# Quality Assurance of Recycled HDPE in the Plastic Packaging Industry

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MASTER THESIS

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# Abstract


The recycling of plastic has the potential to support circular material use, thus decreasing the need for virgin plastics. However, there is an existing issue with assuring quality of recycled plastic materials, causing finished products to perform with poorer properties and unexpected deviations. Based on a thermoformed plastic packaging product, *Product Y*, made of recycled high density polyethylene (HDPE), this thesis is written in collaboration with *Company X* and researches how to assure quality of *Product Y*.

The purpose of the thesis is to research how Company X can achieve uniform quality on the finished products, regardless of when or where the recycled HDPE is manufactured. To fulfill the aim of the thesis, the research questions to be answered are:

1. What affects the quality of recycled post-industrial and post-consumer HDPE to be used for packaging?
2. What is most important regarding the recycling processes to achieve high-quality plastic?
3. What are the issues regarding plastic recycling processes globally?

The method is divided into three parts; a literature study to gain necessary background knowledge on the subject, conducted interviews with internal and external industry representatives to gain insights on how the industry works today, and material testing to compare if the results are corresponding to expected results. The material testing includes Shore D hardness test, measuring of material thickness, tensile test, melt flow index, differential scanning calorimetry, and thermoforming test with a following visual inspection of the finished products.

After analyzing interview findings and material testing, it was concluded that conducting polymer tests for different material properties is important for quality assurance. The customer and plastic processing company should agree on the testing procedure. Cooperation between the involved parties is crucial for successful quality assurance of the recycled material. Transparency, global standards, and a coordinated approach will help overcome quality assurance challenges in plastic recycling today.



**Keywords:** Thermoforming, Plastics, Recycling, Packaging Industry, HDPE

# Sammanfattning

Återvinning av plast har potential att stödja cirkulär materialanvändning, vilket minskar behovet för nyvara. Det förekommer däremot problematik med att kvalitetssäkra återvunnet plastmaterial, vilket ger färdiga produkter sämre mekaniska egenskaper, med oväntade avvikelser. Detta projekt är skrivet i samarbete med bolaget *Company X*, och bygger på en termoformad plastförpackningsprodukt, *Product Y*, tillverkad av återvunnen högdensitets-polyeten (HDPE). I projektet undersöks hur man kan kvalitetssäkra *Product Y* som en termoformad, färdig produkt. Syftet med projektet är att undersöka hur *Company X* kan uppnå en enhetlig kvalitet på slutprodukten, oavsett när eller var den återvunna HDPE:n tillverkats. För att uppfylla givet syfte ska följande frågeställningar besvaras:

1. Vad påverkar kvaliteten på återvunnen HDPE, från postindustriell produktion och produktion av konsumtionsavfall som ska användas för förpackningar?
2. Vad är viktigast när det gäller återvinningsprocesserna för att uppnå högkvalitativa plastmaterial?
3. Vilka är de problem, ur ett globalt perspektiv, som rör återvinningsprocesserna för plast?

Metoden är uppdelad i tre delar; en litteraturstudie för att få nödvändig bakgrundskunskap om ämnet, intervjuer med interna och externa branschföreträdare för att få insikter om hur återvinnings- och plastindustrin fungerar idag, samt materialprovning för att jämföra om resultaten motsvarar de förväntade resultaten. Materialproverna omfattar Shore D hårdhetsmätning, mätning av materialtjocklek, dragprov, smältindex (MFI), differentiell svepkalorimetri (DSC) och termoformning med efterföljande visuell inspektion av de färdiga produkterna.

Efter analys av intervju- och materialtestresultat drogs slutsatsen att testning av flera olika materialegenskaper är en grundläggande faktor för kvalitetssäkring. Vidare bör kund och plastbearbetningsföretag komma överens om en passande testprocedur. Även samarbetet mellan berörda parter är avgörande för en framgångsrik kvalitetssäkring av återvunnet material. Öppenhet, globala standarder och ett samordnat tillvägagångssätt kommer att bidra till att lösa problemen med kvalitetssäkring inom dagens plaståtervinning.

**Nyckelord:** Termoformning, Plast, Återvinning, Förpackningsindustri, HDPE

# Acknowledgments

This master thesis in mechanical engineering was written at the Department of Design Sciences at Lund University, together with the global packaging solutions company, Company X. We would like to begin with thanking everyone at Company X involved in this project, especially our supervisor at the company, for the cooperation, and for giving us the opportunity to work with such an important and interesting project.

We would also like to send a special thanks to our supervisor at Lund University, Katarina Elner-Haglund, for always guiding, supporting, and encouraging us throughout this project. Without her important feedback and expertise within the field, this project would not have been possible. Whenever we felt unsure about things, she was always there to guide us towards the right direction.

Furthermore, we would like to thank all interviewees; Rickard Jansson, Henrik Eriksson, Anette Munch Elmér, Lars Josefsson and Anders Sjögren, for providing us their insight and knowledge within the field of recycled plastics and material testing.

We also would like to thank Company T2 in Europe, for inviting us to come and visit their facilities, and Company X2 in Europe, for letting us perform the material testing at their producing site.

Lastly, we would like to thank each other, as well as our families and friends for the continuous support throughout the project.

Tora Abrahamsson

Lund, June 2023

Juliana Kalling

Lund, June 2023

# Table of contents

# List of acronyms and abbreviations

| | |
|---|---|
| AQL | Acceptable Quality Level |
| DSC | Differential Scanning Calorimetry |
| HDPE | High Density Polyethylene |
| LDPE | Low Density Polyethylene |
| LLDPE | Linear Low Density Polyethylene |
| MFI | Melt Flow Index |
| MFR | Melt Flow Rate |
| MSW | Municipal Solid Waste |
| NIR | Near Infrared |
| PA | Polyamide |
| PCR | Post Consumer Recyclate |
| PE | Polyethylene |
| PET | Polyethylene Terephthalate |
| PIR | Post Industrial Recyclate |
| PP | Polypropylene |
| PS | Polystyrene |
| PSW | Plastic Solid Waste |
| PVC | Polyvinyl Chloride |
| PVDC | Polyvinylidene Chloride |
| PW | Plastic Waste |
| TDS | Technical Data Sheet |
| VLDPE | Very Low Density Polyethylene |
| WG | Waste Generation |
| QSS | Quality Specification Sheet |

# Acronyms of Companies

**Company X** – Collaborating Company for the Master Thesis

- Company X1 – Acquired company by Company X
    - Company X1 in Asia – Producing site of i.e., Product Y
    - Company X1 in the Americas – Producing unit monitoring production of i.e., Product Y
        - Company E1 – Extrusion company for North American production
        - Company ET1 – Extrusion and thermoforming company for Central American production of Product Y
        - Company T1 – Thermoforming company for North American production of Product Y
- Company X2 in Europe – Acquired thermoforming company for European production of Product Y
        - Company E2 – Extrusion company in Europe

**Product Y** – Product of Focus for the Master Thesis

*Company T2 in Europe* – External thermoforming company in Europe

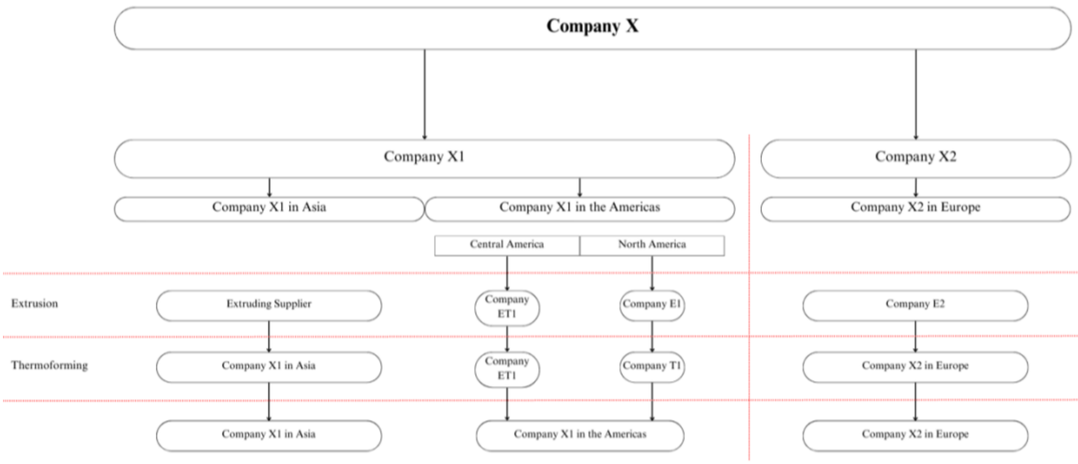


**Figure A Mindmap over production of Product Y with Company X**

# 1 Introduction

*In this chapter, the overall topic of the study, its problematization, and background is found. Furthermore, the purpose, and the research questions are to be defined. Lastly, the scope, limitations and outline are presented.*

## 1.1 Background

Within the industry of producing goods, the use of recycled plastics has been increasing. A report from the Organization for Economic Cooperation and Development (OECD), the Global Plastics Outlook, shows that plastic production has doubled over the past two decades, with only 9% of it currently being effectively recycled. The report further reveals that global plastic production reached 460 million tonnes in 2019. (OECD, 2022)

Throughout the lifetime of plastic materials, the market size of plastic waste generation has grown (Hopewell, 2009, 1). Since 2005, the value of global exports of plastic or plastic-made goods has more than doubled, nearly reaching $1.2 trillion in 2021. Although the volume of plastic exports has grown slightly slower, it has still followed a comparable trajectory, rising to 369 million metric tons in 2021. (UNCTAD, 2022)

Due to high production and consumption demand, plastic solid waste (PSW) is a significant contributor to global waste generation, leading to an increasing challenge for disposal. The level of waste generated varies by country, e.g., income level, disposal resources, and legislated trade agreements worldwide. Management of waste is a complex process due to requirements from multiple sources providing different information, such as identifying factors in waste generation, reliable data, and forecasts of vast waste volumes. (Singh et al. 2017, 410)

Recycling involves waste being reused in offered products, extending life cycles for plastic raw materials, including both post-consumer (PCR)-, and post-industrial (PIR)- recycled materials. The recycling of plastics has the potential to support circular material use. However, to ensure successful implementation, it is crucial to have the necessary equipment and expertise to meet the market's demands for recycled materials as a source for new products. This requires competence and investment in upgrading recycling facilities. (RISE, 2022)

## 1.2 The Plastic Packaging Industry

Plastic is one of the most common materials used for packaging due to its low cost, good processing properties, and good physicochemical properties. Mostly the plastic is used for food packaging, in the forms of films, sheets, bottles, cups, trays, etc.

Polyethylene (PE) is the most common plastic produced in the world. It is used in the plastic packaging industry in various forms due to its ability to be hard and rigid, as well as soft and pliable. High-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene are the three types of PE often used in the packaging industry. Other common plastic packaging materials are e.g., Polypropylene (PP) and Polyethylene terephthalate (PET). (Balakrishnan, P. et al. 2014)

## 1.3 Company Introduction

This thesis is in collaboration with a company within the packaging industry, Company X. With more than 70 years in the field, Company X is a global packaging supplier active in over 30 countries that offers a wide range of packaging products, counseling, and service.

The company designs, prototypes, tests, and delivers complete packaging solutions and complimentary services, striving to reduce customer costs for logistics, product protection, and the environmental impact on their supply chains. Many of the customers are international industrial groups, working in industries such as telecom, energy, lithium batteries, and automotive. Currently, Company X is working on becoming a green industrial packaging company, reviewing Life-Cycle Assessments (LCA) to optimize resources.

Among the sustainable work, one pillar involves sustainable cushioning solutions during transportation of sensitive, delicate electronic products that demand protection. The goal is to maintain both quality and functionality when exposed to external impact. Company X uses thermoformed HDPE with a customized design for this purpose. Considering the environmental aspects in today's society, Company X would like to use as high an amount of recycled content, HDPE, in the thermoformed cushioning product as possible.

Focusing on one specific product, Product Y, produced in the Americas, Europe, and Asia, this thesis will investigate the root causes of these deviations, to suggest further improvements in recycled material quality and traceability in the recycled-plastic industry. What has been observed is that the extruded plastic foil from different global regions shows different levels of quality visually, in the final thermoformed design for Product Y, depending on where the semi-finished material, i.e., the extruded foil, is produced. The production of Product Y is distributed between three different producing sites, with a total of four production lines, illustrated in Figure 1.1 below. As shown in Figure 1.2, the main issue with Product Y was initially aesthetic, observed in the two American production lines. Further description of the production will be highlighted in Section 4.2 Producing sites. An encrypted drawing of Product Y is seen in Figure 1.3 below.

