ductility of a material, which implies a lower ability to deform. This implies that the strain should be lower with higher crystallinity. However, this is not what Figure 4.3 illustrates. Thus, Figure 4.6 shows that the degree of crystallinity increases with recycled content, thus increased concentrations of short molecule chains, and aging, the increase is still slight. It is therefore reasonable to assume that these small changes in crystallinity may not affect the strain at yield point that significantly.

What is expected to affect the results in Figure 4.3 is also the length of the molecular chains. In Sections 2.4 and 2.11 it is explained that the shorter the molecular chains the less ductile the material. This could explain the small decrease in strain within the material groups as the molecular chains shorten during aging. However, this theory would imply that there should be an overall decrease in strain at yield point with the higher recycled content, since higher recycled content means higher concentration of shorter molecular chains.

In general, the average strain at yield point presented in Figure 4.3 shows unexpected

results. It is possible that the results would be different if additional tests are to be performed. However, this is not certain since the error bars in Figure 4.3 are, as mentioned, in the majority of cases relatively small, which implies that the results are appropriate.

5.2.5 Strain at Breakage Point

Figure 4.4 illustrates the strain at breakage point. The chart generally shows a somewhat consistent average result. However, the large error bars indicate a high overall variation between the tests. The error bars approximately range between 60%-170% of the average strain at breakage point. As mentioned in the discussion of strain at yield point, see Section 5.2.4, the strain is affected by crystallinity and molecular chain length. This implies that the expected result would be a clear downward trend. The chart shows a, to some extent, decreasing trend within the material groups. This could be explained by shorter molecular chains, as discussed in the section above. But the wide distribution makes the conclusions drawn from Figure 4.4 unreliable. To counteract this unreliability, more tests should be performed to investigate if there is a more exact average strain at breakage span.

An explanation for the wide distribution of strain at breakage point could be the distribution of crystallinity. As seen in Figure 4.6, all material samples are approximately 30% crystalline. This implies that approximately 70% of the material is made up of amorphous parts. In Section 2.10, it is explained that the distribution of the crystallinity may not be uniform depending on factors such as the cooling rate during the processing. This could mean that all of the tested samples may have different distributions of crystalline versus amorphous areas in the material. The amorphous regions of the material are more prone to breaking than the crystalline regions. This is because the amorphous regions lack ordered tightly packed molecular structure. This could explain the wide distribution of strain at breakage point. However, since all samples used in the study were produced in the same way, the distribution of the amorphous versus crystalline areas should not differ. But, this has not been further investigated and therefore cannot be completely ignored.

5.2.6 Impact test

Compared to the bar charts for the tensile tests, the one for the impact tests shows a clear decline in impact strength with a higher recycled content. The impact strength more than halved between 30% PIR PP and 70% PCR PP. Moreover, 30% PIR PP has a uniform result within the material group, whilst there is a reduction for 30% PCR PP between unaged and aged 500h materials. For the rest of the materials, there are differences between the aged samples, though these differences do not show a clear trend. For some material groups, the unaged material impact strength is higher, and for some the aged 500h or 1000h material is higher.

The result could be explained by the way that the crystallinity differs and changes between the samples. A material with high crystallinity implies a highly ordered and tightly packed molecular structure. This limits the material's ability to deform

plastically, which in turn implies that the more crystalline a material is, the more brittle it becomes, mentioned in Section 2.10. Thus, the impact energy cannot be absorbed, which is what an impact test measures. This insight supports the result of the impact test, presented in Figure 4.5, where it is illustrated how the impact strength decreases with increasing recycled content. The results that can be observed in Figure 4.6 supports this as crystallinity increases with more recycled content.

What should be taken into account as well is that the overall crystallinity, presented in Figure 4.6, is fairly even between the samples. This implies that the clear decline in impact strength illustrated in Figure 4.5 may not only be the result of a slightly changing crystallinity.

Using this insight should thus imply that the impact strength within each sample group should decrease. The reason is that crystallinity increases during aging, explained in Section 2.11, as well as that the molecular chains shorten during aging. But this is not what Figure 4.5 illustrates in all cases. For example, the bars representing 50% PCR PP increases with aging, which is a clear contradiction. The reason for this is unclear and can depend on many factors. To begin with, it is clearly shown that the majority of the bars in Figure 4.5 have large error bars. The error bars range approximately between 58%-147% of the average impact strength. This implies that there was a wide spread in the test results, which in turn may imply that the result shown in Figure 4.5 might not be a fair representation of the impact strength. Furthermore, each bar represents the mean value of only five tests. To obtain a more clear and trustworthy representation, additional tests could be performed.

Furthermore, Figure 4.5 reveals that the impact strength for all samples consisting of 30% PIR PP is high and uniform between samples. Similar results are not represented by any of the other material groups. The noticeable result may be explained by the presence of additives, such as impact modifiers, and the fact that the amount of additives used was the same in all of the project's samples. Furthermore, the amount of additives is what Volvo Cars uses today. This implies that the amount of additives used in the samples is optimal for the 30% PIR PP material. This would explain why the result for the 30% PIR PP is relatively high and uniform, which could be considered an optimal result for a hard trim interior panel part.

Moreover, a factor that will have had an effect on the impact strength results is the presence of two distinct peaks, the small peak and the big peak, caused by underlying molecular heterogeneity. As mentioned in Section 3.6, the DSC shows two distinct peaks in all materials except for the 30% PIR PP. Furthermore, the small peak increased with the recycled content, while the big peak decreased. This is the result of two distinct molecular weights, likely caused by chain scission during mechanical recycling. Shorter or degraded molecular chains tend to crystallize faster and thus separately from the longer chains, as mentioned in Section 2.10. Since the chains are shorter there is less of it to fold when forming crystals. As mentioned in Section 2.10, smaller crystallites affect the mechanical properties and particularly the ability to absorb energy, which an impact test measures. This may therefore be

the explanation for the overall decreasing trend in impact strength shown in Figure 4.5. However, the molecular structure was not further investigated, which withholds a firm conclusion.

5.2.7 Perceived Quality

Based on the visual results of the PQ assessment, see Section 4.4, all the materials tested would be approved by the PQ department at Volvo Cars, at least if the visual evaluation category "Defect" were to be dismissed. This is allowed in this case, since this category is affected by the manufacturing. For the assessment, the hard trim panels were not evaluated, but plates consisting of the different materials instead. The category "Defect" should therefore be evaluated for the parts themselves. If the actual component would possess the same, or other, defects, this would not be considered ok.

Continuing with the color measurement, all materials were outside of the accepted tolerance. However, as explained in Section 2.12, visual assessment triumphs over measured result. Thus, all samples were approved. The result reveals that, color-wise, the materials become more questionable as the percentage of PCR increases. This was expected since a higher concentration of recycled content implies inconsistent color dispersion, as explained in Section 2.3.

The PQ assessment was carried out judging only the dark color "Charcoal". Assessment of another color could possibly show a different result. Volvo Cars' hard trim interior panels are offered in different colors, which implies that the same perceived quality assessment performed needs to be performed on all offered colors. Furthermore, it is essential to perform the PQ assessment on the actual component with the chosen material compound since this may also differ from the assessment done on the plates. In addition, the color and appearance of the hard trim interior panels will be affected by the nearby materials in the car. Because of this, it is necessary to consider how the combination of materials could affect perceived quality.

The approval from the PQ department at Volvo Cars is based on their reference and what the company has been deemed to be considered "Ok". An interesting question to explore would be whether this regulation could change. Could a customer possibly accept a lower perceived quality or appearance if that would imply a car with a lower CO_2 footprint.

5.3 CO_2 footprint

Examining the results of the carbon footprint calculations, found in Section 4.5, a greater decrease in emissions occurs after 50% PCR PP compared to the current use of 30% PIR PP. In fact, changing the material of the hard trim interior panels to 30% PCR PP will increase the CO_2 footprint. To obtain a CO_2 footprint reduction, Volvo Cars has to switch material to 40% PCR PP, or a material with higher PCR PP concentration.

Overall, the interior hard trim panels do not contribute to a large portion of the total car weight, in fact approximately only 0,33% as the total car weight is about 1800kg, see Section 3.8. However, Volvo Cars' factory in Torslanda has a capacity to produce up to 200 000 cars per year, as mentioned in Section 3.8. This implies that the current material used for the hard trim panels, 30% PIR PP, is approximately responsible for an emission of 1 792 400kg CO_2e yearly. To put this value in context, it corresponds to the emission caused by 10,5 million 33 cl Coca Cola aluminum cans. If Volvo Cars' were to use 30% PCR PP for their panels instead, the CO_2 footprint would increase with approximately 92 500kg CO_2e yearly, which resembles the CO_2e value for 544 000 Coca Cola cans. However, if they were instead to use 70% PCR PP for their panels, the CO_2 footprint would decrease by approximately 809 500kg CO_2e yearly, this is equal to the CO_2e value for approximately 4,7 million Coca Cola cans.

When analyzing the calculated CO_2e it is essential to remain aware that the unit should be seen as indicates, as mentioned Section 3.8, since a complete LCA has not been done by the supplier. These CO_2e values can also shift if Volvo Cars and/or Polykemi would change the supplier of material. Furthermore, this is a calculation of how the amount of material affects the carbon footprint. This implies that the manufacturing and transportation, for example, are not included in the calculations.