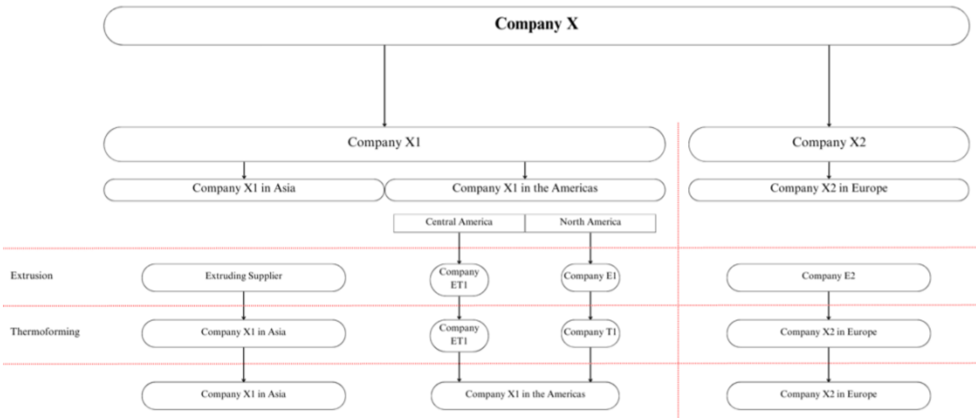


**Figure 1.1 Mindmap over production of Product Y with Company X**

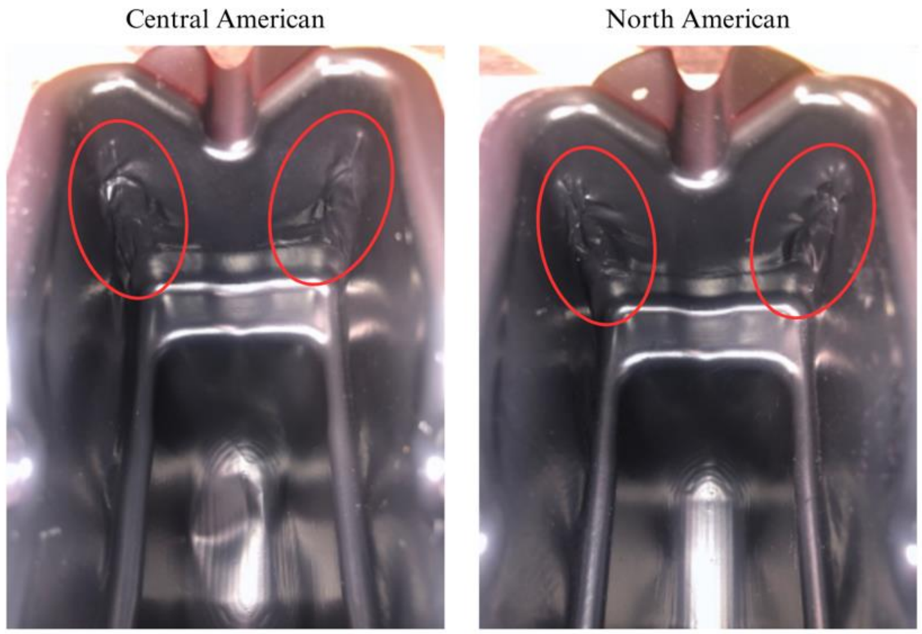


**Figure 1.2 Initial aesthetic issues in the corners of Product Y at the American producing lines**

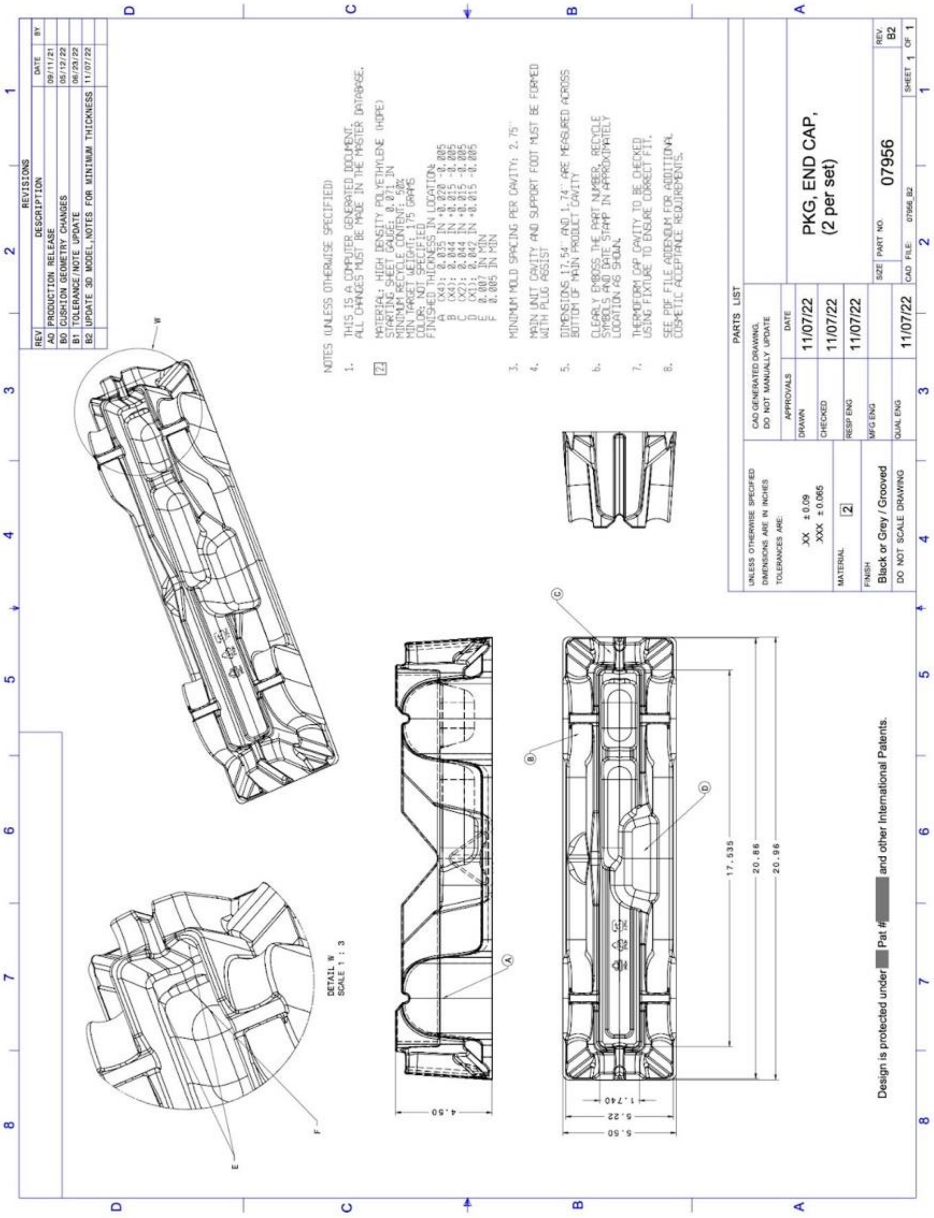


**Figure 1.3 Encrypted drawing of Product Y**

## 1.4 Purpose

The purpose of this project is to research how Company X can achieve a long-term solution for a uniform quality on the finished thermoformed product, regardless of when or where the recycled HDPE is sourced, extruded and thermoformed. Focusing on the production of the cushioning product, made of recycled HDPE, the aim is to present guidelines on how to ensure quality on the final product.

## 1.5 Research Questions

To fulfill the goals and the aim of this thesis the research questions to be answered are:

1. What affects the quality of recycled post-industrial and post-consumer HDPE to be used for packaging?
2. What is most important regarding the recycling processes to achieve high-quality plastic?
3. What are the issues regarding plastic recycling processes globally?

## 1.6 Limitations

In this degree project, High-Density Polyethylene (HDPE) is the only plastic taken into consideration, and other plastics are not further researched. However, the final guidelines and findings in this degree project can hopefully be applied in approaching other similar materials and issues as well. The material testing procedure will be chosen and executed based on the time limitations of this thesis. Furthermore, no research or testing will be focusing on specific processing settings for extrusion- and thermoforming machines, as well as mold-, or product design alterations.

# 2 Methodology

*In this section the methodology is presented, describing the way of working throughout the project.*

## 2.1 Literature Study

The initial step in the project was to gain a deeper knowledge about the subject to create valuable interview questions and support how to best conduct the material testing. This was done by collecting information on what literature and publications exist on the topic that can be of help in the execution of the project. The information was gathered from a variety of different sources such as books, research papers, and public information. To begin, prior course literature was used, as well as search databases such as LUBsearch (Lund University Libraries), to find literature, research papers, and academic journals on the subject. In this stage, keywords like "HDPE", "plastic recycling", "thermoforming" and "polymers" were used to filter out the different publications relevant for use in the thesis.

## 2.2 Interviews

During the initial phase of the project, ongoing meetings and interviews were conducted with Company X representatives within the topic, to gather information about the issue and the current situation. By e-mail, virtual chat forums, and video call applications such as Zoom and Microsoft Teams, representatives from the three production sites got to answer questions on the topic. This was done by creating a so-called *Question Bank*, with the same questions provided to all three sites, for facilitated comparison.

The question bank was divided into three parts: the current issue with Product Y, the suppliers and the recycling process of used material, and the sites' manufacturing and testing processes of the material and final product.

Moreover, further external interviews were conducted with representatives from the industry with knowledge of recycling processes, polymers, thermoforming, and material testing. A thermoforming company, Company T2 in Europe, was visited, and the other interviews were held using Zoom or Microsoft Teams.

Research on the companies was conducted to prepare relevant questions for each candidate. If permission was given, the interviews were recorded. Based on what area of knowledge the interviewee held, specific questions regarding this topic were asked. However, all candidates were asked questions about quality assurance regarding recycled plastics. Furthermore, all candidates were initially requested to do a short presentation about themselves, the position at the company, and what the company does.

During the interviews, the prepared questions were asked, and short notes were taken continuously in order to summarize a transcript of the interview later. These summaries were then sent to each candidate for approval. All external interviews, except the company visit at Company T2 in Europe, were held in Swedish and then translated into English.

## 2.3 Material Testing

To execute the material testing at the testing site in Europe, rolls of extruded foil, made of recycled HDPE, were gathered, and shipped from the three involved locations in Asia, the Americas, and Europe. To make the testing as true to reality as possible, the delivered material from each region was requested to have the same properties as used at each production site for Product Y respectively. All rolls were of 100% recycled content, however with different ratios between post consumer-, (PCR) and post industrial (PIR) recyclate. Two of the rolls consisted of a mix between PIR and PCR material, while the third roll was of 100% PIR material. Moreover, one roll with virgin HDPE was tested for reference. Material from the North American production at Company X1 in the Americas was chosen to be tested since the Central American supplier is under review. The Tensile-, melt flow index (MFI), and differential scanning calorimetry (DSC) testing were performed in an external laboratory, with the help of a laboratory assistant. The Shore D hardness testing, material thickness, as well as the thermoforming test following visual inspection, were done at the facilities of Company X2 in Europe.

To conduct comparisons between the material properties along the extruded rolls through testing, samples of the foil were cut off from two regions from each roll. As Figure 2.1 is illustrating below, the foil rolls were divided into three regions, for facilitated tracking during material testing. One sample was taken from the initiating part of the roll, region A, and a second one from the middle part of the roll, region B. Both samples had a size of about 700x500mm. Despite the request for a material with no differences from usual production, some of the extruded rolls were customized for the thesis' testing procedure. A smaller batch of extruded foil was used, compared to an average roll when thermoforming Product Y. The European recycled material was however of the original size for the production of Product Y. Due to time limitations, no samples of the inner layer, region C, were sampled.

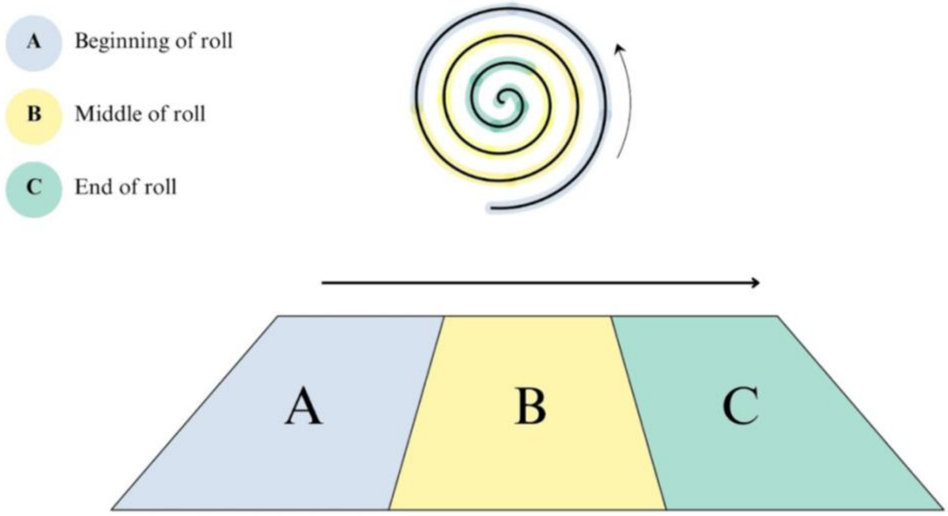


**Figure 2.1 Illustration of collected foil samples for material testing, both rolled, and rolled out**

The tests performed for this project were chosen based on two aspects: what tests the sites are conducting in regard to quality control today, and what was said during the conducted interviews with the representatives in the field of polymer testing, which can be found in Section 4.1. Summary of Interviews.

### 2.3.1 **Shore D Hardness Test**

This test was performed to compare the materials' hardness, to possibly link the result to the other tests performed. Before the foil samples were cut off the rolls, the Shore D hardness test was performed on each roll, with a PosiTector SHD, i.e., a handheld durometer, see Figure 2.2.


**Figure 2.2 Shore D hardness testing with a durometer**

Each roll was measured in three different locations: L-left side, M-middle, and R-right side, see Figure 2.3. In each location, three tests were performed, and an average value was calculated.

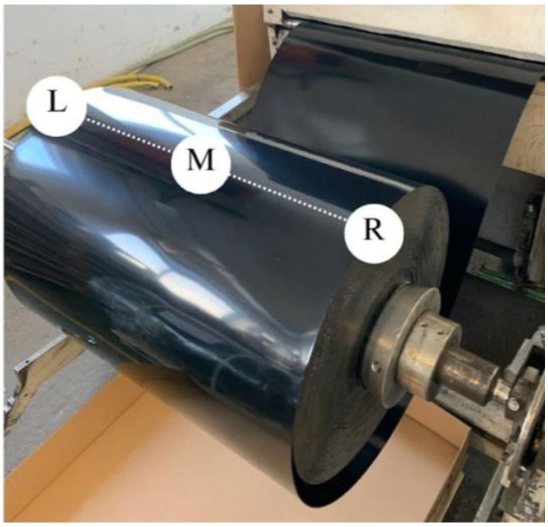


**Figure 2.3 Locations for hardness testing on the rolls. L = Left, M = Middle, R = Right**

### 2.3.2 **Thermoforming Test**

Due to out-of-control events, the roll from North America could not be thermoformed because of the width being too big for the European thermoforming machine. However, the other rolls were able to be thermoformed and placed in the machine, managed by a machine operator, one by one. The pre-heating temperature, speed, and thermoforming temperature, along with other machine parameters were altered by the operator in order to get a satisfying result. Based on the limitations of this thesis in Section 1.6: Limitations, no machine settings were researched or suggested but were merely managed by the machine operator. The machine used was an ILLIG RDKP72 thermoforming machine, used with both vacuum, and air pressure.

When the thermoforming procedure was done, samples of the finished product were collected for further visual inspection. Furthermore, the wall thickness of the finished product samples was measured on one of Product Y's stated critical locations with a caliper.

### 2.3.3 **Melt Flow Index (MFI)**

To characterize the polymer-melt and degradation of the material, see Section 3.6.1.1.1: Melt Flow Index, i.e., the viscosity of the material, the MFI test was performed. The melt flow rate, also referred to as the melt flow index (MFI), was measured with MFI equipment, where the material was heated and inserted into the machine. A standard weight pushed down the melted material through a die. The weight of the total exerted material was calculated and provided how many grams of material that had been transferred through the machine.

Normally, granules of plastic material are used for MFI testing, thus another way of creating MFI specimens had to be created in order to perform the test, due to the foil.

Material for the test was punched out of each region B-sample. I.e., one MFI test was conducted for each roll.  About 5 grams of each material was collected, and punched out of the foil samples with a hole puncher, with the geometry of circles with a diameter of about 5 mm. This procedure is shown below in Figure 2.4.

The reason for performing MFI on the B-samples was due to the customized smaller batch of rolls being tested. This was making region B the most suitable part to be used for testing, enabling a more uniform comparison between the rolls.

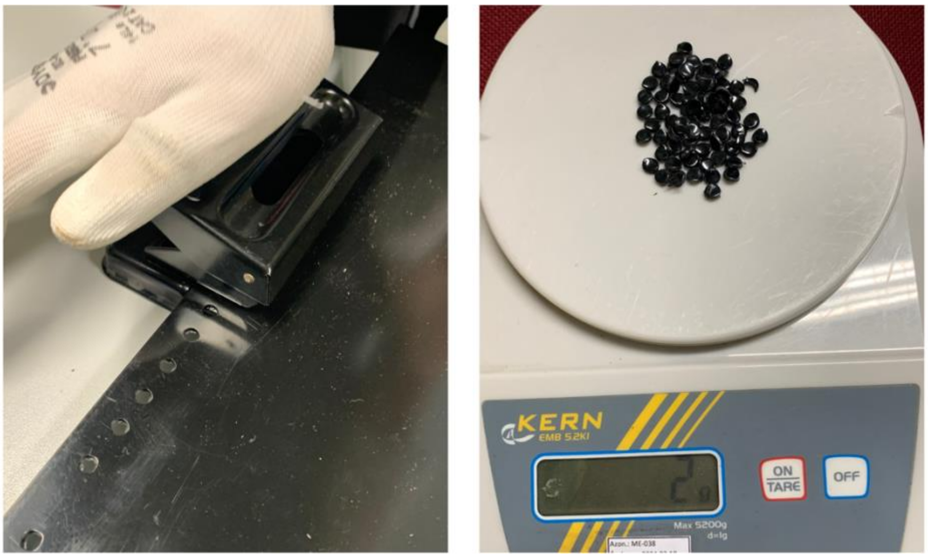


**Figure 2.4 Procedure of collecting materials for MFI test**

The MFI test was performed in an external polymer test laboratory at a university located near the sites of Company X2 and conducted with help from a laboratory assistant. The MFI equipment used for the testing was CEAST MFI 7024.000 (Serial number: 21329), see Figure 2.5 below. The unit used was grams/10 min, the temperature was 190 °C and the standardized weight was 2.16 kg.