5.4 Material recommendation for Volvo Cars

Volvo Cars do not have any distinct tolerances of the material per say, only on the finished component. Therefore, 30% PIR has been used as a guide and reference when making a recommendation.

Since impact strength shows the greatest overall variation among the properties measured, even though other mechanical properties show large singular variances, it strongly influences how much recycled content can be used in Volvo Cars' hard trim panels without compromising performance. Even though other mechanical properties affects Volvo Cars' decision of material, the impact strength will be the property that first limits the concentration of PCR content. Figure 4.5 illustrates that changing the material from 30% PIR PP to any of the other materials tested would imply a reduction in impact strength, for example, changing to 40% PCR PP would imply a decrease with approximately 28% when unaged and a reduction with 40% when aged 500h. The only other material that demonstrates the same high standard as 30% PIR PP is the unaged 30% PCR PP, but when aged the impact strength decreases considerably, approximately 30%. A switch to 30% PCR PP would also imply an increase in carbon footprint with approximately 92 500kg CO_2e yearly, which is not the goal. Judging by impact strength, the results indicate that Volvo Cars should continue to use 30% PIR PP since a change to a PCR PP would imply a reduction in impact strength. However, it is possible that an increase in additives, especially impact modifiers, could improve the impact strength for PCR PP materials. If an increase in additives was possible without compromising any other aspects or mechanical properties, it is possible that a PCR PP material with a

higher recycled content could be used in the hard trim interior panels of Volvo Cars, as the impact strength is what regulates the choice. However, with the measured decrease in impact strength, it cannot be guaranteed that the material tested with current additives can perform as well. Therefore, the recommendation is for Volvo Cars to continue using 30% PIR PP, although there is the possibility of a higher percentage of PCR PP.

However, the objective of the study was to recommend Volvo Cars with a PCR PP material to use for their interior hard trim panels. If a PCR PP material is required, then 30% PCR PP is recommended. Any other material will imply an even greater decrease in impact strength. That said, this switch will imply an increase in CO_2 footprint along with the fact that the impact strength when the material ages is unreliable if no other additives are incorporated. With respect to the other measured mechanical properties, this switch will imply:

- E-modulus will increase with approximately 5% between the unaged values
- Stress at yield point will decrease with approximately 9% between the unaged values
- Strain at yield point will increase with approximately 3% between the unaged values
- Strain at breakage point will decrease with approximately 1%

Acknowledge that the above presented values are for unaged material. When aged, the measured values may differ more or less. While 30% PCR PP may not always be the optimal material choice in terms of mechanical properties other than impact strength, it will still be the recommended option for Volvo Cars in this case. This is because the impact strength regulates the choice.

5.5 Future work

To further this project, the main aspect to focus on would be additional thorough testing on a complete component, both evaluating the mechanical properties and the appearance. The hard trim panel may behave differently when tested, compared to the tested samples. Overall, a higher quantity of performed tests and more data would be useful. Further tests, apart from those performed in this study, that would be beneficial to carry out are tensile and impact tests in cold conditions and aging for a longer time period, preferably 3000h. Aging with UV light and not just heat would also be interesting to investigate. For this project, it was not considered, but since the hard trim panels will be exposed to sunlight in some capacity, it would be insightful to see how UV light affects the material. Since only two aged materials were used in the DSC-tests, additional aged samples for all material groups would be useful to analyze. Further investigation of how and whether the crystallinity changes with time for all materials would help to see trends and support why the material behaves as it does. Since much of the analyzes in this project are built on the variation of molecular weight between the materials it would be useful to investigate them on a molecule level to see if the analyzes are correct. Many of the test results imply this connection, but actual tests would be necessary to prove this.

As mentioned in Section 5.4, increasing additives in the material mix may change the properties. Therefore, it is possible that a higher percentage of PCR PP may perform better when additives are adjusted. Changing the additives and repeating the tests performed would therefore be necessary. Investigation of a lower percentage of PCR PP than 30% could also be a further consideration. The results of this project indicate that 30% PCR PP is not an equal or better alternative to the used 30% PIR PP, but lowering the amount of PCR may change the properties. Another investigation could be to analyze samples with other percentages, for example 45% PCR PP. This would perhaps show the overall trend of mechanical properties and obtain a more detailed material recommendation for Volvo Cars.

6

Conclusion

The purpose of this study was to examine how the amount of PCR PP would affect the properties of Volvo Cars' hard trim interior panels. To investigate this, the study was guided by four research questions, the first concerning the maximum PCR PP content that can be used while still maintaining the same, or increasing, mechanical properties as the currently used material. Based on the materials examined in the project, their respective additives, and the supplier of the material, it is evident that 30% PCR PP is the only investigated PCR material that will partially maintain the mechanical properties as the currently used material.

Continuing with the next research question which similarly addressed the maximum PCR PP limit that can be used while still meeting the aesthetic requirements for the interior hard trim panels. On the basis of the materials investigated in this study, the materials additives and used supplier, it is apparent that the PCR PP content can be increased to the highest studied PCR PP content, 70% PCR PP, without compromising the visual quality required for the interior hard trim panels.

Proceeding to the third research question regarding what affects aging, of PCR PP materials, has on the mechanical properties. It can be concluded that the effects of aging the material, for 500h as well as 1000h, are not fully clear across all properties. The E-modulus shows a relatively uniform result regardless of time aged. The impact strength proves unexpected results with incoherent trends with regards to aging. The strain at yield point together with the strain at breakage shows sign of slight tendencies to be affected by aging in an expected way. In both cases the overall tendency is that the value decreases with aging. The final mechanical property, the stress at yield point, is the property which seems most affected by aging. This property increases with aging.

Lastly, the final research question concerned if and how the CO_2 footprint of the interior hard trim panels would change depending on the amount of recycled content. The evidence suggests that the overall CO_2 footprint will decrease with the amount of PCR PP. However, 30% PCR PP has a higher CO_2 footprint than 30% PIR PP that is used by Volvo Cars today. Acknowledge that this analysis is based on CO_2 footprint data received from the utilized supplier.

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A

Appendix 1

A.1 Notes from interviews and study visits

The following section presents notes from the interviews and discussions conducted with key individuals involved in the project. These conversations provided valuable insights and knowledge relevant to the project's scope and objectives.

A.1.1 Notes from study visit at Polykemi and Rondo with Patrik Axrup, Johan Svenmo and Patrik Lindqvist (Date: 2025-02-25)

Note: The English translation of this interview was made with the assistance of AI, specifically ChatGPT.

Company Overview

Polykemi is a family-owned company that manufactures custom polymer products tailored to customers' needs. The company operates globally with a presence in the USA, Mexico, Denmark, Germany, the Czech Republic, and China. Their production facilities are located in Sweden, the USA, and China, with a production capacity of 130,000 tons. The largest customer segment is the automotive industry, especially Volvo, followed by sectors like home appliances, vacuums, garden products, and construction.

Production Process

Polykemi's production process includes the following steps:

- Mixing of polymers
- Cooling
- Drying
- Cutting
- Post-mixing
- Packing

Recycled Materials

Polykemi places a high importance on the traceability of recycled materials. They work closely with direct producers rather than traders or recycling companies to ensure the origin of the material is known. The company uses a range of recycled materials, including PC, PP, PA6, ABS, PE, PBT, PA66, TPE/TPO, and PS/HiPS. Materials undergo rigorous lab testing and internal upgrading to ensure homogeneity and remove contaminants such as heavy metals through XRF testing.

Investment in Recycling Technology

Polykemi has made significant investments in equipment for handling fibers from textiles and enhancing the density of raw materials. Machines like compactors, cutters, and extruders (e.g., Erema, which processes contaminated materials) are used for upgrading materials, particularly Post-Consumer Recycled (PCR) materials. This includes handling marine debris such as ropes and nets, which are often non-homogeneous and require special processing.

PCR Materials

PCR materials are used primarily upon customer request. These materials are generally more expensive due to the infrastructure needed for collection, sorting, and cleaning. However, Polykemi's approach to recycling in Sweden, where the country uses green energy, helps reduce the CO_2 footprint. The company blends recycled content with virgin material to ensure better stability and quality. This method also facilitates easier coloring of the material.

CO₂ Emissions

The CO_2 equivalents of Polykemi's products depend on the amount of recycled material used. The CO_2 emission values are as follows:

- 30% PIR: 1.55 kg CO_2e/kg
- 30% PCR: 1.63 kg CO_2e/kg
- 40% PCR: 1.44 kg CO_2e/kg
- 50% PCR: 1.24 kg CO_2e/kg
- 60% PCR: 0.90 kg CO_2e/kg
- 70% PCR: 0.85 kg CO_2e/kg
- Virgin material: 2.16 kg CO_2e/kg

As for their CO_2e values, they are ' CO_2e Values based on Cradle to Gate ISO 14044:2016, background data Ecoinvent 3.9 evaluated with Environmental Footprint 3.1.'. The specific samples are based on a PCR source in Sweden with washing in Sweden, but a full LCA has not been completed yet, so the values are based on assumptions and should be considered indicative at this stage. If future sourcing is from other countries in Europe, the values for PCR will likely be much higher, as transport and energy types used in washing PCR drive the CO_2e .

Prices

As mentioned, PCR is more expensive than PIR due to infrastructure. They can not give exact prices, but virgin material is the most expensive, then PCR, and PIR is the cheapest.