**Figure 2.5 MFI equipment used for testing**

### 2.3.4 **Tensile Test**

To determine the materials' strength, which is affected by the degree of degradation of the material, the tensile test was performed, and the deformation was analyzed. The test is further described in Section 3.6.1.2.1 Tensile Test. In order to perform the tensile test, specimens had to be punched out of the sheet material. A punching tool design was made with assistance from the supervisor at the testing site. The tool design was created to follow standard dimensions used for tensile specimens, apart from the foil thickness being 1.8mm, as well as an added radius in the corners. The drawing of a standard specimen is shown in Figure 2.6.

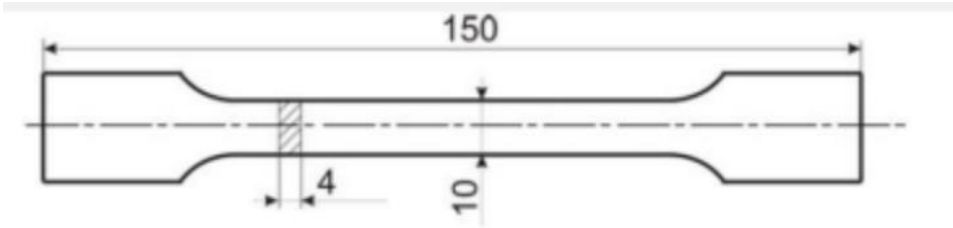


**Figure 2.6 Standard drawing used for creating the customized punching tool**

Images showing the final punching tool design are shown in Figure 2.7.

**Figure 2.7 Final customized punching tool design**

The dimensions of the final punching tool design are shown below in Table 2.1.

***Table 2.1 Punching tool dimensions***

| | |
|---|---|
| Length total | 150 mm |
| Width at ends | 20 mm |
| Length at ends | 30 mm |
| Waist | 10 mm |
| Radius | 10 |

Ten specimens were punched out of each foil sample, and named with a unique written code accordingly, to avoid mix-ups. The materials were numbered according to Table 2.2 below.

*Table 2.2 Materials used for testing*

| | |
|---|---|
| 111 | European virgin HDPE |
| 222 | European recycled HDPE |
| 333 | Asian recycled HDPE |
| 444 | North American recycled HDPE |

Not all ten specimens were needed for testing. However, some were used for calibration of the machine, and some were brought in case of unexpected events during the testing procedure. All specimens were punched in the extrusion direction, following the extrusion flow to avoid differences due to molecular orientation. Further background on molecular orientation and different properties in the extrusion- or transverse direction of an extruded foil is described further in Section 3.5.1: Sheet Quality. The specimens are shown below in Figure 2.8.


**Figure 2.8 Tensile test specimens created with the punching tool**

The material thickness was then measured for three randomly chosen specimens per foil sample for comparison. The tensile test was performed in the same external polymer laboratory as the MFI test, with help from the same laboratory assistant. The equipment used for the tensile test was an Instron 3366 (Serial number: K7326) which can be seen below in Figure 2.9. The machine was connected to a computer, collecting, and calculating the data during the testing procedure, following the standard ISO 527-1:2012 (E). The load cell measuring range was 10kN, with a crosshead speed of 50mm/min. The preload used was 1N with a preload speed of 1mm/min. The test temperature was 23°C ± 0.5°C.

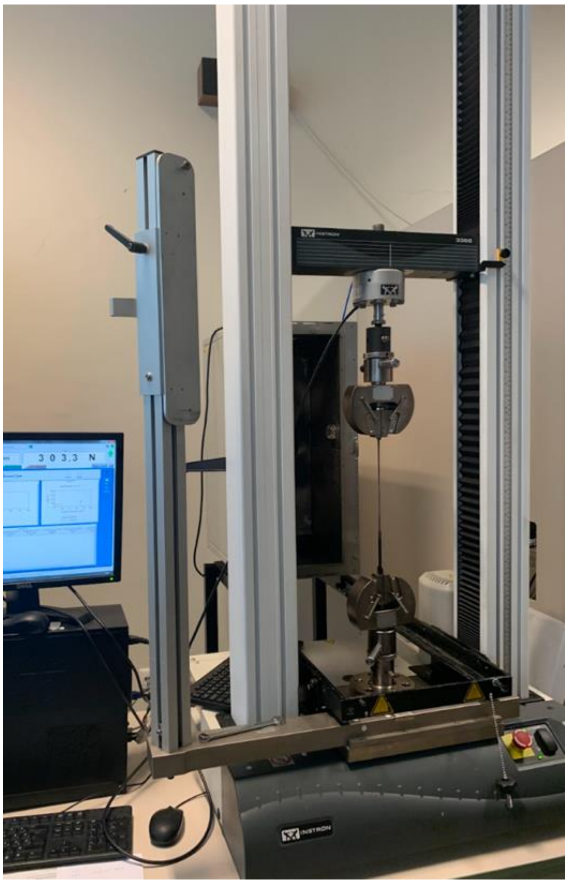

**Figure 2.9 Tensile test machine**

### 2.3.5 **Differential Scanning Calorimetry (DSC)**

To analyze the materials' crystallinity and melt temperature, differential scanning calorimetry was performed. The DSC can be used for i.e., identification of polymer blend content, or tracing contamination. This test is further described in Section 3.6.1.3.1: Differential Scanning Calorimetry. The DSC test was also performed in the external polymer laboratory at the university nearby the producing site and with help from the same laboratory assistant as for the Tensile and MFI tests.

A specimen for the differential scanning calorimetry (DSC) was taken from all region B-samples, i.e., one DSC test was performed for each roll. The equipment used for this test was a TA DSC Q200 device, see Figure 2.10 below. Similar to the MFI testing, it was decided to test DSC on material taken from region B-samples.

**Figure 2.10 Differential scanning calorimetry equipment used for testing**

The material samples were heated from 30°C to 190°C in a neutral nitrogen atmosphere at 20°C/min, followed by a controlled cooling at 20°C/minute. This was followed by another heating, also at 20°C/minute to 190°C.

# 3 Theory

*In this chapter, already existing literature and research will be presented, as a theoretical background for the thesis.*

## 3.1 Plastic Recycling

This subsection will focus on the concept of plastic recycling, covering its challenges, strategies, and implemented initiatives, to determine how this can affect material quality on PCR and PIR HDPE material.

### 3.1.1 **Recycling Strategies**

#### *3.1.1.1 Defining Post-Consumer and Post-Industrial Material*

When recycling, materials are often categorized as either post-consumer material (PCR) or post-industrial material (PIR). PCR and PIR materials are mainly distinguished by origin. PIR materials come from the manufacturing process, while PCR materials are commonly described as waste generated by end-users, i.e., originating from households or from commercial, industrial, and institutional facilities as end-users. The category also includes items that are returned to the supply chain, such as surplus stocks from trade.

The classification of PCR and PIR materials is separate from the status as waste or by-products. Depending on designation, both types of materials can be either waste or by-products. If considered waste, the prefix will be determined by the ISO classification system: PIR waste will result in PIR recyclates, while PCR waste will lead to PCR recyclates. (CPA 2021, 24) Further definitions are explained in Table 3.1-3.2.

***Table 3.1 Packaging WG: Description of post-consumer materials in packaging (CPA 2021, 26)***

| **Post-consumer packaging (PCR)** | | |
|---|---|---|
| **Product and polymer** | **Origin** | **Description** |
| All polymers* | Households | Household packaging. Films, cups, trays, tubes, bottles, and containers |

| | | |
|---|---|---|
| All | Retailers | Films, pallets and crates |

*Polymers used in the plastic packaging sector: PE, PP, PET, PS, PA

*Table 3.2 Packaging WG: Description of post-industrial materials in packaging (CPA 2021, 26-27)*

| **Post-industrial packaging (PIR)** | |
|---|---|
| **Product and polymer** | **Origin** |
| All | Industrial extrusion/Slitting Process (Reel production) |
| Start-up lumps, strands, and sprues | Plastic converting process |
| Faulty production | Plastic converting, thermoforming, and packaging process |
| Punch remnants, offcuts, and remaining pieces of fabrication | Thermoforming and packaging process |

### 3.1.2 **Recycling Processes**

Some initiatives have been introduced in the recycling processes to minimize environmental impact, while still maintaining asked functional standards. However, these processes still have some steps to take in maintaining and assuring the quality of the materials and final designs. Furthermore, waste composition and its origination site determine the necessary organizational and technological methods for material recycling. Consequently, multiple recycling practices have been developed. (Parameswaranpillai 2021, 3; Feil et al. 2020, 285)

In general, recycling processes can be divided into three types of processes: mechanical recycling, chemical recycling, and energy recovery.

Mechanical recycling, also referred to as primary-, or secondary recycling, depending on if it is PIR-, or PCR material, recovers PSWs through mechanical means, allowing the transformed PSW to retain its desired function (Beghetto et al. 2021, 6). I.e., collecting, cleaning, drying, sizing, extrusion, and manufacturing (Parameswaranpillai 2021, 4). The recycled material can be used entirely as 100% recycled or be combined with virgin material. This method is mainly applicable to thermoplastic materials, common for PE (Delva et al. 2019, 5; Adelodun 2021). This is also one of the most common, and profit-oriented processes among current alternatives. Mainly due to its economic benefits, which also can produce a variety of products of different shapes.

Chemical recycling includes processes that manage polymer chains to chemically produce small molecules, later used as feedstock in new polymers, other chemicals, and in the manufacturing of fuels. Some of these chemical processes involve gasification, hydrocracking, pyrolysis, depolymerization, methanolysis, and aminolysis (Beghetto et al. 2021, 10-11; Parameswaranpillai 2021, 5). It is mostly used in manufacturing of food packaging products since the material will be of virgin quality. This method is stated to have a high potential for future use, however, it is currently more expensive compared to other methods. However, with its standard being one of the most sustainable recycling methods of today, the cost could change. (Parameswaranpillai 2021, 5)

Energy recovery is a recovery method primarily used in the EU for post-consumer PSWs, usually for applications where mechanical recycling is not accessible or cannot be applied. However, this recycling method does not properly fulfill the definition of recycling since it is not able to produce another product from used material. (Parameswaranpillai 2021, 5-6)

#### *3.1.2.1 Mechanical Recycling*

As previously briefed, mechanical recycling is the only recycling method within the packaging industry, mainly due to economic benefits. The process involves various pretreatment and separation procedures that differ based on the source of the plastic waste. The quality of the manufactured product is most commonly compromised through processes of waste preparation, cleaning, and separation. Waste deterioration, unbalanced shapes and sizes of PSWs, as well as dissimilar colors also influence the complexity of mechanical recycling. (Delva et al. 2019, 5)

#### *3.1.2.2 The Mechanical Recycling Process*

The process order can vary depending on the material source and intended products, but as a general guideline, these key steps are typically followed:

1. Separation and sorting
2. Milling and grinding
3. Washing and cleaning
4. Drying
5. Compounding
6. Reprocessing

Mechanical recycling begins with separation and sorting of polymeric materials of municipal solid waste (MSW). When commencing this, the collection is an integral part of the separation process. The partition is based on physical properties such as density, type, and color, enabling the sorting process. Sorting plastic waste is crucial for its recycling and recovery, as plastic materials lose these characteristics due to contaminants in waste streams and aging over time, which is compounded by the presence of a mixture of polymers. (Parameswaranpillai 2021, 31)

Sorting technologies must be capable and precise, detecting contaminants, improving separation efficiency, identifying polymer mixtures, and selecting appropriate additives. Manual sorting is the most commonly used method, but it can be challenging, tedious, and time-consuming, depending on the identification of plastic constituents. Common sorting technologies are spectroscopic methods, like

NIR spectroscopy viewed in Figure 3.1, and automated sorting systems. (Parameswaranpillai 2021, 21-22)

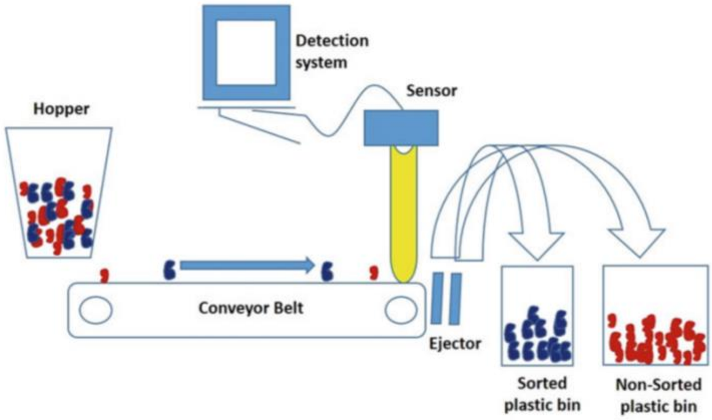


**Figure 3.1 Principle of NIR-spectroscopy (Parameswaranpillai 2021, 22)**

After sorting the plastics, it is grinded into flakes and transformed into granules and fragments. Since the obtained plastic material from previous steps still could be contaminated, the grinded material goes into the process of cleaning. Depending on the source of the plastic waste, it is washed with various solvents based on present impurities. E.g., washing with water in cyclones. Chemical washing may also be performed for further impurity removal, using surfactants and alkaline solvents.

Leaving the material to dry is crucial, and the time depends on the mechanical properties of the plastic. Some plastics may be more sensitive to hydrolysis than others. (Parameswaranpillai 2021, 31)

Once the material is dried, the plastic wastes are usually revised. Some plastic waste faces a second sorting process, and approved materials are mixed and combined. Later, grinded flakes are compounded, and additives and pigments can be added during this stage. Occasionally, the plastic flakes are also extruded into homogeneous pellets. (PlasticsEurope 2023; Beghetto et al. 2021, 10)

Reaching the final step, the plastic residues are sometimes transformed into pellets. This is accomplished through extrusion or further molding techniques. Finally, the recycled plastic is packaged and ready for further manufacturing and production of new products.

Despite the popularity of mechanical recycling, it faces challenges in assuring quality, both in the process steps and in the maintenance of the material throughout the process. It is mainly difficult to avoid impurities in recycled materials completely, especially with PCR. Due to the wide range of application fields, there is also a wide range of different impurity types, and other plastic mixtures being present when being recycled. This can result in a creation of phase separations, and further compatibility issues. Hence, a proper separation method from contaminants is highly desirable when performing mechanical recycling.

When utilizing mechanical recycling for PIR materials, the most critical parameter is the loss in physical properties of the polymer, due to repeated heating and shear in the extrusion process. Property values, such as impact strength and elongation at break, decrease faster than a linear decrease rate and are therefore important to test carefully, to determine critical property loss in a regrind stream. (Throne 2008, 215-217)

Another challenge is the previously added additives and colorants on the material being recycled. Prior additives and colorants can risk inhibiting the compounding stage, adventuring the aimed homogeneity to be fulfilled. Finally, assuring the quality of the manufactured products is recommended since the processed material can risk being compromised through the process steps. (Parameswaranpillai 2021, 31-32)

#### *3.1.2.3 Guidelines for Rigid PE Packaging*

The Swedish plastic packaging recycling center Svensk Plaståtervinning, is using mechanical recycling when recycling post-consumer plastic materials. In order to tackle the previously mentioned challenges, Svensk Plaståtervinning have published a manual, aimed at packaging producers to use as a guideline when designing their PE packages. The guidelines are divided into five categories: ‘Colors and printing’, ‘Fillers’, ‘Labels’, ‘Closures and other components’, and ‘Barriers and multiplayer materials’.

To ensure recyclability, it is recommended to limit the amount of color and printing on the packaging. Avoid adding fillers due to difficulty with separation during recycling. When adding labels, it is recommended to use small labels if needed, and avoiding paper labels completely. Use closures and other components made of the same material as the packaging, preferably uncolored. Multilayer materials can be used for better barrier properties, but metal foil, PA, PVC, and PVDC are to be avoided. If these materials must be used, the packaging cannot be identified and sorted as rigid PE and should instead go to waste-to-energy-recovery. (Svensk Plaståtervinning 2023, 58-65)

### 3.1.3 **Challenges with Plastic Recycling**

*3.1.3.1 Challenges with Plastic Recycling Processes*

Mechanical recycling has limitations that arise from the processing steps involved. These limitations include problems and challenges that can occur in each processing step, such as impurities and contamination, non-miscibility of polymer shares, and degradation. These issues can result in a loss of polymeric recyclate properties, leading to deficient end-product properties such as surface deflections, or discoloration. Although with proper control of processing conditions, many polymers can undergo multiple cycles of mechanical recycling without a significant loss of performance, and it is important to be aware of the limitations of this method (Auer et al. 2023, 2).

Current common challenges in the plastics recycling process are stated to be caused by i.e., identification-, and handling problems, impurities, wide density ranges, and quality problems on the recyclate. Common quality problems according to Auer et al. (2023, 7) can be:

- Recyclability of polymers limited by mechanical recycling and degradation
- Discoloration
- Odor formation
- Undesirable fate of additives in the recyclate.

3.1.3.1.1 Challenges in Identifying and Sorting Plastic Waste

When compounding plastic waste, purity levels primarily influence further downstream processes, affecting the recyclate quality (Auer et al. 2023, 4). In the internal process, the sorting step involves sorting lightweight packaging. However, the sorting performance of NIR sorters is limited by high belt speeds, overlapping, contaminated-, wet-, and fully printed packaging surfaces, and labels covering more than 30% of the packaging with differing polymers. NIR sorters are also unable to differentiate between food and non-food packaging, sort brand-specific materials for extended producer responsibility, or identify certain plastic types or multilayer packaging. (Auer et al. 2023, 3-4)

After identifying the plastic type with NIR, compressed air nozzles are typically used for handling. However, flexible films pose challenges due to their lightweight nature and unpredictable trajectory, making accuracy difficult. Additionally, cylindrical objects in a particular roll-on conveyor belts moving in the opposite direction cannot be discharged accurately, creating further errors in separation, which can lead to unwanted mixtures of materials, which then would affect product quality.

Sorted material in recycling facilities is typically shredded and sorted using float-sink separation based on specific density, where PE will float. However, modifications to plastic density, such as the addition of fillers or expansion, can lead to deviations from typical density properties. Multilayer composite materials can also cause problems by making it impossible to sort into mono-materials due to overlapping density ranges. Additionally, the presence of elastomers with similar densities can cause missorting, risking quality. (Auer et al. 2023, 4)

#### 3.1.3.1.2 Challenges within Processes of Plastic Waste

After the prior steps, the plastic waste is compounded into recyclates. At this stage, any contamination or impurity would cause further issues in the compounding process, affecting recyclate qualities. Problems faced in reprocessing can roughly be divided into plastic non-miscibility, basic degradation of polymer materials, and impurities in the polymer stream. (Auer et al. 2023, 4)

As previously stated, missorting in the recycling process leads to insufficient sorting purity of the fractions. During compounding, this could cause further problems. Different melting points and processing temperatures of mixed thermoplastic fractions can cause quality losses in the recyclate.

The presence of low melting point components leads to overheating, degradation, and reduced optical and mechanical properties in the final product. Moreover, additives such as antistatic agents, plasticizers, colorants, and oil can hinder recycling efficiency. Compatibilizing agents can be added to polymer blends to improve interfacial adhesion but are expensive and may have limited effectiveness. Removing higher melting components can clog melt filters, requiring significant cleaning efforts. (Auer et al. 2023, 4-6)

Insoluble or non-melting impurities must be removed from the melt to ensure the high-quality and desired properties of the extrudate material. Mechanical recycling has a limit to the number of reprocessing cycles for mixed plastic waste streams. Further exposure to heat, oxidation, light, ionic radiation, hydrolysis, and mechanical shear during processing leads to polymer chain degradation. In particular, the thermal and mechanical shear degradation during melt processing leads to reduced mechanical and rheological properties. (Auer et al. 2023, 5)

#### 3.1.3.1.3 External Challenges

Looking into external factors contributing to reprocessing, the lack of data on the PCR plastic waste stream presents an additional challenge to plastic waste reprocessing, primarily due to constant changes in waste volume and composition. This data gap originates from packaging manufacturers and distributors, who produce diverse packaging solutions and materials without sharing information about their composition. To create a sustainable approach to plastic packaging recycling, all stakeholders along the supply chain must exchange waste-related data and cooperate. Access to more in-depth data is essential for predicting future waste volumes and compositions, enabling reprocessing of high-value end products, and closing material and product loops. (Auer et al. 2023, 5-6)

Lastly, improper consumer disposal of plastic waste is also a problem causing effects on recycling efforts. A study from the German Association for Secondary Raw Materials and Waste Disposal found that 30% of lightweight packaging waste collected ends up in residual waste. The issue is not due to a lack of willpower but rather a lack of understanding. A survey revealed that 60% of respondents lacked knowledge about proper waste separation. Packaging distributors increasingly rely on consumers to separate packaging, even requiring the removal of additional materials like paper bands on yogurt cups. In addition to improper disposal, food residue left in packaging contributes to the problem and results in unpleasant odors from recycled materials. (Auer et al. 2023, 6)

#### *3.1.3.2 Challenges with Plastic Recycling in Industry*

Widening the perspective to the industrial point of view, bottlenecks are faced in the packaging industry, affecting the applicability and quality assurance of plastic recycling in production. Compared to the processing challenges, industrial challenges are mainly rooted in costs, competitiveness, and supply availability.

The usage of recycled plastic in the industry is continuing to grow, along with customer demand (European Parliament, 2018). Even the cost of recycling is noted to decrease, enabling recycled plastics to be competitive with virgin plastics (CPA, 2021, 26). However, as in many industries, there are further economic drivers setting the management of recycled plastics at risk.

According to a 2017 report published by the Australian government agency CSIRO, The Commonwealth Scientific and Industrial Research Organisation, the key economic drivers influencing the viability of thermoplastic recycling within the industry are quality-, and the cost competitiveness of recycled resins, compared to virgin materials. Furthermore, an analysis of the intellectual property landscape reveals a surge in patent filings over the past five years, reflecting an overall growth of the industry. Further, it suggests this trend to enhance competition in R&D activities within the field. (Locock 2017, 44; Hopewell 2009)

Plastic recyclers are vulnerable to competition from resin producers, reaching production needs, and further quality demands from plastic processors, requiring significant amounts of recycled plastic that adhere to highly regulated specifications. Plastic materials are customizable to satisfy the functional or aesthetic requirements of each manufacturer. The variety of raw materials increases the complexity of the recycling process, making it expensive and impacting the ultimate quality of the end product. The challenge is that PIR recyclates are providing a limited production waste when the amount of PCR recyclates are estimated to remain steady. Consequently, in order to meet current demands, forecasts are referring to PCR recyclates as being the next step to take in plastic production. (CPA 2021, 26)

Considering the fluctuations in material quality, pricing, and oil prices, recycled plastic manufacturing operations face potential viability issues. As a result, producers may prefer virgin materials to minimize risks. (Kosior et al. 2020, 154-155) (European Parliament, 2018) This can indicate the need for policy incentives to increase recycling rates, particularly by strengthening the market for secondary materials through means such as decoupling product prices from oil prices and improving the quality and consistency of plastic waste feedstock. (Larrain, M. et al. 2021, 12)

#### 3.1.3.2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a commonly used method within the industry to provide an overall picture of the total environmental impact during the life cycle of a product. LCA considers the environmental impacts of materials, manufacturing, transportation, use, and disposal.

Plastic materials are generally positive from a life cycle perspective in terms of:

- Manufacturing, as it holds low energy consumption
- Transportation, due to its low density
- Usage, due to its long durability along with its low density

However, it is important to consistently consider all stages of plastics' life cycles in the pursuit of sustainable production. (Polymercentrum 2021)

## 3.2 Polymers

In the field of plastics, it is common for the terms 'plastic' and 'polymer' to be used synonymously. However, from a technical perspective, the two terms have distinct meanings. Polymers are defined as chemical compounds formed through the reaction of organic monomers. The majority of polymers are blended or compounded with various additives, including thermal stabilizers, colorants, fire retardants, UV stabilizers, fillers, reinforcing agents, and other product-specific components. The term 'plastic' refers to the polymer and associated additives in finished form, typically as resin pellets, or powders. However, in practical usage, the terms 'plastic' and 'polymer' are often utilized interchangeably. (Throne 2008, 171-172)

Polymers can be broadly classified into two categories: thermoplastic and thermosetting. Thermoplastic polymers are characterized by their ability to be repeatedly heated and molded several times without significant alterations to their physical properties, normally forming new products up to 6-7 times, before the molecular chains are too short and the properties will be too poor. Polyethylene (PE) is an example of a thermoplastic polymer. In contrast, thermosetting polymers are not able to be reshaped after undergoing a single heating and molding process. The process of thermoforming primarily involves the transformation of thermoplastic materials. (Throne 2008, 172)

Thermoplastics can be further classified into two categories: amorphous and semi-crystalline. When a thermoplastic polymer is exposed to heat, it undergoes a physical transition from its low-temperature hard state to a rubbery state over a temperature range of several degrees. The temperature at which this transition occurs is known as the glass transition temperature and is typically reported as a single temperature value. Polymers that only possess a glass transition temperature are referred to as amorphous polymers and constitute approximately 80% of all thermoplastic polymers utilized in thermoforming. Semi-crystalline polymers, on the other hand, exhibit a second physical transition from their rubbery state to a molten state. This second transition also occurs over a temperature range of a few degrees and is referred to as the melting temperature. Examples of semi-crystalline polymers include polyethylene (PE) and polypropylene (PP). Thus, all polymers have a glass transition temperature, while only crystalline polymers have a melting temperature (Throne 2008, 172-173). Below in Figure 3.2, it is presented how polymers are divided into different subgroups.

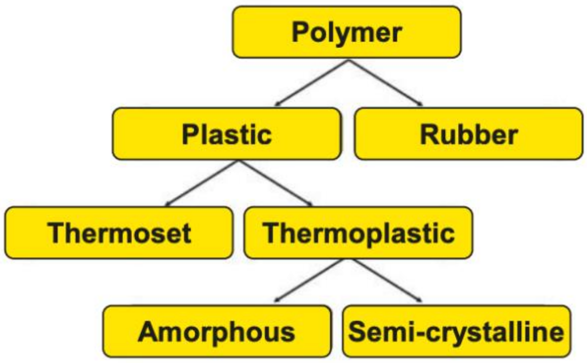


**Figure 3.2 Polymer division into subgroups (Bruder 2015, 6)**

### 3.2.1 **Polyethylene (PE)**

Polyethylene (PE) is a semi-crystalline commodity plastic. Commodity plastics are the most common group, suitable for various applications. These represent 90% of today’s thermoplastics in use and are not very expensive (Gemini Group, 2022).

This polymer is the most widely used, with more than 60 million tons manufactured globally every year. (Bruder 2015, 9; Throne 2008, 171)

*3.2.1.1 Classification*

Polyethylene can be classified based on density and the lateral branches on the chains of the polymer. According to Bruder (2015, 9), some examples of PE classes are:

- Low Density Polyethylene (LDPE)
- Linear Low Density Polyethylene (LLDPE)
- High Density Polyethylene (HDPE)
- High Molecular Weight High Density Polyethylene (HMW-HDPE)
- Ultra High Molecular Weight Polyethylene (UHMWPE)
- Medium Density Polyethylene (MDPE)
- Cross-linked Polyethylene (PEX)

Below is an illustration showing examples of different molecular chains structure depending on their PE classification, Figure 3.3.

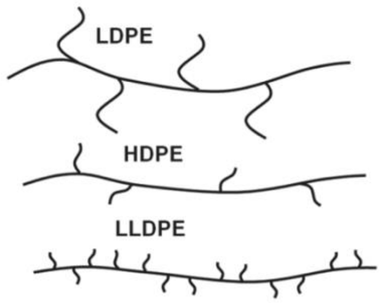


**Figure 3.3 Examples of different polyethylene with lateral branches on the molecular chains. (Bruder 2015, 9)**

When ethylene is polymerized into polyethylene, different processing methods will result in more or less lateral branches on the molecular chains. Chains with only a few lateral branches will result in higher crystallinity, molecular weight, and density since the chains can be packed more densely. Linear polyethylene, like HDPE, has only a few or sometimes no lateral branches at all. (Bruder 2015, 9)

*3.2.1.2 Properties*

The presence of lateral branches, the degree of crystallinity, and density i.e., the type of PE, will have an influence on the mechanical properties of the polymer. Some of the advantages of PE are its low material cost, low material density, toughness, high elongation, high elasticity down to below -50°C, and superior chemical resistance.

Some disadvantages are its stiffness, being easily scratched, its tensile strength, and its difficulty to handle temperatures above 80°C. (Bruder 2015, 9; Ashter 2014, 41)

#### *3.2.1.3 High Density Polyethylene (HDPE)*

Below in Table 3.3, some standard values of HDPE properties are presented. These values are provided by Company X through an internal handbook on material properties.