Supply Chain and Demand

Polykemi faces challenges in ensuring the consistent quality of PCR materials due to the variability in supply, as they do not have guaranteed volumes from suppliers. Because of this many possible suppliers are needed. With regard to the feedstock, Polykemi ensures that the feedstock is thus reliable and good. The demand for PCR material has been increasing, but new facilities are being opened to meet this demand. Currently, Polykemi works exclusively with European suppliers, while markets like China and the USA are adopting similar methods for upgrading recycled materials.

PCR PP Granule Composition

The PCR PP granules used by Polykemi primarily consist of packaging materials and municipal waste collected at public recycling stations. The materials that are sourced from household packaging, particularly during the summer and autumn, tends to have a stronger odor which can be problematic. The granules are free from metal contaminants, food residues, and other impurities. Additionally, the materials are polymer-sorted to ensure high quality and consistency.

Certifications and Future Plans

Polykemi is working towards obtaining third-party certifications for their products, including ICC+ certification, which is currently available only for PIR materials. They are pursuing certification for PCR materials, though this is more difficult due to the complexities involved in sourcing and processing.

Material Testing and Internal Upgrading

The material first arrives at Rondo, a Polykemi subsidiary, where it has been washed but may still contain contaminants like wood chips, metal, or paper remnants. To check for impurities, the material undergoes XRF testing. If necessary, it is processed using an Erema extruder to remove these impurities. Afterward, additional lab tests verify the removal of contaminants and check mechanical properties, melting index, and fluidity to ensure quality. Once tested, the material is labeled by quality and sent to Polykemi for production. The final compound is made by mixing granulate from various suppliers, adding additives like pigments, and blending in virgin material for stabilization and easier coloring. The mixture is extruded at 245-250°C, cooled in water, dried, and cut into granules before being packaged and shipped to the customer.

Quality Control

To ensure consistent quality, Polykemi conducts extensive testing on all materials, including XRF tests for contamination and mechanical property assessments. The company blends different material qualities and suppliers to meet customer requirements. This quality control process is crucial when working with PCR materials, as these can vary in properties.

How does Polykemi differ from other producers of recycled PP? Are your granules comparable to other producers of granules? If they differ, how and how much?

Polykemi's recycled PP granules are likely quite specific compared to other producers, depending on the sources and processes used. It is difficult to make direct comparisons, as variations in sourcing and production methods can result in differences in the final product. The uniqueness comes from Polykemi's tailored approach to upgrading and blending materials, ensuring a customized quality for each batch.

A.1.2 Interview with Inger Jacobsson and Hanna Ljungholm at the Perceived Quality department (Date: 2025-03-17)

Note: The English translation of this interview was made with the assistance of AI, specifically ChatGPT.

How is the process when evaluating materials?

You look at the material under a lightbox and measure it, often it is more com-

plicated when it comes to a component. There are more factors to consider, and you often spend more time examining the material, taking into account where the component is placed, etc.

Is there a risk that the evaluation becomes subjective?

Since the visual assessments are made by humans, there is a risk, yes. However, there are always at least two people involved in the evaluation, and sometimes more if opinions differ greatly. In addition, measurements of the material are taken, which can be compared to the visual assessments, though the visual assessments weigh more heavily.

How important is the visual assessment?

There are tolerances with requirements, but it is the visual that decides. Gloss, texture/embossing, and color interact, so the result may look different than what is measured. Color and gloss can be measured nowadays, but texture/embossing cannot.

Are the guidelines determined by trends?

The most important thing is that the customer thinks the materials look good and premium. If the customer changes their perception, it is possible that the tolerances are adjusted, but it is not done based on trends.

How much can the material differ from the reference?

There are different tolerances regarding lightness, colors, and gloss. Each material/surface has its own tolerances.

What is the goal within PQ?

The goal is for the material not to differ more than the allowed tolerance for the reference material. This is examined visually and measured. The visual assessment takes priority over the measurements and weighs the most.

What are the tolerances for “interior hard trim panels”?

The tolerances for interior dark colors are as follows:

- Delta L tolerance: 0.5
- Delta a and b tolerance: 0.2
- Plus/minus 0.3 in gloss

At what stage in the process is PQ examined?

Work is done in both the early and late stages. The aim is to ensure that not too many materials are mixed. PP (Polypropylene) is a softer variant, while POM (Polyoxymethylene) and others tend to be glossier. Tips are given to avoid using certain materials that are harder to work with. Input is provided on how to apply different textures. After aging, others check the colors and similar properties.

A.2 Tensile test

A.2.1 Stress-strain diagrams

In the following Figures, A.1 - A.6, the stress-strain diagrams obtained from the tensile tests for each material can be seen.

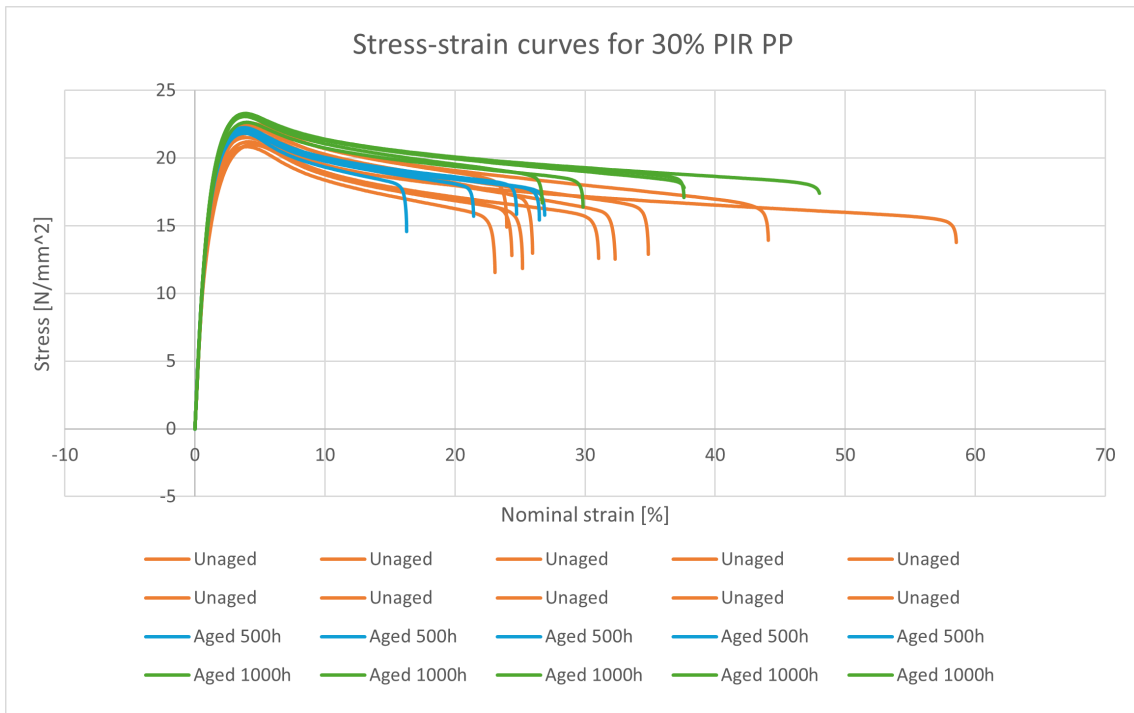


Figure A.1: The stress-strain curves for 30% PIR, note that there are 10 tests for the unaged

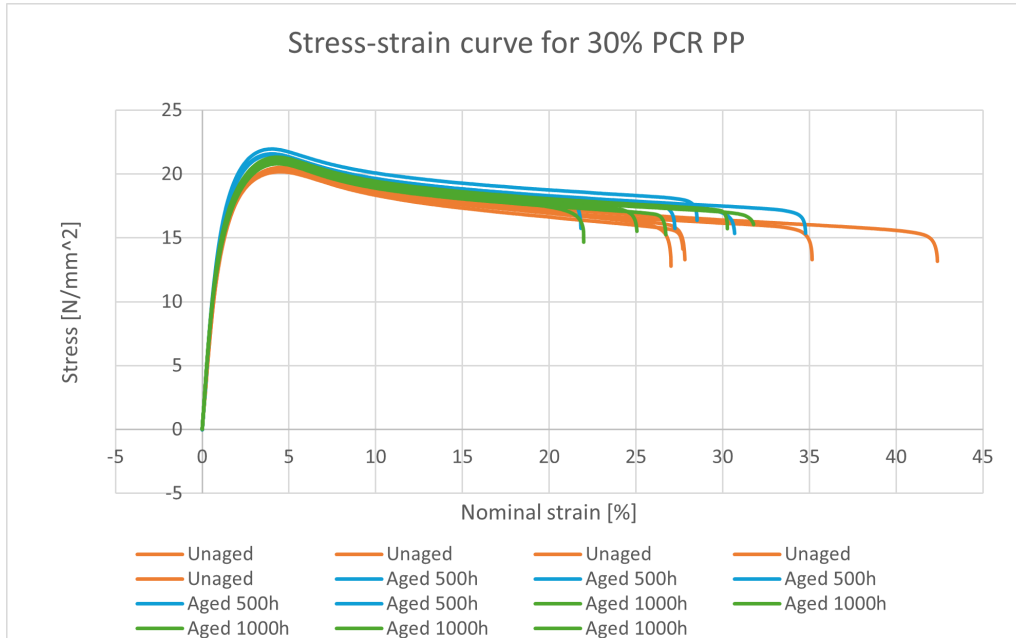


Figure A.2: The stress-strain curves for 30% PCR

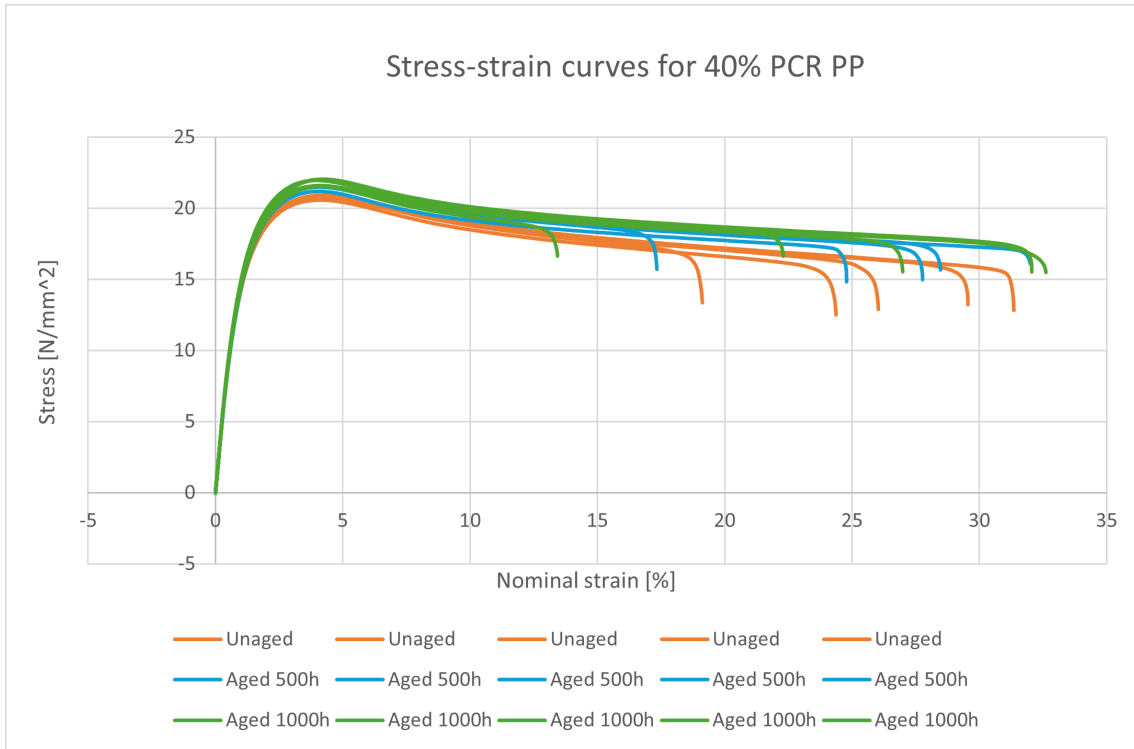


Figure A.3: The stress-strain curves for 40% PCR

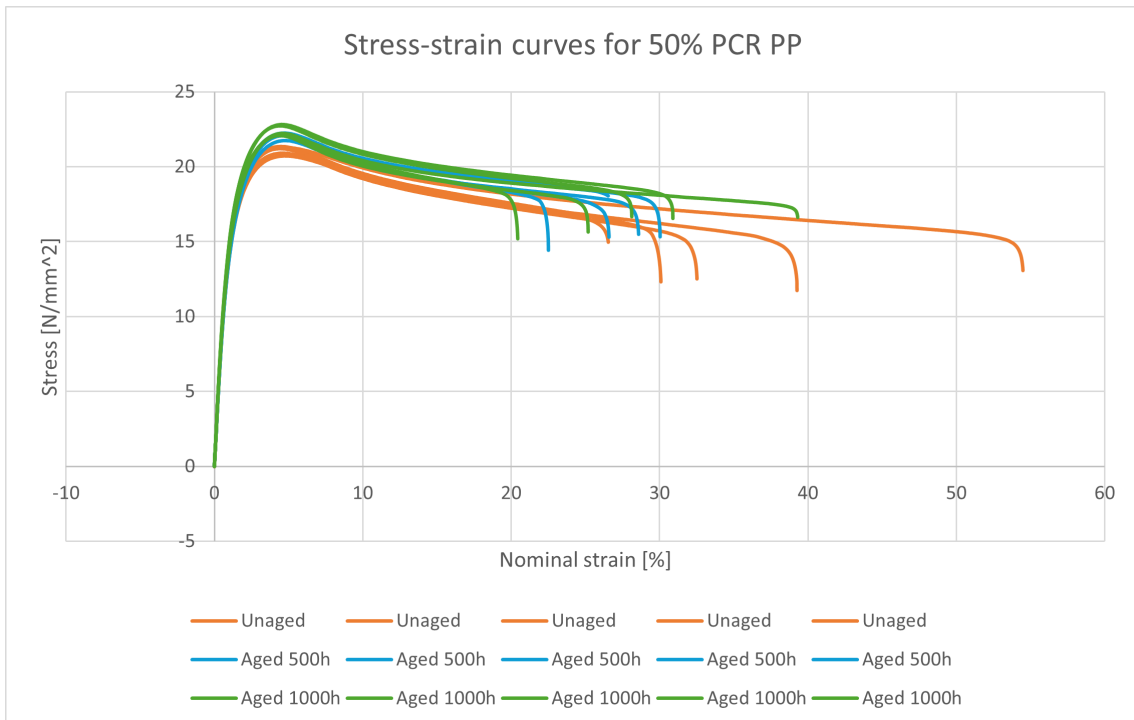


Figure A.4: The stress-strain curves for 50% PCR

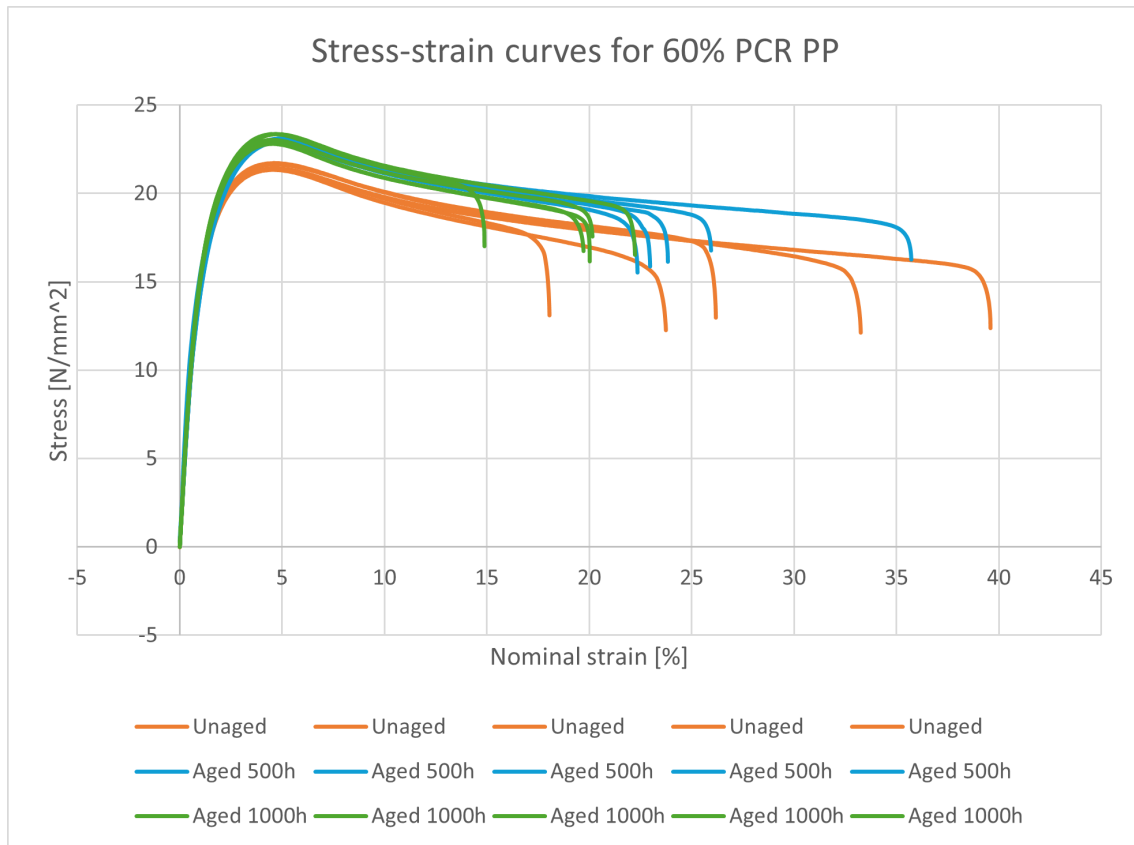


Figure A.5: The stress-strain curves for 60% PCR

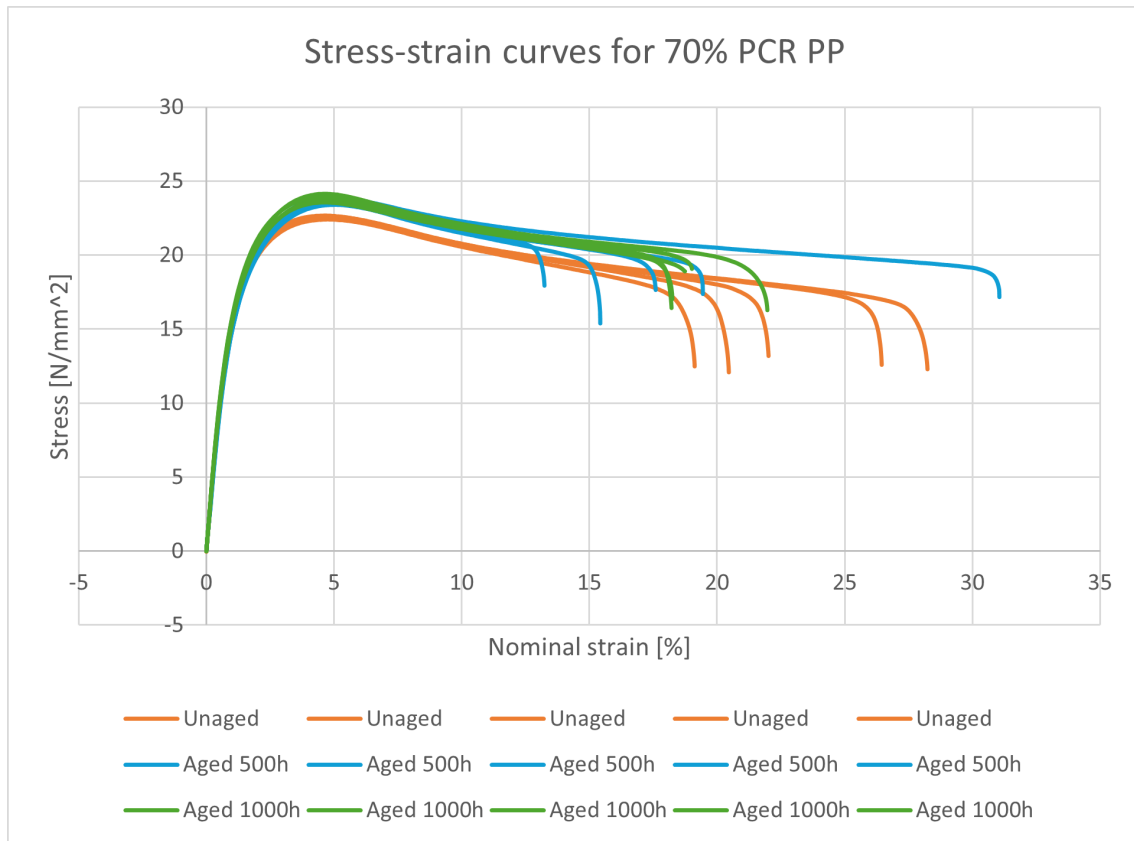


Figure A.6: The stress-strain curves for 70% PCR

A.2.2 Tensile tests - All parameters

Following are all the parameters obtained from the tensile tests with a description of the parameters of the program used called TestXpert:

- Date/Clock time - Date/Clock time
- L_{0Stand} - Gage length, standard travel
- L_{0CH} - Gage length, crosshead
- L_0 - Gage length
- σ_{low} - Tensile modulus, begin
- σ_{high} - Tensile modulus, end
- E_t - Tensile modulus
- σ_y - Yield stress (stress at yield point)
- $\epsilon_{y(corr.)}$ - Yield strain (corr.) (strain at yield point)
- $\epsilon_t Y$ - Nominal yield strain
- σ_M - Tensile strength
- ϵ_M - Strain at tensile strength
- ϵ_B - Strain at break
- h - Specimen thickness
- b - Specimen width
- A_0 - Cross-section

	Specimen no.	Specimen designation	Date/Clock time	L ₀ Stand	L ₀ CH	L ₀
				mm	mm	mm
30PIR_1	1	30PIR_1	45701,41402	50	115,055954	50
30PIR_2	2	30PIR_2	45701,41902	50	115,0000019	50
30PIR_3	3	30PIR_3	45701,42241	50	115,000001	50
30PIR_4	4	30PIR_4	45701,42566	50	114,9999979	50
30PIR_5	5	30PIR_5	45701,42804	50	115	50
30PIR_1	6	30PCR_1	45701,43084	50	114,9999996	50
30PIR_2	7	30PCR_2	45701,43334	50	115,0000002	50
30PIR_3	8	30PCR_3	45701,43502	50	114,9999993	50
30PIR_4	9	30PCR_4	45701,43652	50	115,0000011	50
30PIR_5	10	30PCR_5	45701,43837	50	115,0000009	50
30PIR_1_500	31	30PIR_1_500	45721,5289	50	114,9999983	50
30PIR_2_500	32	30PIR_2_500	45721,53084	50	115,000001	50