*Table 3.3 Standard values, HDPE properties from Company X's handbook, 2023*

| Property | Value |
|---|---|
| Density | 0.96 g/cm$^3$ |
| Water absorption | 0.015 % |
| Shrinkage | 2,0-4,5% shrinkage range, 2,5% recommended value |
| Tensile modulus | 1000-1200 MPa |
| Yield stress | 20-25 MPa |
| Impact strength (notched) | 15 KJ/m$^2$ |
| Elongation at break | >50% |
| Hardness (Shore D) | 55-64 |
| Service temperature | min -40°C, max short-term 90°C, max long-term 80°C |
| Softening temperature | >80°C |
| Melting temperature, $T_m$ | 150-170°C |
| Chemical & Oil resistance | Good |

## 3.3 Extrusion

The second largest processing method for thermoplastic materials is extrusion, which is a continuous process to make e.g., sheets, foil, or films out of plastic pellets or powder. Some advantages are the possibility to make wide sheets and thin-walled products. Many thermoplastic materials can be used for extrusion, although requiring high viscosity and no surface lubrication. PE is one of the materials that can be used for extrusion. (Bruder 2015, 119)

When extruding thermoplastic foil material, on rolls or pre-cut foil panels, i.e., so-called semi-finished products, the initial step of production is to produce polymers. Thereafter pre-process the polymers to create extrudable stock, i.e., materials like granulate or powder. The last step is to process the stock materials into sheet-material. When pre-processing, a variety of different additives like dyes, fillers, lubricants, etc., are available for making the plastics suitable for manufacturing and processing. Depending on the requested demands it is possible to add aging- or light protection, flame inhibitors, antistatic treatments, or alloying with other plastic materials, including recyclates, which is also part of the pre-processing. (Schwarzmann 2019, 63)

Depending on what type of tool is used after the extruder, the extrusion process can be divided into different categories according to Bruder (2015, 121) e.g.:

- Straight extrusion
- Extrusion with angled tool
- Extrusion of plates and sheets
- Co-extrusion
- Film blowing

During the extrusion process, solid polymer, often a mix between virgin pellets and regrind flakes, is fed to an extruder for melting. When melted, the plastic is squeezed through a shaping die, with a gap at the end adjusting the sheet thickness. (Throne 2008, 205) A slit tool is used, and the thermoplastic resin is melted and extruded between rollers and formed into a plate or thick foil (Bruder 2015, 122). These rollers are speed- and temperature-controlled. (Throne 2008, 205) For extrusion, sheet material thickness varies between 0.1 mm to 50 mm, with a width of up to 2000 mm. Although, there are machine assemblies for extrusion widths of up to 5000 mm available (Schwarzmann 2019, 64). An illustration showing an extrusion line can be seen in Figure 3.4 below.

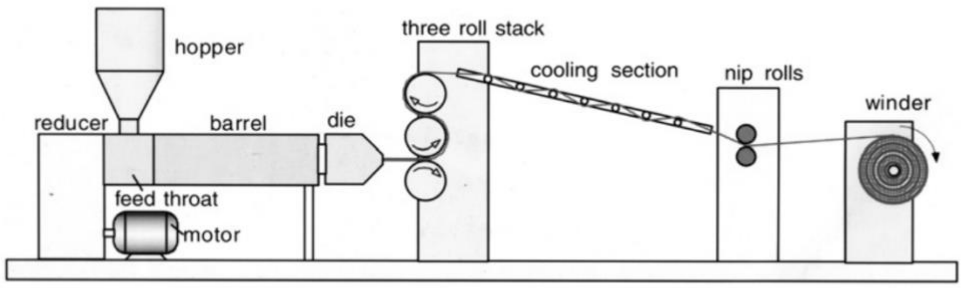


**Figure 3.4 Sheet/flat film extrusion line (Throne 2008, 206)**

## 3.4 Thermoforming

Thermoforming is defined as the process of reshaping thermoplastic semi-finished products, such as foil or sheets, at high temperatures to create formed parts. (Schwarzmann 2019, 1)

### 3.4.1 Thin- and Heavy Gauge

The thermoforming process is commonly categorized based on the gauge i.e., the thickness of the sheet, as indicated in Table 3.4. Additionally, the process can be classified according to the way the sheet is supplied to the thermoforming press. In the case of a thin sheet, it is typically extruded into rolls, sometimes spanning up to 3000 meters in length, and is continuously introduced into roll-fed machines. If the sheet is too thick to be rolled, it is sectioned into individual pieces, arranged into stacks, and then fed into what thermoformers refer to as cut-sheet machines, either manually or through an automated system. (Throne 2008, 5)

***Table 3.4 Thermoforming processes***

| **Type of thermoforming** | **Sheet thickness (mm)** |
|---|---|
| Light-/thin-gauge | <1.5 (Film/foil: <0.25) |
| Heavy-gauge | >3 (Sheet: >13) |

Traditionally, thin-gauge thermoformed products have surface area-to-thickness ratios of up to 100,000:1, a characteristic that is unparalleled by other manufacturing processes.

Moreover, the process of thermoforming is distinguished as a differential stretching process, which leads to a non-uniform wall thickness of the product. Techniques that may improve wall thickness uniformity include mechanical or pneumatic stretching of the heated sheet before it comes into contact with the mold surface. However, the tolerance of wall thickness usually ranges between 10-20%, and since some sections of the formed parts are designed to minimum critical thicknesses, the products will often contain more material than actually needed for optimal performance. As a result of the elastic stretching of the sheets during thermoforming, the products are subjected to significant residual stress. (Throne 2008, 7)

### 3.4.2 Positive- and Negative Forming

There are two types of forming, positive and negative, illustrated in Figure 3.5 below. For positive forming, the molding reflects the outer contour of the form where the return forces in the material, along with the contour molding forces are effective in the same direction. Negative forming reflects the inner contour of the form where the return forces in the material and the forming forces are mutually opposed. (Schwarzmann 2019, 6-7)

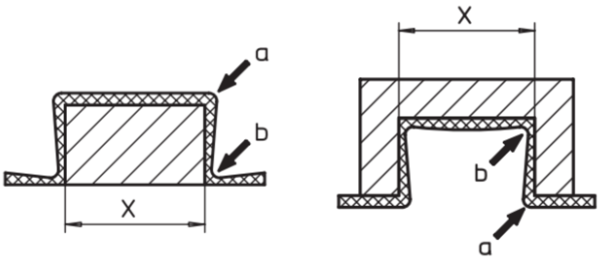


**Figure 3.5 Positive forming (left) and negative forming (right), where X is the molded dimension from mold (Schwarzmann 2019, 7)**

### 3.4.3 Vacuum- and Pressure Forming

Thermoforming can be done by either vacuum forming or pressure forming and refers to molding using vacuum and compressed air (Schwarzmann 2019, 1). According to Schwarzmann (2019, 5), the process sequence of thermoforming consists of the following steps:

1. Heating
2. Pre-forming
3. Contour molding
4. Cooling
5. Demolding

#### *3.4.3.1 Vacuum Forming*

During the vacuum forming process, the application of vacuum to the heated material is facilitated by a vacuum pump. This action causes the material to adhere to the surface of the mold and gives rise to a forming pressure that is equivalent to the disparity between the atmospheric pressure and the vacuum produced by the vacuum pump, with the maximum limit being approximately 1 bar (100,000 Pa) (Schwarzmann 2019, 8).

The steps in the vacuum forming process are heating of the semi-finished material to its forming temperature within the elastoplastic range, forming it with a shape defined by the thermoforming tool, followed by cooling under forced retention, continuing until a temperature where the formed part achieves geometrical stability, and lastly demolding the geometrically stabilized formed part. The part can then be stamped or milled out to be separated from the remainder of the sheet. The leftover scrap can then be recycled and used to produce new semifinished products (Bruder 2015, 126; Schwarzmann 2019, 1).

Normally, the mold is single-sided, meaning that only one side of the sheet is in contact with the shaping surface, and the other side is open to the environment

(Throne 2008, 5). According to Ashter (2014, 15), the main issue with vacuum forming is the variations in material thickness across the formed part.

#### *3.4.3.2 Pressure Forming*

During pressure forming, compressed air will push the heated material against the tool surface, relying on a sealed compressed-air chamber. The compressed air will flow as forming air into this chamber. Maximum forming pressure is available at different levels, from 0.25 MPa to 0.6-0.8 MPa, up to 20 MPa on special duty machines. (Schwarzmann 2019, 8)

### 3.4.4 **Troubleshooting**

The two main aspects to take into consideration when troubleshooting and solving problems regarding extrusion is to understand the equipment operation, along with the polymer in use. Comprehending these separately is not enough to provide correct information on how to solve the problem. Furthermore, molten-state polymers behave differently than other liquids since polymers have both an elastic and viscous component. (Wagner, Mount, and Giles 2014, 209)

When thermoforming, the problems, causes, and solutions are often categorized into production, tooling, machinery, polymer materials, and design. (Thorne 2008, 240) Moreover, Wagner, Mount, and Giles (2014, 285) explains the so-called "Five-Step Process"; defining the problem, fixing the problem, identifying the root cause, taking corrective action to eliminate the problem, and following up and monitoring this action to verify that the problem is eliminated. By following the process, problems can be defined, corrected, and eliminated.

When troubleshooting a problem, the first step should be removing as many process variables as possible. These should then be added back to the process one at a time to be able to determine what aspect could possibly be the cause of the problem. (Thorne 2008, 241)

## 3.5 Quality Control

### 3.5.1 **Sheet Quality**

The sheets, either supplied as thin-gauge roll stock or palletized for heavy-gauge forming, will affect the part quality, which means the thermoformer needs to receive good quality sheets from the supplier to be able to form good quality parts. Throne (2008, 205) argues that together with the supplier, thermoformers should create an agreement on the requirements of the quality conditions. This is supported by Wagner, Mount, and Giles (2014, 309), who also states that procedures like process variables, and quality of finished products, along with specifications on testing of incoming materials should be established and monitored.

According to Wagner, Mount, and Giles (2014, 309), these procedures should be completed by developing and implementing tasks to achieve testing and evaluation of incoming raw materials, as well as finished products, monitoring the steps in the extrusion process, and methods of sampling and the frequency. Moreover, procedures to test and classify products with deviations and to accept or reject finished products should be aimed for.

It is important that thermoformers have a good understanding of the extrusion process to be able to understand what the supplier can and cannot provide. Limitations in the extrusion process might be machinery-driven or may be specific to a given polymer (Throne 2008, 205). Another important aspect to consider is regarding cooling and stresses in the sheets. When the sheets are moved from the extrusion die to be shipped, in rolls or pallets, the material will continue to cool. Since the sheet is rubbery elastic during this process, stresses and orientation are often frozen in to be relieved when the sheet is re-heated to be formed (Throne 2008, 210). I.e., stresses are locked into the extruded sheet during the extrusion process, which means the macro-molecules are locked into position, i.e., molecular orientation. This defines the dimensions of length, width, and thickness for the sheet. Therefore, as a reflection of thermal expansion, the sheet's or formed part's dimensions can change when exposed to shifts in temperature (Schwarzmann 2019, 51). The molecular orientation can be higher or lower depending on the polymer being extruded, where a high molecular orientation leads to anisotropy, thus different properties in the machine- or transverse direction. (Wagner, Mount, and Giles, 2014)

Overall, it is hard to manufacture plastic sheets with no quality issues at all. Examples of issues that might appear in sheets and cause quality problems are e.g., thickness variation, variation in light-gauge sheet roll width or heavy-gauge sheet width and length, or undesirable surface conditions. (Throne 2008, 210-211; Wagner, Mount, and Giles 2014, 350-358)

Throne (2008, 211) further argues that many issues are caused by additives. The combination of additives requires careful consideration to prevent any compromise in sheet quality, according to Throne (2008, 211) Small modifications to the type or amount of additives may change the final sheet quality. Additionally, sheet quality may be altered by modifications to the extrusion temperature or the residence time of the material in the extruder.

#### *3.5.1.1 Evaluation of Incoming Sheets*

According to Throne (2008, 218) and Wagner, Mount, and Giles (2014, 310) it is of high importance that thermoformers ensure that the incoming sheets meet the demands and live up to the highest quality standards, specified on the purchase order. The machine operator can do a visual and dimensional inspection of the sheets while fed into the forming machine, and most commonly the thermoformed products will not demand major testing. Overall, Throne (2008, 218) further argues that the most important factor in testing and evaluating incoming material is consistency. A defined inspection protocol should be carried out thoroughly, regularly and should be done by an experienced technician. (Throne 2008, 218)

### 3.5.2 **Testing Methods**

Regardless of the reason behind the need for quality control methods, there are existing methods to be used, many of which focus on verifying the incoming material quality and comparison of outgoing product quality with customer specifications. Many of the methods available require development of specific testing procedures in addition to fulfilling the customer needs. Throne (2008, 211)

Testing procedures for thermoformers such as the American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO) include some standardized tests which can help evaluate materials and products and are many times run by the resin supplier for acceptable quality limit (AQL) programs. However, some tests should be done by the thermoformer as well, concerning the parameters critical to the process and the product performance. (Throne 2008, 211-212)

Appendix B shows an example of a checklist with specifications thermoformers and sheet suppliers, i.e., extruders, can use for comparison with the product specifications. Some of the specifications, like mechanical properties, should be monitored by the thermoformer, while in many cases both the extruder and the thermoformer are responsible to monitor specifications, e.g., filler condition or surface finish. Thermoformers are also responsible for translating the AQL given by the customer into meaningful requirements to meet with the supplier. (Throne 2008, 215)

## 3.6 Plastic Testing Concepts

Multiple analytical techniques are used in polymer testing and characterization to evaluate the physical and chemical structure of polymers and their additives. (Naranjo 2008, 1)

### 3.6.1 **Material Testing Techniques**

#### *3.6.1.1 Melt Rheology*

Rheology is a scientific field that focuses on studying deformation and flow of materials. To understand the deformation and flow of a solid and molten polymer in the extruder and in the die, it is important to be able to best execute the extrusion process (Wagner, Mount, and Giles 2014, 233). Polymer melts are characterized by being viscoelastic, shear thinning, and having temperature-dependent flow properties, and viscosity is the most commonly used parameter to determine the behavior of polymers during processing. Shear deformation measurement devices are usually utilized to measure melt viscosity since the majority of polymer processes are dominated by shear rate. However, some polymer processes, such as thermoforming, are dominated by either elongational deformation or a combination of shear and elongational deformation. Additionally, some polymer melts exhibit significant elastic effects during deformation. Rheometry is the analytical technique that measures rheological properties for process design and evaluation. (Naranjo 2008, 127)

##### 3.6.1.1.1 Melt Flow Index

The characteristics of the polymer melt can be qualified and measured in a variety of methods within the industry. One commonly used method to characterize polymer melt is the melt flow index, which is a simple and quick way of doing quality control. The process involves heating a polymer sample in a barrel, and then pushing it out through a short cylindrical die using a weight-activated piston. The weight of the extruded polymer in grams within a 10-minute timeframe determines the polymer's melt flow index. More material indicates shorter molecular chains, thus a more degraded material. (Naranjo 2008, 147) An illustration of the MFI procedure is shown in Figure 3.6 below.