30PIR_3_500	33	30PIR_3_500	45721,53218	50	115,0000007	50
30PIR_4_500	34	30PIR_4_500	45721,53374	50	114,9999995	50
30PIR_5_500	35	30PIR_5_500	45721,53517	50	114,9999998	50
30PIR_1_1000	66	30PIR_1_1000	45740,51394		115,000001	115,000001
30PIR_2_1000	67	30PIR_2_1000	45740,51549		115,0000008	115,0000008
30PIR_3_1000	68	30PIR_3_1000	45740,51767	50	115,0592748	50
30PIR_4_1000	69	30PIR_4_1000	45740,51931	50	114,9999991	50
30PIR_5_1000	70	30PIR_5_1000	45740,5205	50	115,0000042	50
30PCR_1	56	30PCR_1	45721,57211	50	115,0000003	50
30PCR_2	57	30PCR_2	45721,57333	50	114,9999961	50
30PCR_3	58	30PCR_3	45721,57473	50	114,9999981	50
30PCR_4	59	30PCR_4	45721,57613	50	115,0000012	50
30PCR_5	60	30PCR_5	45721,57722	50	115,0000042	50
30PCR_1_500	61	30PCR_1_500	45740,50705		114,999999	114,999999
30PCR_2_500	62	30PCR_2_500	45740,50838		114,9999996	114,9999996
30PCR_3_500	63	30PCR_3_500	45740,50977		115,0000037	115,0000037
30PCR_4_500	64	30PCR_4_500	45740,511		114,9999997	114,9999997
30PCR_5_500	65	30PCR_5_500	45740,5123		115	115
30PCR_1_1000	91	30PCR_1_1000	45771,40554	50	114,9999998	50
30PCR_2_1000	92	30PCR_2_1000	45771,40744	50	114,9999993	50
30PCR_3_1000	93	30PCR_3_1000	45771,40876	50	115,0000008	50
30PCR_4_1000	94	30PCR_4_1000	45771,41051	50	115	50
30PCR_5_1000	95	30PCR_5_1000	45771,41227	50	115,0000006	50
40PCR_1	11	40PCR_1	45701,44046	50	114,9999973	50
40PCR_2	12	40PCR_2	45701,44209	50	115,0000013	50
40PCR_3	13	40PCR_3	45701,44343	50	115,0000017	50
40PCR_4	14	40PCR_4	45701,44492	50	114,9999999	50
40PCR_5	15	40PCR_5	45701,44605	50	114,9999996	50
40PCR_1_500	36	40PCR_1_500	45721,53676	50	114,9999989	50
40PCR_2_500	37	40PCR_2_500	45721,53846	50	115,0003029	50
40PCR_3_500	38	40PCR_3_500	45721,54082	50	114,9999999	50
40PCR_4_500	39	40PCR_4_500	45721,54218	50	114,9999986	50
40PCR_5_500	40	40PCR_5_500	45721,54368	50	115,0000005	50

40PCR_1_1000	71	40PCR_1_1000	45740,52234	50	115	50
40PCR_2_1000	72	40PCR_2_1000	45740,52355	50	114,9999995	50
40PCR_3_1000	73	40PCR_3_1000	45740,52728	50	115,0000002	50
40PCR_4_1000	74	40PCR_4_1000	45740,52844	50	115,0000033	50
40PCR_5_1000	75	40PCR_5_1000	45740,52939	50	114,9999989	50
50PCR_1	16	50PCR_1	45701,44747	50	114,9999974	50
50PCR_2	17	50PCR_2	45701,44904	50	114,9999978	50
50PCR_3	18	50PCR_3	45701,4505	50	115,0000016	50
50PCR_4	19	50PCR_4	45701,45191	50	115,0000006	50
50PCR_5	20	50PCR_5	45701,45358	50	114,9999978	50
50PCR_1_500	41	50PCR_1_500	45721,54595	50	114,9999987	50
50PCR_2_500	42	50PCR_2_500	45721,54755	50	114,9999979	50
50PCR_3_500	43	50PCR_3_500	45721,54883	50	115,0000011	50
50PCR_4_500	44	50PCR_4_500	45721,55006	50	114,9999967	50
50PCR_5_500	45	50PCR_5_500	45721,55145	50	115,0000009	50
50PCR_1_1000	76	50PCR_1_1000	45740,53061	50	114,9999972	50
50PCR_2_1000	77	50PCR_2_1000	45740,53184	50	114,9999985	50
50PCR_3_1000	78	50PCR_3_1000	45740,53294	50	115,0000008	50
50PCR_4_1000	79	50PCR_4_1000	45740,53404	50	115,0000014	50
50PCR_5_1000	80	50PCR_5_1000	45740,53535	50	115,0000012	50
60PCR_1	21	60PCR_1	45701,45557	50	114,9999983	50
60PCR_2	22	60PCR_2	45701,45662	50	114,9999991	50
60PCR_3	23	60PCR_3	45701,45802	50	115,0000016	50
60PCR_4	24	60PCR_4	45701,45889	50	114,9999984	50
60PCR_5	25	60PCR_5	45701,45993	50	114,9999974	50
60PCR_1_500	46	60PCR_1_500	45721,55376	50	115,0000014	50
60PCR_2_500	47	60PCR_2_500	45721,55541	50	115,0000031	50
60PCR_3_500	48	60PCR_3_500	45721,55728	50	114,9990092	50
60PCR_4_500	49	60PCR_4_500	45721,55859	50	115,0000005	50
60PCR_5_500	50	60PCR_5_500	45721,55984	50	115,0000007	50
60PCR_1_1000	81	60PCR_1_1000	45740,53653	50	115,0000012	50
60PCR_2_1000	82	60PCR_2_1000	45740,5376	50	114,9999971	50
60PCR_3_1000	83	60PCR_3_1000	45740,53858	50	114,9999988	50
60PCR_4_1000	84	60PCR_4_1000	45740,53997	50	114,9999983	50
60PCR_5_1000	85	60PCR_5_1000	45740,54102	50	114,9999999	50
70PCR_1	26	70PCR_1	45701,46112	50	114,9999986	50
70PCR_2	27	70PCR_2	45701,46228	50	114,9999996	50
70PCR_3	28	70PCR_3	45701,4633	50	115,0000024	50
70PCR_4	29	70PCR_4	45701,46442	50	114,9999986	50
70PCR_5	30	70PCR_5	45701,46557	50	114,9999968	50
70PCR_1_500	51	70PCR_1_500	45721,56409	50	115,0158046	50
70PCR_2_500	52	70PCR_2_500	45721,56532	50	114,9999997	50
70PCR_3_500	53	70PCR_3_500	45721,56631	50	115,0000012	50
70PCR_4_500	54	70PCR_4_500	45721,56734	50	114,9999986	50
70PCR_5_500	55	70PCR_5_500	45721,56895	50	115,0000004	50
70PCR_1_1000	86	70PCR_1_1000	45740,54207	50	115,0000007	50
70PCR_2_1000	87	70PCR_2_1000	45740,54352	50	114,9999977	50
70PCR_3_1000	88	70PCR_3_1000	45740,5445	50	115,0000008	50

70PCR_4_1000	89	70PCR_4_1000	45740,54554	50	114,9999951	50
70PCR_5_1000	90	70PCR_5_1000	45740,54669	50	115,0000001	50

σ_{low}	σ_{high}	E_t	σ_Y	ε_Y (corr.)	ε_{tY}	σ_M
MPa	MPa	MPa	MPa	%	%	MPa
1,473065535	2,071244401	1196,357732	21,52214385	7,093129358	3,896749909	21,52214385
1,439118082	2,058636184	1239,036204	21,00106648	7,213648415	4,350591258	21,00106648
1,294880799	1,920790009	1251,818419	21,20524329	7,33343991	4,147888645	21,20524329
1,334605516	1,950208325	1231,205618	20,98595149	7,392398089	4,464856936	20,98595149
1,37472545	2,014108274	1278,765648	20,84885151	7,464004149	4,018932427	20,84885151
1,224256321	1,807004733	1165,496824	21,86430359	8,075041278	4,472740992	21,86430359
1,405445211	1,981716535	1152,542647	22,36388544	7,48194305	4,145822519	22,36388544
1,454971774	2,118505984	1327,06842	22,57599802	7,618138042	4,179385251	22,57599802
1,30704918	1,912757405	1211,416451	22,55361538	7,777894271	4,213139036	22,55361538
1,393850611	2,051390632	1315,080041	22,22359924	7,845489743	4,30672269	22,22359924
1,302239248	1,945701973	1286,925451	21,83711881	6,981189971	3,796637634	21,83711881
1,522518805	2,151939752	1258,841894	22,07039438	7,141945804	3,889240149	22,07039438
1,426593872	2,084103454	1315,019165	22,06038908	7,088484569	3,92067202	22,06038908
1,45159642	2,068182595	1233,172349	21,98542004	7,119212406	3,917058048	21,98542004
1,491854783	2,148623016	1313,536466	22,24979159	6,873575571	3,794692918	22,24979159
2,015504287	2,947273493	1863,538413	23,21482737	3,963367545	3,95521285	23,21482737
1,995060481	2,884691997	1779,263034	22,64811297	3,981007067	3,968878594	22,64811297
1,307534845	2,036946923	1458,824156	23,19484506	7,169629195	4,03952372	23,19484506
1,329976336	2,000594526	1341,236381	23,07468321	6,979160492	3,810064925	23,07468321
1,360152543	2,004775624	1289,246162	23,29953822	7,795499794	3,877788485	23,29953822
1,229236042	1,831498117	1204,524151	20,19522169	7,672051666	4,396885052	20,19522169
1,195821994	1,793236324	1194,828661	20,4528883	7,930082964	4,594378006	20,4528883
1,625470972	2,378525139	1506,108335	20,18385724	7,760425293	4,516139726	20,18385724
1,269962031	1,844828343	1149,732624	20,36886076	7,460456972	4,345250707	20,36886076
1,425052548	2,139675599	1429,246102	20,5317755	7,839706742	4,680694739	20,5317755
1,929388047	2,819969746	1781,163398	21,96248422	3,986191831	3,977870043	21,96248422
1,85891418	2,722068912	1726,309464	21,52610667	4,112748044	4,105066646	21,52610667
1,879823318	2,743673748	1727,700859	21,55660192	3,949039172	3,940234265	21,55660192
1,884537436	2,76266618	1756,257487	21,57368879	3,964479969	3,957175804	21,57368879
1,87746928	2,746514646	1738,090734	21,58288723	3,990093634	3,982074573	21,58288723
1,324920744	1,941716439	1233,59139	20,81142816	7,607403438	4,378476012	20,81142816
1,292307873	1,845681898	1106,74805	21,10933481	7,436766297	4,190812757	21,10933481
1,439647207	2,087711041	1296,127668	21,19244385	7,456073119	4,365854649	21,19244385
1,228510228	1,832866564	1208,712671	21,01096251	7,541637866	4,379914741	21,01096251
1,453014838	2,134859769	1363,689862	21,31971852	7,156550337	4,196380509	21,31971852
1,409416073	1,98530153	1151,770914	20,89164679	8,052369213	4,356732678	20,89164679
1,308067584	1,884833723	1153,532277	20,56778604	7,843396628	4,145331541	20,56778604
1,323956706	1,920474044	1193,034675	20,91927577	7,770974095	4,273063764	20,91927577
1,183643795	1,774686442	1182,085294	20,80545625	7,718131779	4,178098631	20,80545625
1,33120914	1,994170532	1325,922784	20,68676475	7,860898551	4,281979865	20,68676475
1,3948782	2,075108959	1360,461519	21,49652397	7,22252957	4,051806448	21,49652397
1,195795198	1,831071061	1270,551727	21,54128507	7,418616204	4,079677785	21,54128507
1,372211826	2,000849829	1257,276006	21,18595626	7,479141444	4,126025526	21,18595626
1,369667425	2,058804577	1378,274304	21,56119295	7,539375494	4,168469851	21,56119295
1,398252533	2,021128388	1245,75171	21,48692657	7,426741907	4,094015601	21,48692657