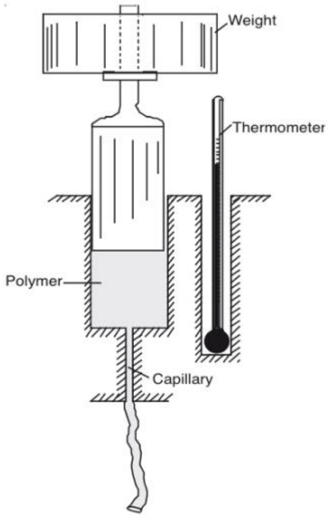


**Figure 3.6: Melt flow index measured by an extrusion plastometer (Naranjo 2008, 147)**

*3.6.1.2 Testing of Mechanical Properties*

By testing the mechanical properties of polymers, the short- and long-term response to loaded content can be determined. Usually, properties for short-term response can be obtained by short-term tensile- and impact tests, while long-term response can be measured by e.g., creep testing and dynamic tests. (Naranjo 2008, 185)

3.6.1.2.1 Tensile Test

The short-term stress-strain tensile test is the most frequently used mechanical test. During the tensile test, a standard specimen is subjected to a constant elongational strain rate, to determine the deformation. For thermoplastic materials, the deformation is time-dependent and can be irreversible (Naranjo 2008, 185). Since this testing method has been originally designed for other types of materials with a linear elastic stress-strain curve, it is not ideal for testing polymers, but is commonly accepted as a valuable tool to evaluate the properties. There are some standardized tests available for evaluating the stress-strain behavior of polymers, such as ISO 527-1. (Naranjo 2008, 187)

3.6.1.2.2 Impact Test

Impact loads will be applied to almost all polymer components during the product life cycle. Many polymers are ductile and robust, and therefore suitable for this kind of loading, but even the most ductile materials can fail in a brittle manner at very low strains. This usually happens at low temperatures, when the temperature goes below the polymer's temperature range, and at high rates of deformation. There can be quite a difference in impact strength of a copolymer and polymer blend of the same material. Moreover, different types of fillers, together with their size, can have an impact on the properties of a polymer. (Naranjo 2008, 200-201)

One of the most widely used tests for impact strength is the Charpy test. During a Charpy test a small notched or unnotched simply supported sample gets struck by a swinging hammer and the bending impact strength is evaluated. This type of test thus enforces a bending load on the test samples. (Naranjo 2008, 202) One impacting factor regarding the impact resistance of a polymeric material is temperature, and brittle behavior can be developed by lowering the temperature. Moreover, the processing conditions, such as the barrel temperature during extrusion, as well as the residence time inside the barrel can also affect the impact properties of a plastic part. Longer residence times and higher processing temperatures will therefore have a disadvantageous effect on the impact properties. (Naranjo 2008, 212-213)

#### 3.6.1.2.3 Shore D Hardness Test

The Shore D hardness test relates to the hardness of the material tested on a scale of values between 0 to 100, where a higher number discloses an increased hardness. It is measured with a Shore durometer, which is measuring the resistance of plastics toward indentation. There are various Shore hardness scales, like Shore A or Shore H, but the Shore D scale applies to harder plastics. When performing Shore D hardness tests, the durometer needle is placed against the plastic, and pressure is applied. It is recommended to take more than one measurement at various points on the material and calculate the average value. (Essentra Components, 2022)

### *3.6.1.3 Thermal Properties*

#### 3.6.1.3.1 Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) is an analytical tool used for identifying various properties, physical and thermal, of polymers. It can be used for identifying or estimating melting and mesomorphic transitions, entropy, enthalpy, changes in heat capacity ($C_p$), and characterization of the glass transition temperature ($T_g$). $C_p$ is defined as the amount of energy a material sample can hold successfully. Moreover, knowing the $C_p$ values of materials is beneficial for extruders, and can be used for the estimation of energy required to melt the material fed into the extrusion machine, increasing the efficiency of the process, etc.

According to Singh and Kumar Singh (2021) the DSC tool is crucial in the field of semicrystalline polymers, due to the phase transitions being dependent on the heating and cooling rate. DSC is used for determining the degree of crystallinity of materials, thus the degradation of the material, which is done by analyzing melting peaks. It can also be used for polymer blend identification or contamination tracing.

If more than one melting peak appears in the resulting graph, it indicates a blend of polymers that are not miscible homogeneously.

The DSC tool consists of a thermal scanning chamber where the material gets heated and cooled, and a computer for calculations and analysis. When performing the DSC analysis, less than 10 mg of sample and a heating rate of less than 10°C/min should be used for gaining valid results. (Singh, A. and Kumar Singh, M. 2021, 201-220)

# 4 Results

*This section will present the results gained through internal- and external interviews, as well as the material testing.*

## 4.1 Summary of Interviews

***Table 4.1 Information about interviewed representatives***

| Name | Company/Institution | Position | Date of interview |
|---|---|---|---|
| Rickard Jansson | Svensk Plaståtervinning | Development Engineer | 24-03-23 |
| Henrik Eriksson | Baerlocher | Technical Product Manager | 28-02-23 |
| Anette Munch Elmér | Polykemi | Head of Development | 01-03-23 |
| Lars Josefsson | | Senior Professor - Chemical Recycling of Plastic Waste | 01-03-23 |
| Candidate 1<br>Candidate 2 | Company T2 in Europe | Former Owner<br>Operational Manager | 16-03-23 |
| Anders Sjögren | Ad-Manus | Ph.D. - Material Science, CEO and Owner of Ad-Manus. | 06-03-23 |

The interview questions along with the full interview summaries can be found in Appendix C.

### 4.1.1 Rickard Jansson – Svensk Plaståtervinning

Rickard Jansson is a development engineer and a material expert at Svensk Plaståtervinning in Motala, Sweden. After studying engineering, Rickard Jansson has worked with material technologies and material science for the past 15 years. Previously working within the automotive-, aviation- and military defense industry, Jansson started at Svensk Plaståtervinning three years ago, focusing on environmental- and sustainability issues.

Svensk Plaståtervinning is owned by large parts of the Swedish business community through the Plastbranschens Informationsråd (IKEM and SPIF), the Swedish

Association of Consumer Goods Suppliers, the Swedish Trade Federation along with the Swedish Retail Federation. The company offers a national system for circular recycling and collection of plastic packaging for producers and businesses and is now building the world's largest and most efficient plastic recycling facility, Site Zero. (FTI 2023)

The full interview summary, along with interview questions can be found in Appendix C.1. The main takeaways from interviewing Rickard Jansson were:

- The importance of efficient processes in waste separation-, and recycling communities to reach a global standard
- Design for recycling is an important factor of the plastic packaging industry
- Sorting-, and washing technologies are crucial in quality assurance of PCR material, as it determines the purity of recycled materials
- Investments on advanced technology is needed for sorting-, and washing facilities, i.a., an increased number of NIR scanners can improve sorting accuracy
- A circular recycling process is the fundamental concept for replacing virgin materials, leading to a better quality of recycled materials. This by applying more fractions of polymer materials, along with a more accurate sorting
- Due to the sorting process, PCR material is most often not of pure HDPE. It is frequently contaminated with other polymers i.a., LDPE or PP

### 4.1.2 Henrik Eriksson – Baerlocher

Henrik Eriksson is an LTH alumni in the field of chemistry and has later worked at Polykemi in Ystad for about 15 years. At Polykemi Henrik Eriksson worked with recycled plastics, gaining experience on how the plastic recycling industry works. Now Eriksson works at Baerlocher, as a technical product manager, responsible for the technical aspects of the polymer products. Throughout time, this field has gradually started to involve recycling procedures.

Baerlocher produces so-called pastilles, containing stabilizers and additives with 100% active content. This pastille is added as a granule with the grinded polymer flakes before being regranulated into raw material. The pastille concept simplifies the handling of the additives for the recyclers. The additive formulations are compounded to contribute to reaching the best possible properties of plastic materials.

The full interview summary, along with interview questions can be found in Appendix C.2. The main takeaways from interviewing Henrik Eriksson were:

- The type of sorting technique determines the quality level of recycled PCR material
- Sorting efficiency is connected to how modern the sorting technology is, and when the sorting facility was built
- The washing-, and sorting processes will determine how clean and pure the PCR material will be, and might be the most important step in assuring quality of PCR materials
- Testing for quality assurance can include tensile testing, measurement of ash content, and DSC testing
- Additives like hindered phenols and phosphites, in combination with acid scavengers, can be applicable to a material like HDPE to inhibit the degradation of mechanical properties
- Recyclers want to maximize profits by using higher process temperatures which causes degradation of the polymers, leading to a negative impact on the outcoming material quality
- The cost of the polymer will increase with the number of set specifications and requirements

### 4.1.3 Anette Munch Elmér – Polykemi

Anette Munch Elmér is an LTH alumni with a Ph.D. in the field of chemistry. At the moment Anette Munch Elmér is the head of development at Polykemi in Ystad, working with frequently developing new materials.

Polykemi is a company with more than 250 employees, making customized thermoplastic raw materials, mainly to be used for interior details within the automotive industry. Besides Sweden, Polykemi has production in China and the USA. Rondo is an affiliate of Polykemi, handling the production of recycled materials, which is PIR material only. Rondo mechanically recycles the PIR material and upcycles it with various additives to be used again.

The full interview summary, along with interview questions can be found in Appendix C.3. The main takeaways from interviewing Anette Munch Elmér were:

- The use of additives, such as antioxidants, for each recycling cycle will help protect the plastic and, making it last for a longer period of time
- Repeated heating of plastic material causes the polymer chains to degrade, leading to poorer mechanical properties and difficulty in further material processing
- The importance of maintaining a good relationship with the suppliers, and to choose suppliers carefully
- Proper dialogue between parties contributing to the quality assurance
- The testing procedure for quality assurance depends on customer needs and requirements. One example could be if a customer wants material with high impact strength, the material should be tested for this property
- The three interrelated factors; the production process, the shape of the desired part, and the material used, primarily determines the final properties and quality of recycled materials
- Uniform global quality level is more based on the organization than the region

### 4.1.4 **Lars Josefsson – Chemical Recycling**

Lars Josefsson has worked over 30 years at one of the big chemical companies in Stenungsund, Inovyn, that manufactures a wide range of chemicals used as raw materials in industrial processes (Inovyn 2023). Josefsson has had 12 different roles at the company and was the CEO between the years 2001-2009. Since 2011 Lars Josefsson has worked within the field of sustainability and plastic recycling.

The full interview summary, along with interview questions can be found in Appendix C.4. The main takeaways from interviewing Lars Josefsson were:

- Chemical recycling being the long-term future solution in the recycling field
- Chemical recycling being the sole method to obtain virgin material with virgin properties by recycled material
- Society needs to accept chemical recycling as an official recycling method
- Chemical recycling is not applicable as a recycling method today due to the early stage and high cost
- Repeated heating of material throughout a recycling process causes poorer material properties
- The importance of sorting-, and washing processes for PCR material related to quality
- The importance of Design for recycling for a facilitated recycling process
- Investments are required within the recycling field to achieve high material quality

### 4.1.5 **Company T2 in Europe**

Company T2 in Europe has been working with one of the companies that got acquired by Company X in 2022, and mainly produces to European customers. Company T2 in Europe focuses on producing products within consumer markets, the food sector, the pharmaceutical sector along with the industrial sector, hence having insights into the utilization of recycled materials when thermoforming. Since Company T2 in Europe does not have a direct involvement to the focused product of this thesis, Company T2 in Europe could carry a somewhat objective perspective on how global collaborations can affect quality assurance. There were two candidates present for this interview – one being the operational manager of Company T2 in Europe, the other being the former owner of Company T2 in Europe. Working with both PIR-, and PCR-materials, Company T2 in Europe described its way of working, and explained the thermoforming industry in this interview.

The full interview summary, along with interview questions can be found in Appendix C.5. The main takeaways from interviewing Company T2 in Europe were:

- The relationship/cooperation between extruders and thermoformers affects production quality
- The properties of recycled materials, e.g., shrinkage percentage, are difficult for thermoformers to interpret, affecting production quality
- Certification management is disorganized and can be interpreted in multiple ways
- Challenges and prerequisites at producing sites are based on different business-, national-, and corporate cultures, affecting production quality globally
- Maintaining uniformity in the size of regrinded flakes is crucial for successful extrusion

### 4.1.6 **Anders Sjögren – Material Testing**

Anders Sjögren, a teacher at LTH and founder of Ad Manus Materialteknik AB, is an expert within the material testing field. Ad Manus Materialteknik is an independent company offering testing and analysis of materials and components, specializing in the testing and analysis of plastic and composite materials (Ad Manus 2020). Anders Sjögren was consulted regarding the material testing part of this thesis. The list of testing equipment available, together with the problem statement of this master thesis, was presented to him and discussed thoroughly.

The full interview summary, along with interview questions can be found in Appendix C.6. The main takeaways from interviewing Anders Sjögren were:

- Overall testing recommendations for quality assurance involved Charpy Impact test, Tensile test, Shore D hardness test, MFI, and DSC
- Difficulty in drawing conclusions on material behavior by only testing Shore D Hardness
- Conducting a DSC test helps to portray potential differences in the level of crystallinity in a material, in order to target possible contaminations or blends
- Conducting an MFI test can provide a proper indication on how degraded a recycled material is when compared to virgin material
- Recommendation to create a customized tensile specimen punching tool

## 4.2 Producing Sites

This section presents each producing site producing Product Y. A question bank has been sent out to each site covering the following topics:

- Current production status of Product Y
- Current suppliers along with vendor routine
- Processing
- Recycling process

The questions used in the question bank can be found in Appendix D.1. The answers from the question bank are presented in two formats; the numeric answers listed in Table 4.2 below, and written answers that are summarized into written presentations of each producing site, in the subsections further down.

*Table 4.2 Processing data between producing sites managing the production of Product Y*

| **Questions** | **Company X1 in the Americas (Company ET1)** | **Company X1 in the Americas (Company T1- & E1)** | **Company X1 in Asia** | **Company X2 in Europe** |
|---|---|---|---|---|
| Forming method | Vacuum | Vacuum & pressure | Vacuum | Vacuum & pressure |
| Positive or negative forming? | Positive | Positive | Positive | Positive |
| Preforming? | | No | No | No |
| Rolls/sheets | | Rolls | Rolls | Rolls |
| Dimensions of rolls | | 1.8 mm x 710 mm | 1.8 mm x 690 mm | 1.8 mm x 700 mm (index 550 mm) |
| Forming temperature | | 155 °C | Maximum machine temperature: 550 °C | Ca 150 °C |
| Molding tool temperature | | 50 - 55 °C | Maximum machine temperature: 70 °C | 40 - 50 °C (Depends on room / external temperature) |
| Vacuum pressure | | 25 psi (0.17 MPa) | -0.1Mpa / 0.8 MPa | 1.8 bar air pressure and 2 bar demolding |
| Cooling temperature | | N/A | 15 °C +/- 3°C | N/A |
| Cycle time | | 25-45 sec depending on the process. Currently at 25 sec | 36 sec | 15.6 sec |
| PCR or PIR | 100% PIR | 75% PIR / 25% PCR mix | Mixed, ratio hard to trace | 100% PIR |
| % recycled material | 100% | 100% | 100% | 100% |

### 4.2.1 Company X2 in Europe

Company X2 in Europe was acquired by Company X in 2022 and thermoforms Product Y in-house. Having one vendor based in Europe, Company X2 in Europe manages solely PIR material for Product Y.

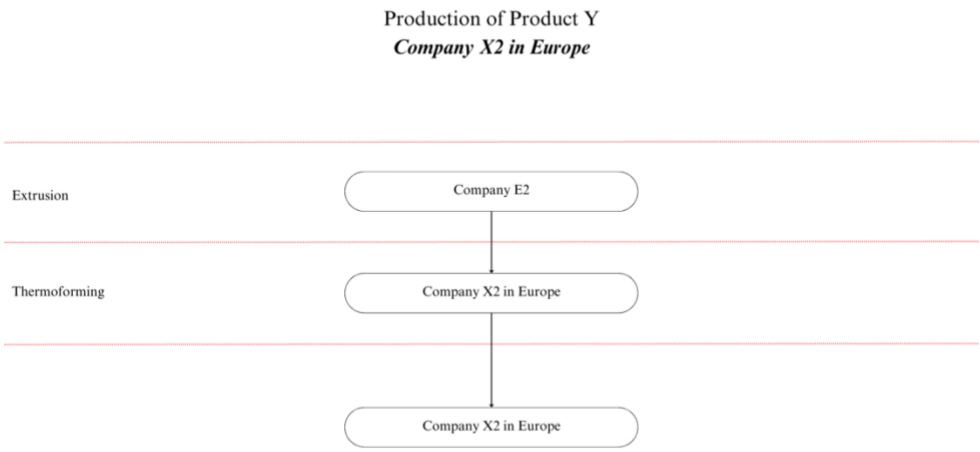


**Figure 4.1 Production of Product Y – Company X2 in Europe**

*4.2.1.1 Product Y*

Company X2 in Europe is not facing any current issues with Product Y. Thin gauge is applied when thermoforming, and the set wall thickness to the product is 1.8 mm.