1,701592792	2,267488058	1131,790532	21,95917344	7,280345224	3,974422786	21,95917344
1,357457229	1,970773455	1226,632453	21,59392715	7,682165567	4,132476906	21,59392715
1,354919059	1,965014939	1220,191758	22,03490764	7,4620417	4,273363187	22,03490764
1,344452273	1,880636817	1072,369088	21,5389315	7,920372139	4,109852716	21,5389315
1,436344889	2,051406299	1230,12282	22,0212581	7,427764123	4,142466459	22,0212581
1,285826163	1,868381393	1165,11046	20,72202803	8,930360957	4,724463694	20,72202803
1,328669755	1,963095499	1268,851487	21,35153124	8,275214546	4,452472855	21,35153124
1,304050723	1,944751081	1281,400715	21,20844101	8,271768055	4,436000264	21,20844101
1,32032643	1,947174437	1253,696013	21,28803086	9,085314642	4,846164429	21,28803086
1,339701861	1,923811375	1168,21903	20,9077208	8,534679454	4,627203822	20,9077208
1,442943757	2,133391207	1380,8949	22,1177919	7,934493208	4,52193141	22,1177919
1,350630501	2,060110503	1418,960005	22,0765232	8,055184956	4,664694831	22,0765232
1,493299622	2,115921201	1245,243157	21,74584663	8,343920682	4,782172863	21,74584663
1,395146532	2,060295474	1330,297884	22,18082186	8,134874861	4,709615015	22,18082186
1,46421851	2,081096916	1233,756812	22,24875846	8,108679822	4,709131786	22,24875846
1,287362354	1,846107474	1117,49024	22,72571247	8,851701385	4,545406782	22,72571247
1,262544768	1,729995532	934,9015285	22,22724728	8,998545771	4,563655912	22,22724728
1,35711493	1,863374656	1012,519451	22,0746058	8,755033185	4,381824131	22,0746058
1,387127199	1,903500438	1032,746478	22,14947956	8,954314473	4,57474952	22,14947956
1,342898298	1,949080861	1212,365127	22,81811077	8,920766667	4,546831748	22,81811077
1,337405504	1,969231762	1263,652517	21,33654487	8,495836264	4,498964459	21,33654487
1,26087477	1,855990888	1190,232235	21,38954274	8,755935189	4,63962517	21,38954274
1,380258605	1,983225371	1205,933533	21,42538378	8,984455879	4,722355899	21,42538378
1,298125848	1,937056179	1277,860661	21,64371993	8,811586288	4,690690314	21,64371993
1,299702223	1,916971732	1234,539017	21,72218655	8,745278114	4,608674777	21,72218655
2,003565346	2,61866332	1230,195947	22,91500929	8,212865164	4,954895707	22,91500929
1,520943708	2,193086756	1344,286096	22,91786305	8,253141141	4,780491409	22,91786305
1,411521352	1,930892198	1038,741692	23,09433356	9,265887161	4,900160176	23,09433356
1,463381788	2,291234453	1655,70533	22,89660198	8,198384231	4,799685664	22,89660198
1,547847651	2,276757216	1457,819129	23,10956853	8,15617518	4,925540398	23,10956853
1,44360007	2,063027726	1238,855312	23,03181123	8,097527259	4,443199277	23,03181123
1,324746013	1,867855163	1086,218301	23,35452196	9,091959158	4,698334687	23,35452196
1,505508981	2,151840953	1292,663944	22,96696509	8,012465426	4,368599646	22,96696509
1,394060736	2,045356184	1302,590896	22,80886766	8,364522223	4,558317002	22,80886766
1,465048345	2,07868175	1227,266811	23,36077881	8,249374427	4,677238507	23,36077881
1,384797039	2,034253899	1298,91372	22,583895	8,800611606	4,616074825	22,583895
1,364839377	2,046390802	1363,10285	22,67180878	8,830127319	4,667065826	22,67180878
1,387617887	1,989577291	1203,918808	22,52685517	8,945258733	4,707227692	22,52685517
1,450737449	2,084318806	1267,162713	22,62801955	8,914486688	4,735357923	22,62801955
1,286644663	1,914585184	1255,881044	22,41101318	9,004949145	4,737561401	22,41101318
1,716693223	3,007108358	2580,83027	23,62345477	8,335016847	4,915911898	23,62345477
1,793908094	2,91927077	2250,725351	23,50186381	8,272203096	4,96187543	23,50186381
1,644596378	2,412913994	1536,635231	23,63242991	8,257025815	4,7836863	23,63242991
1,740008468	2,564401381	1648,785825	23,90147586	8,435533022	4,976539674	23,90147586
1,608465797	2,394847394	1572,763194	23,4010903	8,702269865	5,060434737	23,4010903
1,564274671	2,265879174	1403,209005	24,14309767	8,21147819	4,672181889	24,14309767
1,393383398	2,04476462	1302,762445	23,75634319	8,366955718	4,703946416	23,75634319
1,445256114	2,039973185	1189,434141	23,67424644	9,451508177	4,70418678	23,67424644

1,442266696	2,111672181	1338,81097	23,56518406	8,447727014	4,56572262	23,56518406
1,463883841	2,133042123	1338,316563	23,92023003	8,257382625	4,55619936	23,92023003

ε_M	ε_B	h	b	A_0
%	%	mm	mm	mm ²
7,070000172	63,29881989	4,1	10	41
7,197500229	29,43042321	4,1	10	40,59
7,329999924	28,92724071	4,1	10	40,59
7,383999825	35,37211449	4,1	10	41
7,456500053	27,87694973	4,1	9,9	40,59
8,069999695	37,39635663	4	10	40
7,460000038	30,82680239	4	9,9	39,6
7,608500004	29,05764371	4	9,9	39,6
7,769999981	49,25651525	4	9,9	39,6
7,83949995	39,76490694	4	10	40
6,980000019	20,74973368	4,1	9,9	40,59
7,120999813	25,84414634	4,1	10	41
7,079999924	31,38550459	4,1	10	41
7,101500034	31,10484194	4,1	10	41
6,860000134	29,09719144	4,1	10	41
3,95521285	48,12180188	4,1	10	41
3,968878594	29,83831302	4,1	10	41
7,179999828	42,34719734	4,1	10	41
6,980000019	31,20169697	4,1	10	41
7,789999962	43,02799525	4,1	10	41
7,670000076	32,50490098	4,1	10	41
7,929999828	47,38738437	4,1	10	41
7,752500057	39,91654145	4,1	10	41
7,449999809	31,83755268	4,1	10	41
7,840000153	32,55172384	4,1	10	41
3,977870043	28,52099459	4,1	10	41
4,105066646	34,77893012	4,1	10	41
3,940234265	30,68666443	4,1	10	41
3,957175804	21,82654511	4,1	10	41
3,982074573	27,242838	4,1	10	41
7,599999905	31,3204606	4,1	10	41
7,420000076	26,51699374	4,1	10	41
7,445000172	36,06745616	4,1	10	41
7,539999962	29,62090099	4,1	10	41
7,150000095	34,67671049	4,1	10	41
8,029999733	31,1437991	4,1	9,9	40,59
7,829999924	29,64132726	4,1	9,9	40,59
7,760000229	36,30086667	4,1	9,9	40,59
7,717999935	24,25090922	4,1	9,9	40,59
7,860499859	34,77057913	4,1	9,9	40,59
7,21999979	21,9894378	4,1	10	41
7,424499989	33,13654048	4,1	10	41
7,46999979	29,49272463	4,1	10	41
7,539999962	32,43938315	4,1	10	41
7,414500237	36,68563549	4,1	10	41

7,230000019	37,3241041	4,1	10	41
7,671500206	31,9127578	4,1	10	41
7,451000214	36,57361647	4,1	10	41
7,894999981	18,76369723	4,1	10	41
7,410999775	26,84911445	4,1	10	41
8,920000076	45,47464088	4,1	10	41
8,270500183	35,53300937	4,1	10	41
8,270000458	32,09027854	4,1	10	41
9,079999924	60,55654865	4,1	10	41
8,520000458	38,05844382	4,1	10	41
7,929999828	27,30260827	4,1	10	41
8,06000042	31,47045182	4,1	10	41
8,324000359	33,56619312	4,1	10	41
8,130000114	31,60504442	4,1	10	41
8,090000153	34,9264967	4,1	10	41
8,836500168	33,80505926	4,1	10	41
8,963500023	26,43794821	4,1	10	41
8,720999718	31,07326946	4,1	10	41
8,920000076	45,36964352	4,1	10	41
8,909999847	36,85283523	4,1	10	41
8,489999771	29,4947009	4,1	10	41
8,75	45,47035048	4,1	10	41
8,970000267	23,98124313	4,1	10	41
8,81000042	32,1876656	4,1	10	41
8,739999771	39,27730888	4,1	9,9	40,59
8,149999619	26,92249121	4,1	10	41
8,239999771	28,10644187	4,1	10	41
9,229999542	31,98342881	4,1	10	41
8,210000038	28,78382911	4,1	10	41
8,149999619	40,59163163	4,1	10	41
8,081000328	25,46446877	4,1	10	41
9,069999695	28,30268204	4,1	10	41
7,995999813	25,07281733	4,1	10	41
8,357500076	25,09829786	4,1	10	41
8,229999542	19,83374699	4,1	10	41
8,793999672	34,20702849	4,1	9,9	40,59
8,829999924	27,9051066	4,1	9,9	40,59
8,930000305	32,47116408	4,1	9,9	40,59
8,899999619	26,47474489	4,1	9,9	40,59
9,00249958	25,13967899	4,1	9,9	40,59
8,368499756	22,48421657	4,1	10	41
8,292499542	20,21060639	4,1	10	41
8,25	18,21517921	4,1	10	41
8,430000305	36,18412621	4,1	10	41
8,699999809	24,66296091	4,1	10	41
8,199999809	23,22178253	4,1	10	41
8,359999657	23,46671365	4,1	10	41
9,430000305	25,57938202	4,1	10	41

8,43999958	24,61945573	4,1	10	41
8,248000145	27,1595667	4,1	10	41

A.3 DSC values

The obtained peak temperature, enthalpy, and crystallinity can be seen in Figures A.7 and A.8.

Total crystallinity
Limits: 100-190°C

Material:	Curve 1			Curve 3		
	Peak temp. [°C]:	Enthalpy [Jg ⁻¹):	Crystallinity [%]:	Peak temp. [°C]:	Enthalpy [Jg ⁻¹):	Crystallinity [%]:
PIR 30%	166,48	-56,7	27,3913043	166,14	-63,81	30,82608696
PIR 30%	167,01	-55,3	26,7149758	165,83	-63,27	30,56521739
PCR 30%	166,17	-56,29	27,1932367	165,34	-63,95	30,89371981
PCR 30%	165,46	-54,01	26,0917874	166,44	-62,63	30,25603865
PCR 40%	164,8	-56,1	27,1014493	167,13	-63,68	30,76328502
PCR 40%	166,96	-56,59	27,3381643	165,29	-63,04	30,45410628
PCR 50%	164,46	-61,49	29,705314	164,41	-65,71	31,74396135
PCR 50%	165,64	-57,66	27,8550725	164,94	-63,96	30,89855072
PCR 60%	166	-57,79	27,9178744	166	-65,03	31,41545894
PCR 60%	164,31	-57,3	27,6811594	164,78	-66,1	31,93236715
PCR 70%	165,98	-60,35	29,1545894	164,98	-67	32,36714976
PCR 70%	165	-59,2	28,5990338	165,13	-66,5	32,12560386
PCR 40%_500h	163,86	-60,13	29,0483092	164,84	-63,82	30,83091787
PCR 40%_500h	166,67	-59,24	28,6183575	165,33	-63,74	30,79227053
PCR 70%_500h	166,67	-61,83	29,8695652	165,65	-66,3	32,02898551
PCR 70%_500h	166,46	-63,48	30,6666667	164,95	-67,18	32,45410628

Crystallinity big peak
Limits: 140-190°C

Material:	Curve 1			Curve 3		
	Peak temp. [°C]:	Enthalpy [Jg ⁻¹):	Crystallinity [%]:	Peak temp. [°C]:	Enthalpy [Jg ⁻¹):	Crystallinity [%]:
PIR 30%	166,48	-43,88	21,1980676	166,14	-48,72	23,53623188
PIR 30%	167,01	-44,44	21,468599	166	-48,4	23,38164251
PCR 30%	166,17	-43,48	21,0048309	165,34	-45,74	22,09661836
PCR 30%	165,62	-41,05	19,8309179	166,44	-46,16	22,29951691
PCR 40%	164,8	-38,9	18,7922705	167,13	-44,03	21,2705314
PCR 40%	166,96	-42,43	20,4975845	165,29	-44,24	21,37198068
PCR 50%	164,63	-39,2	18,9371981	164,41	-43,37	20,95169082
PCR 50%	165,64	-40,44	19,5362319	164,94	-42,97	20,75845411
PCR 60%	166	-39,23	18,9516908	166,16	-42,88	20,71497585
PCR 60%	164,31	-38,84	18,763285	164,78	-41,63	20,11111111
PCR 70%	165,98	-40,95	19,7826087	164,98	-42,81	20,68115942
PCR 70%	165	-39,19	18,9323671	165,13	-41,24	19,92270531
PCR 40%_500h	163,86	-39,38	19,0241546	164,84	-43,48	21,00483092
PCR 40%_500h	166,84	-38,43	18,5652174	165,33	-41,26	19,93236715
PCR 70%_500h	166,83	-38,84	18,763285	165,65	-39,1	18,88888889
PCR 70%_500h	166,63	-40,38	19,5072464	164,95	-40,9	19,75845411

Figure A.7: Values for big and small peak together, and the small big peak

Crystallinity small peak
Limits: 100-140°C

Material:	Curve 1			Curve 3		
	Peak temp. [°C]:	Enthalpy [Jg ⁻¹]:	Crystallinity [%]:	Peak temp. [°C]:	Enthalpy [Jg ⁻¹]:	Crystallinity [%]:
PIR 30%	No peak			No peak		
PIR 30%	No peak			No peak		
PCR 30%	127,09	-2,36	1,14009662	127,09	-1,62	0,782608696
PCR 30%	127,06	-2,28	1,10144928	127,23	-1,38	0,666666667
PCR 40%	127,22	-3,67	1,77294686	128,39	-2,09	1,009661836
PCR 40%	127,56	-3,68	1,77777778	127,72	-2,76	1,333333333
PCR 50%	127,05	-4,28	2,06763285	127,04	-3,52	1,700483092
PCR 50%	127,56	-4,44	2,14492754	127,55	-3,83	1,850241546
PCR 60%	128,28	-5,34	2,57971014	128,9	-4,58	2,212560386
PCR 60%	127,88	-5,45	2,63285024	128,21	-4,52	2,183574879
PCR 70%	128,55	-6,58	3,17874396	129,22	-6,16	2,975845411
PCR 70%	127,89	-6,51	3,14492754	128,22	-5,92	2,859903382
PCR 40%_500h	127,43	-4,54	2,19323671	126,93	-2,54	1,22705314
PCR 40%_500h	127,58	-4,26	2,05797101	127,58	-1,34	0,647342995
PCR 70%_500h	128,89	-8,43	4,07246377	129,23	-4,82	2,328502415
PCR 70%_500h	128,87	-9,06	4,37681159	128,87	-5,69	2,748792271

Figure A.8: The values for the small peak

A.4 Impact test - results

Following are the measured values of the impact tests along with what type of break occurred.

Material (unaged):	Measured value (J):	Note:	Material (aged 500h):	Measured value (J):	Note:	Material (aged 1000h):	Measured value (J):	Note:
PIR 30% - 1	6,39	Breaks completely	PIR 30% - 1	6,51	Breaks completely	PIR 30% - 1	7,03	Breaks completely
PIR 30% - 2	6,34	Breaks completely	PIR 30% - 2	7,05	Breaks completely	PIR 30% - 2	6,52	Breaks completely
PIR 30% - 3	6,43	Breaks completely	PIR 30% - 3	6,82	Breaks completely	PIR 30% - 3	6,01	Breaks completely
PIR 30% - 4	5,91	Breaks completely	PIR 30% - 4	6,63	Breaks completely	PIR 30% - 4	7,08	Breaks completely
PIR 30% - 5	6,36	Breaks completely	PIR 30% - 5	5,16	Breaks completely	PIR 30% - 5	5,49	Breaks completely
Mean value:	6,286		Mean value:	6,434		Mean value:	6,426	
PCR 30% - 1	6,57	Breaks completely	PCR 30% - 1	5,56	Breaks completely	PCR 30% - 1	3,84	Breaks completely
PCR 30% - 2	6,7	Breaks completely	PCR 30% - 2	4	Breaks completely	PCR 30% - 2	4,29	Breaks completely
PCR 30% - 3	6,12	Breaks completely	PCR 30% - 3	4,95	Breaks completely	PCR 30% - 3	3,03	Breaks completely
PCR 30% - 4	6,45	Breaks completely	PCR 30% - 4	5,05	Breaks completely	PCR 30% - 4	3,3	Breaks completely
PCR 30% - 5	5,71	Breaks completely	PCR 30% - 5	2,62	Breaks completely	PCR 30% - 5	4,23	Breaks completely
Mean value:	6,31		Mean value:	4,436		Mean value:	3,738	
PCR 40% - 1	5,19	Breaks completely	PCR 40% - 1	5,2	Breaks completely	PCR 40% - 1	3,4	Breaks completely
PCR 40% - 2	4,87	Breaks completely	PCR 40% - 2	3,4	Breaks completely	PCR 40% - 2	3,22	Breaks completely
PCR 40% - 3	4,99	Breaks completely	PCR 40% - 3	3,07	Breaks completely	PCR 40% - 3	3,87	Breaks completely
PCR 40% - 4	3,39	Breaks completely	PCR 40% - 4	3,37	Breaks completely	PCR 40% - 4	3,84	Breaks completely
PCR 40% - 5	4,03	Breaks completely	PCR 40% - 5	2,67	Breaks completely	PCR 40% - 5	4,57	Breaks completely
Mean value:	4,494		Mean value:	3,542		Mean value:	3,78	
PCR 50% - 1	2,53	Breaks completely	PCR 50% - 1	3,97	Breaks completely	PCR 50% - 1	4,05	Breaks completely
PCR 50% - 2	3,07	Breaks completely	PCR 50% - 2	4,81	Breaks completely	PCR 50% - 2	4,17	Breaks completely
PCR 50% - 3	3,67	Breaks completely	PCR 50% - 3	4,3	Breaks completely	PCR 50% - 3	4,41	Breaks completely
PCR 50% - 4	3,55	Breaks completely	PCR 50% - 4	2,91	Breaks completely	PCR 50% - 4	4,17	Breaks completely
PCR 50% - 5	2,53	Breaks completely	PCR 50% - 5	1,95	Breaks completely	PCR 50% - 5	3,03	Breaks completely
Mean value:	3,07		Mean value:	3,588		Mean value:	3,966	
PCR 60% - 1	3,07	Breaks completely	PCR 60% - 1	3,76	Breaks completely	PCR 60% - 1	3,51	Breaks completely
PCR 60% - 2	3,15	Breaks completely	PCR 60% - 2	1,54	Breaks completely	PCR 60% - 2	1,57	Breaks completely
PCR 60% - 3	1,17	Breaks completely	PCR 60% - 3	3,09	Breaks completely	PCR 60% - 3	2,91	Breaks completely
PCR 60% - 4	2,71	Breaks completely	PCR 60% - 4	1,89	Breaks completely	PCR 60% - 4	2,82	Breaks completely
PCR 60% - 5	1,21	Breaks completely	PCR 60% - 5	2,74	Breaks completely	PCR 60% - 5	2,64	Breaks completely
Mean value:	2,262		Mean value:	2,604		Mean value:	2,69	
PCR 70% - 1	1,89	Breaks completely	PCR 70% - 1	2,37	Breaks completely	PCR 70% - 1	2,41	Breaks completely
PCR 70% - 2	3,01	Breaks completely	PCR 70% - 2	1,81	Breaks completely	PCR 70% - 2	2,8	Breaks completely
PCR 70% - 3	2,2	Breaks completely	PCR 70% - 3	3,03	Breaks completely	PCR 70% - 3	1,42	Breaks completely
PCR 70% - 4	1,95	Breaks completely	PCR 70% - 4	2,58	Breaks completely	PCR 70% - 4	2,2	Breaks completely
PCR 70% - 5	2,53	Breaks completely	PCR 70% - 5	3,4	Breaks completely	PCR 70% - 5	2,29	Breaks completely
Mean value:	2,316		Mean value:	2,638		Mean value:	2,224	

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