*4.2.1.2 Suppliers*

As viewed in Figure 4.1 above, Company X2 in Europe has one Europe-based supplier providing extruded PIR-rolls. The vendor and Company X2 in Europe have an agreement covering industrial scrap. The scrap Company X2 in Europe gathers during production, is grinded, and sent back to the supplier for recycling.

*4.2.1.3 Vendor Routine*

When considering picking up a new vendor, Company X2 in Europe has the routine of testing different vendor options, focusing on PIR materials solely. Company X2 in Europe would perform thermoforming tests of the materials and monitor the outcome on areas that previously has been reported as critical on other producing sites. Further, a potential vendor is required to carry a certification (EUCertPlast) to be selected.

*4.2.1.4 Testing*

When testing incoming material from suppliers, Company X2 in Europe mainly visually inspects the sizes of the rolls, measuring thickness and width. Hardness tests are also performed on the rolled material before being thermoformed. For finished thermoformed products, size and wall thickness would be looked over, which is based on a given final drawing. Later, fitting tests are conducted. When the product has cooled down from thermoforming, shrinkage is lastly monitored.

*4.2.1.5 Sorting Technique and Cleaning Procedures*

Since Company X2 in Europe grinds leftover scrap from production before sending it back to the extruding vendor, it must be cleaned before grinding. The cleaning routine is mainly based on how dirty the material is from the start, and if there is no observed contamination, it is not necessary to clean. If it is not doable to remove, the non-cleanable areas get cut out from the product. The scrap is collected and categorized into different containers. When filled, grinding commences. While at the extrusion vendor, a filter in the extrusion line is able to filter out additional contaminations.

*4.2.1.6 Material Properties of the Recycled Plastic*

The HDPE for Product Y is of 100% PIR material and is usually black when processed, which is the aim. It is also acceptable if the material has a darker gray color. Company X2 in Europe uses no further upcycling additives apart from black or darker colored pigments along with following the Restriction from Chemicals- (REACH) and Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoSH) regulations for contamination purposes.

*4.2.1.7 Critical Values*

Hardness-, and material thickness are the critical values Company X2 in Europe bases on when checking the incoming material rolls.

*4.2.1.8 Technical Data Sheet*

The provided TDS for the virgin, European material is for an extruded sheet with a thickness of 4.0 mm, which inhibits comparison with the results from the material testing. Further, no TDS for the recycled HDPE material is provided.

### 4.2.2 **Company X1 in Asia**

Company X1 in Asia was acquired in 2022 by Company X and thermoforms Product Y in-house. Managing both PIR-, and PCR materials with an untraceable ratio, this producing site has a total of four vendors. As seen in Table 4.2, the provided forming-, and molding temperature are the maximum temperature of the machine. This is due to the machine not having a probe for heating temperatures, according to Company X1 in Asia. When the heated material later goes to molding, the mold is cooled with water to maintain 70°C, hence it being the maximum temperature.

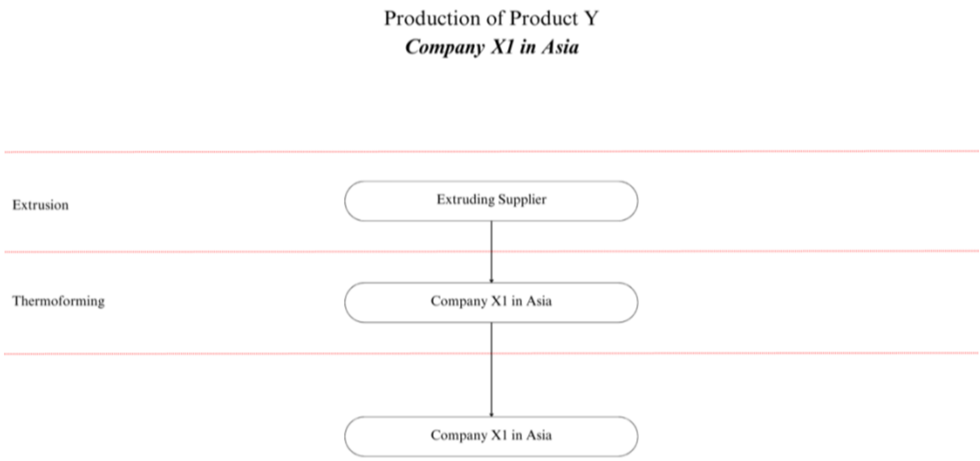


**Figure 4.2 Production of Product Y – Company X1 in Asia**

### *4.2.2.1 Product Y*

Currently, this producing site states to observe three main issues for production of Product Y: damages by the cushion flange, holes in the corners of the product, along with webbing in the corners. These issues are occurring quite regularly (2-3% of entire production), but not always necessarily in the same area of Product Y. The damage on the cushion flange is stated to be caused by human error i.e., *"careless trimming"*. The holes in the corners are motivated to be caused by *"different material properties, which are controlled by temperature"*. Lastly, the webbing in the corners is stated to be caused by *"overheating"*.

Apart from the stated common issues, Company X1 in Asia keeps extra attention to the critical factors, such as wall thickness in the indicated locations on given drawings, along with how the cushion pockets are fitting. Thin gauge is applied when thermoforming, and the set wall thickness of the product is 1.8 mm (+0.05/-0 mm).

### *4.2.2.2 Suppliers*

As viewed in Figure 4.2 above, Company X1 in Asia has a total of four suppliers:

- One pigment supplier, that supplies a pigment paste to the products if necessary
- Two HDPE pellet suppliers who trade pellets from other pellet suppliers. The source is unknown due to claimed business secrets
- One extruding supplier which is managed by an internal unit at Company X1 in Asia. When extruding, Company X1 in Asia performs controls once every three months. If the material is not fulfilling the set critical values, materials get returned

#### 4.2.2.3 Vendor Routine

When considering picking up a new vendor, Company X1 in Asia follows specified working instructions that cover criterias based on the type of vendor, how often the audit is ought to be done, along with a scoring table. Some of the suppliers provide test results of the recycled HDPE provided. However, the producing site does conduct testing internally, which further analysis mainly is based on.

#### 4.2.2.4 Testing

When testing incoming material from suppliers, Company X1 in Asia follows a specified working instruction for incoming materials which covers what to check at which stage, basing the inspections on the delivery order. For finished thermoformed products, fitting tests of cushion pockets are performed, along with product weight which must be below 180g.

#### 4.2.2.5 Sorting Technique and Cleaning Procedures

According to Company X1 in Asia, sorting is executed manually at vendors. Regarding the cleaning procedure at vendors, Company X1 in Asia responds that data is not applicable. Additionally, Company X1 in Asia collects production scrap for recycling. Hence, the company uses around 60% of bought pallet materials with around 40% production scrap.

#### 4.2.2.6 Material Properties of the Recycled Plastic

The HDPE for Product Y contains a mix of 100% recycled PCR-, and PIR materials, with a ratio that is hard to trace due to claimed business secrets at the vendor, which implies the ratio varies. Company X1 in Asia accepts recycled material of all colors except yellow and red as these could affect the process. Upon request, upcycling additives, like humidity-removing powder, along with color pigments could be added to the material, according to the company.

#### 4.2.2.7 Critical Values

For incoming material rolls, critical variables are elongation at break, hardness, and material thickness. The values are presented in Table 4.3 below.

***Table 4.3 Critical values for Company X1 in Asia***

| Critical variables | Value |
|---|---|
| Elongation at break | 400 mm |
| Hardness (Shore D) | 65 |
| Material thickness | 1.8 mm (+ 0.05 / - 0 mm) |

Critical values for a finished Product Y are mainly determined based on set requirements according to a set Acceptance Quality Limit (AQL), but would usually include observations on wall thickness, along with a fitting test, to inspect possible shear stresses. Based on a given drawing of Product Y, requirements are set accordingly.

*4.2.2.8 Technical Data Sheet*

The TDS provided by Company X1 in Asia includes numeric data of different performances that are presented in Table 4.4 below. These performances are categorized based on mechanical properties, basic performances, RoHS, HF, and others. It is unclear whether the TDS is for recycled or virgin HDPE material.

***Table 4.4 Technical Data Sheet HDPE from Company X1 in Asia***

| **Performance** | | **Target** | **Unit** |
|---|---|---|---|
| Mechanical Properties | Tensile fracture length | $\geq$400 | mm |
| | Hardness | 60-65 | N/A |
| Basic Performance | Melt-Flow Index | ≦3 | g/10 min |
| | Density | ≦0.98 | g/cm$^3$ |
| Other | ESD | $10^{8-11}$ | Ω |
| RoHS | Pb + Hg + Cr + Cd | ≦100 | ppm |
| | Cd | ≦25 | ppm |
| | PBB & PBDE | N/A | ppm |
| HF | F | ≦500 | ppm |
| | Cl | ≦500 | ppm |
| | Br | ≦500 | ppm |
| | I | ≦500 | ppm |

### 4.2.3 **Company X1 in the Americas**

Company X1 in the Americas was acquired in 2022 by Company X and has two production lines, one located in North America, and the other in Central America. Both production lines outsource the production of Product Y fully. Managing both PIR-, and PCR materials with a ratio of 75% PIR, and 25% PCR, Company X1 in the Americas has a total of three vendors; one in Central America, and two in North America, who also has been interviewed for this project.

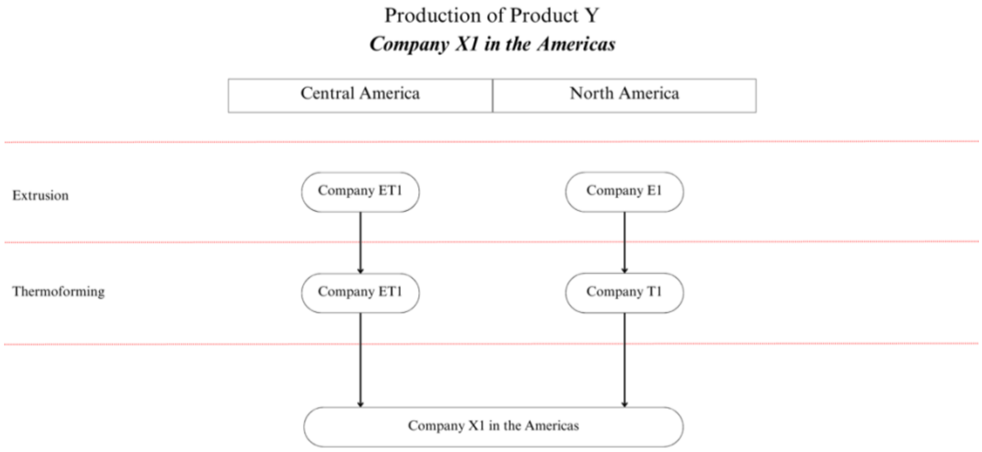


**Figure 4.3 Production of Product Y – Company X1 in the Americas**

*4.2.3.1 Product Y*

Previously, both producing lines within Company X1 in the Americas have been facing aesthetic issues occurring in the same location on the finished thermoformed products. However, it is stated that it is not affecting the functionality of Product Y. An employee at Company X1 in the Americas states that the production parts are in fact functioning better than any prototypes. Despite this, the customer, Company C, has rejected the parts in North America due to aesthetic issues, which are not a part of the specification. However, this issue is claimed to have been solved, which is described further down in the interview with Company T1. Thin gauge is applied when thermoforming, with the starting gauge at 1.8 mm.

*4.2.3.2 Suppliers*

As viewed in Figure 4.3 above, Company X1 in the Americas consists of two production lines. One is located in Central America that has one vendor, Company ET1. This vendor manages the production line from extrusion to thermoforming. The second production line located in North America is managed by two different vendors: one extruding vendor, Company E1, and one thermoforming vendor, Company T1. The vendors at the North American production line have been working with Company X1 for around 20 years.

*4.2.3.3 Vendor Routine*

Due to the long-term working relationship with the current vendors, Company X1 in the Americas has not established a uniform vendor routine for establishing new collaborations. However, vendor audits are performed regularly. For incoming materials, the material vendors do provide a certificate of compliance with each release.

#### *4.2.3.4 Testing*

Since the production line in North America has two different vendors, Company T1 bases the inspection routine on an internal policy document for the incoming material from Company E1. This document covers the number of samples that must be checked per roll, how many rolls that are to be inspected based on the delivered number of rolls, and which. Further, it is implied to check Shore D, material thickness, and width for the sample rolls. For finished products, both Company T1 and Company ET1 follow a Quality Specification Sheet (QSS) covering finished product weight, dimensions, print checks, along with form- and fit checks via drop tests.

#### *4.2.3.5 Sorting Technique and Cleaning Procedures*

The cleaning procedure is not provided by Company X1 in the Americas. However, a video along with an illustrative flow chart is provided. The video demonstrates a full recycling cycle of PCR materials, and the flow chart shows the cycle for PIR materials.

Commencing with PCR-material sorting, the video starts with viewing traveling waste on a conveyor where an employee assists the flow by sorting out some of the waste manually. It is however unclear what is being sorted out, along with if all waste is sorted manually like presented. Thereafter, the sorted material gets shredded into flakes of different sizes that later go through another sorting process, ensuring the different flake sizes are separated. Later, it can be assumed that the material had been washed before seeing it being packed into bags and sent to, what is assumed, extrusion suppliers. The last scene of the video shows a local lab with what it looks like, different scales, and further equipment for sample checks.

Regarding the PIR material, the illustrative flow chart is presented in an encrypted version below in Figure 4.4. The cycle commences with scrap being collected from the previous production, getting shredded into flakes, proceeding to be mixed. When mixed, the material then goes into extrusion to create the wanted material rolls of 100% recycled material. Lastly, the rolls get thermoformed into finished product. Final modifications and inspections are performed, along with collecting production scrap. The finished products are sent to customers, and scrap gets recycled for further production loops.

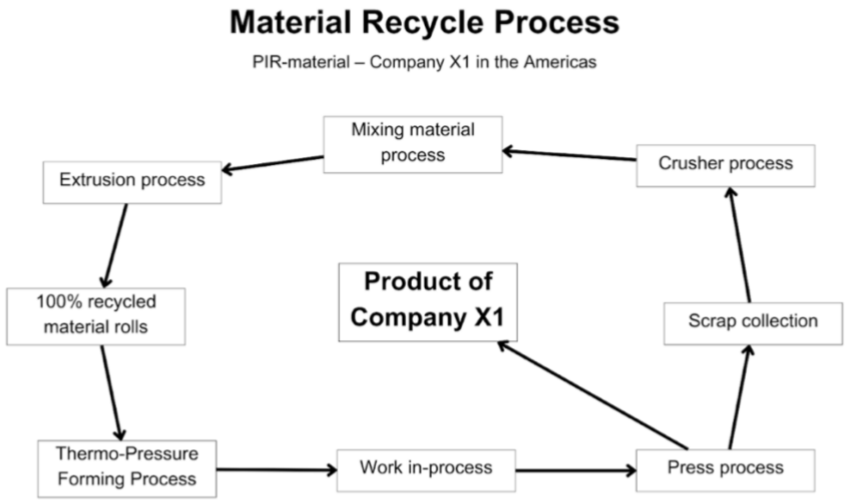


**Figure 4.4 Encrypted version of flow-chart provided by Company X1 in the Americas**

*4.2.3.6 Material Properties of the Recycled Plastic*

The HDPE material for Product Y contains a mix of 100% recycled PCR-, and PIR materials: 75% PIR, 25% PCR. This ratio is stated to vary depending on supply and demand, along with the availability of PCR materials. Company X1 in the Americas accepts PIR materials primarily in black or grey color. It is unclear what colors are accepted for PCR materials, but it can be assumed that PCR is of grey color when mixed. Previously, pigments used to be added for every batch. However, since products made with black color are harder to sort out with common IR detectors, Company X1 in the Americas is not adding any further coloring to the production of Product Y at the moment. It is not stated if any other upcycling additives are added.

*4.2.3.7 Critical Values*

Rolled material for Product Y follows the critical values of hardness and material thickness.

*4.2.3.8 Technical Data Sheet*

The TDSs provided by Company X1 in the Americas are all documents from Company E1. There are a total of four provided documents including a material specification, a safety data sheet (SDS) for virgin PE sheets, a 'Material certification' provided to Company T1, and a 'Recycled products letter' aimed for customers. The material specification includes material characteristics in processing, applications, finishing, and color/texture and capabilities, along with numerical data e.g., tensile strength, impact strength, and melt flow index presented in Table 4.5.

***Table 4.5 An extract from an HDPE material specification from Company E1***

| Property | Test Method | Value | Unit |
|---|---|---|---|
| Specific Gravity | D792 | 0.955 | |
| Melt Flow Index | D-1238 | 0.2-0.3 | g/10min |
| Tensile at Yield | D-638 | 4000 | psi |
| Ultimate Elongation | D-638 | 600 | % |

The SDS states different safety aspects to know when managing a PE material. This includes general identification aspects for hazards, compositions, first-aid measures, and further safety aspects.

The 'Recycled products letter' is purposed for the clientele of Company E1, and basically disclaims the usage of recycled materials. In the letter Company E1 mentions that the recycled materials do not guarantee production relative to the material's physical properties and that Company E1 only can guarantee *"…the physical dimensions, and that the base material being of the polymer family desired for products sold as 'ReCycled'.*" Further, the letter states that technical data sheets for these recycled materials are not available, referring to the "…unpredictable nature of the used material…". To read an encrypted version of the letter, please view Appendix D.2.

The 'Material certification' document that Company T1 receives with the incoming material covers the order number, basic characteristic as material type, along with material color, and from which plant it is sent. Since Company E1 manages many purchase orders for this material, these certifications can be used for multiple order numbers. Being a standard component for the ongoing project of Product Y, all of the material is stated to be of the same specification and should therefore match the provided data sheets – despite having different order numbers.

#### *4.2.3.9 Interview Summaries*

***Table 4.6 List of companies for interviews***

| Company | Interviewee | Date of interview |
|---|---|---|
| Company E1 | General manager<br>Recycling facility manager<br>Regional sales manager (west) | 09-03-23 |
| Company T1 | Senior manufacturing engineer | 08-03-23 |

##### 4.2.3.9.1 Company E1

An interview was conducted with Company E1, an extrusion company part of the North American production line for Product Y in the Americas. The purpose of the interview is to gather a deeper understanding of what root causes there are for the issues on Product Y in the Americas, along with getting overall insights regarding quality assurance within the plastics extrusion industry. The questions for the interview can be found in Appendix D.3.

Commencing with the procedure of choosing suppliers of the recycled HDPE to be used in Product Y, Company E1 initially claims it to depend on whether the material is of PCR-, or PIR-material. Also, traceability is different depending on the material source and its previous life.

The PIR material is commonly gathered from a closed-loop process with the customers who will send back scrap, e.g., cut-outs, formed parts, customer returns like sheets, old stock that has met the end of life, etc., to be grinded and used for new products. Company E1 has the infrastructure to handle scrap in any form possible to be shredded. This recycling process is under full control by the company. Usually, 30-35% of the material is brought back as regrind or scrap.

Regarding the PCR material, Company E1 makes sure to source from large suppliers with good quality sorting and cleaning equipment, having the infrastructure capabilities to ensure precise sorting and the newest technology. The plastics can be sorted by color, density, with NIR, etc, to achieve pure material streams. Further, Company E1 emphasizes that there is a big responsibility to partner up with the right suppliers, to bring in the right product, i.e., the suppliers with the cleanest streams will be chosen. If the material that goes into production is not clean or pure, the outgoing product will not be of good quality, therefore these feedstocks are to be eliminated.

Proceeding to testing routines for incoming material, Company E1 requests samples of each material before it is put into production. This to run tests for validation of the material and to verify consistency. Every load that goes into the door will be checked through the Quality Control (QC) process to check purity. However, the physical properties are tested less frequently.

All the production sites of Company E1 have lab capabilities for easy access to run all necessary tests. The reason for this is accessibility for investigating purity and properties of the material, to get further details. Visual inspection, probing, sample burning to look for contamination, like talc, are performed, as well as inspection through different light spectrums to look for possible mixed-in materials. Also, depending on customer specifications, melt flow, density, and other tests are performed.

Once the material is qualified for production, it will be pelletized to get a homogenous material and during this blending process, the material can be customized according to the customer's quality specifications. Then the material is further tested according to specifications gained from the QC process. These tests will give an indication of if the material has the specific output looked for in extrusion. Because of the use of LOT numbers, as a way of material tracking, the MFI can easily be traced for each material. If something is not correct with the material quality, it will stay in-house, according to Company E1. HDPE will initially be tested by tensile strength, along with density, melt flow, and flexibility. Once a material is verified and put into use, spot checks will be performed. Visual inspection for purity is performed on all materials.

Shifting the focus to testing routines on finished products, Company E1 explains that quality can be split into two functions: the first being quality-, and process control, the second being quality assurance. Covering the first function, Company E1 describes quality control as the *recipe management* of the plastic material. This gets included in the specifications and set requirements that are considered to be hard limits. The process control involves making sure the correct settings, such as speed, motors, and temperatures are used. The operators are required to run material according to specifications, which may vary depending on the customers. Furthermore, Company E1 is using LOT numbers to enable a consistent tracking system of the product throughout the processes. These LOT capabilities will be going through operator records.

Proceeding to the second function of quality, each location belonging to Company E1 has its own specified inspectors and time-required intervals for testing. For PE material, the dimensional tolerances are required to be checked, for continuous monitoring of gauge reading – both in the machine's direction, as well as the transverse direction. Additionally, sheet characteristics when the material is laying flat are to be checked. Further aspects relative to surface attributes can vary depending on the product, while tensile properties and impact strength are required to be checked.

The frequency of testing outgoing material is explained to depend on the resulting volume of material production, along with its required production time. To clarify, there is no standard routine in frequency, as the resulting production volume significantly varies in production time. E.g., there could be a line producing 227 kg (500 pounds) of material per hour, while another line produces 3 000 pounds of material per hour. In the QC departments, however, operator tests are performed each hour. From a quality assurance standpoint, spot-checking of quality control issues and LOT verification is to be audited regularly. However, it also varies depending on the product and location.

When questioned about observed common issues within the extrusion of recycled plastic materials, Company E1 discusses mechanical recycling and how the quality depends on the recycler's efficiency, along with processing equipment and procedures. All types of processing issues e.g., surface quality, and formability issues, are all based on material source, which creates unnecessary internal waste.

Consequently, in addition to past experiences with low-quality materials, Company E1 emphasizes being heavily invested in the QC process, ensuring to have the right recycling equipment to avoid the issue. Further, the believed solution is to partner up with the right suppliers that can ensure clean streams of recyclates going into the production of the foil.

Another solution is to establish a proper sourcing routine for incoming material, along with established internal QC processes. Company E1 explains that delivering a product with lacking quality to a customer that later will be rejected, only leads to more cost, energy, and waste – resulting in a circle of loss for both the company and the environment.

When asked about the mixed 75% PIR, 25% PCR material ratio used for the production of Product Y, it can be assumed that what is requested by the customer, is what is being delivered. In this case, Company X sends requests to Company T1, followed by Company T1 requesting to Company E1.

#### 4.2.3.9.2 Company T1

An interview was conducted with Company T1, being the thermoforming vendor for the North American production line for Product Y in the Americas. Company T1 has worked with both Company E1 and Company X for over 20 years. The purpose of this interview is to gather a deeper understanding of what root causes there are for the issues on Product Y in the Americas, along with getting overall insights regarding quality assurance within the thermoforming industry. The questions for the interview can be found in Appendix D.4.

Commencing with how quality assurance is maintained for incoming extruded material, the employee at Company T1 highlights the focus on the incoming material's physical aspects. Mainly to make sure that the material works for the machine lines. Furthermore, whether the vendors are providing the asked quality is not checked as regularly and is more based on trust. There is no primary focus on the chemical testing of the material.

In regard to the volume in the production line, the employee highlights the aim of putting as few man-hours on inspection as possible. Company T1 receives more than 18 000 kg of rolls per truck at the time, where an employee visually inspects the incoming batch. After that, further decisions on how to inspect the material are followed by a matrix, based on the material volume.

An average inspection would include checking material thickness and roll width, which are all based on yield. From there, it is possible to target potential material errors before the material enters the machine lines, Company T1 states. Some criterias the company follows regarding processing, motivated by what the effect would be if it is not checked, are:

- If the roll width is too wide, it would waste more material.
- If the roll width is too narrow, it would not fit the machine.
- If the roll is too thick, it would run overweight.
- If the roll is too thin, it would run underweight and/or not meet the set thickness criteria.

Due to the high volumes received, Company T1 performs sample checks on around 3-5 pallets out of 26 in a truck-loading and bases the expectations of the materials on specified tolerances. In this stage, inspection involves hardness testing, visual inspections along with width measurements. This is mainly to see if the material would contain any camber, which would affect the material.

Proceeding to the quality assurance of incoming rolls, specifically delivered from Company E1, the company does not do anything specific other than maintaining proper correspondence with Company E1, when errors occur. On a case-by-case basis, Company T1 supplies Company E1 with some product samples when facing more severe issues.

The employee continues to explain about an inspection form specified for the Product Y. When managing PE, the employee states that it is one of the inferior materials available. Continuing, the employee believes as long as the material is recycled properly, it comes out as good as one would expect to get.

When asked about the content ratio between PCR, and PIR material of the Product Y, the employee states that it is mostly handled ad-hoc and that it all comes down to how the material formula is working as the material is running in the extrusion machine. Further, the employee explains that if the material is not forming right, it is possible that extruders add further polymers, additives, and/or even virgin material.

According to the employee, adding virgin material can facilitate the bindings of materials when extruding, which is commented to be more common with PCR material as it contains more oxidation. When asked if the employee would be notified if virgin material were to be added to an extrusion mix, the answer is that it mainly goes under the radar. Unless a specification is heavily demanded, those specifications would not be provided to the thermoformer and further refers to companies' material formulas being business secrets.

Focusing on what effects processing and machine settings can have on a finished product, the employee disclaims being more familiar with machine maintenance than the practical procedures and refers to the colleagues on the floor. The employee could however comment on the possibilities to perform machine adjustments on basic parameters, like temperatures, speed, different types of pressures, time on the mold, cooling time etc. By focusing, and tracking, the recycled materials, these modifications could sometimes help circumvent some of the different formulas of the recycled material, according to the employee.

Apart from the previously mentioned inspection routine, Company T1 records the roll numbers, which is claimed to be beneficial for the troubleshooting process. When the material is fed into the machine, a roll-by-roll inspection is performed. This could include measuring width, gauge, and further assurance on the rolls.

Shifting the focus to how Company T1 quality assures when testing on a finished product, the employee explains that the testing routines are mainly based on a Quality Specification Sheet (QSS), followed by required prints provided by Company C, along with Company X. The QSS contains a list of inspection items that Company T1 needs to look for when a Product Y is thermoformed, e.g., drop tests. These tests of Product Y usually take 30 minutes and are performed around three times per each 10-hour shift.

The employee explains the accuracy in testing to be unique and further believes that the long working history between Company T1 and X1 can be the main explanation for achieving the unique clarity in testing routines. Company T1 knows what to check, and both Company X and Company C are satisfied, the employee states.

Continuing on efficiency, the employee acknowledges how maintaining simplicity is an aim for Company T1, i.e., the company wants to monitor as few inspection items as possible, which is mainly motivated by people management. The employee emphasizes further how inspections are a time sensitive matter, and if an issue would be targeted, that does not involve material flow or trimming dimensions, the issue is caused earlier in the production line, e.g., back in the extruding-, or the sorting phase.

*"The fewer required inspection items that have to be monitored, the faster and more efficient the employees can keep things moving, avoiding shutting down machines, keeping the employees busy."*

Directing the conversation to common issues faced in thermoforming of recycled plastic, the employee at Company T1 states that there are all kinds of issues appearing when managing recycled material. However, the one issue that causes the most problems for thermoformers is when materials are not bonding right, according to the employee. The employee describes the issue as being a challenge for Company T1, as it is hard to detect the issue before the material already is thermoformed. However, the troubleshooting process is somewhat easier, the employee emphasizes.

Since Company T1 manages big volumes of material on a daily basis, it is easier to tell whether the issue is caused by the material content, or by the machine. Most of the time it is the material content being the factor causing issues, which puts thermoforming companies in a rough position generally.

Since most thermoforming companies do not extrude materials, the companies must work with the provided material from suppliers, troubled as untroubled. Consequently, thermoformers, including Company T1, must invest a substantial amount of time adjusting and tuning the machines to enable the troubled material to be thermoformed, including downtimes. This is an expensive challenge being put on thermoformers due to the time consumption, but also as it exhausts the machines – especially when thermoforming companies are working with multiple extruders following individual processes, like Company T1.

To resolve the issue, the employee believes that a maintained dialogue between thermoformers and extruders is crucial. Additionally, thermoformers should also set solid criterias for extruders, according to the employee. Regarding the production line for Product Y, the employee confirms that there is proper transparency between Company T1 and Company E1, making the bonding issue not to be a challenge currently.

When presenting the given issue on the American Product Y that has been targeted throughout the project, the employee claims that the issue is rooted in a mold design problem. As observed, the same issue with the product corners has appeared on both production lines in the Americas. The two production lines are sourcing material from different vendors; hence, the employee concludes the issue is not caused by the possible different material qualities, but by the mold design. The employee further comments that this issue has been resolved concerning Product Y, as Company T1 recently utilized the same molding tool design as Company X2 in Europe. However, on a general note, the bridge between engineers and designers is key in order to avoid and resolve these types of issues, according to the employee.

## 4.3 Results from Material Testing

### 4.3.1 **Shore D Hardness Test**

The hardness test was carried out on the rolled material before being put in the thermoforming machine. The results of the hardness testing can be seen in Table 4.7 below.

*Table 4.7 Results from Shore D Hardness test*

| Material | Left(L) | Middle(M) | Right(R) | Average |
|---|---|---|---|---|
| Virgin - Europe (111) | 55 | 59 | 59 | |
| | 59 | 61 | 60 | 58.55 |
| | 58 | 56 | 60 | |
| | avg = 57.3 | avg = 58.67 | avg = 59.67 | |
| Recycled - Europe (222) | 58 | 60 | 55 | |
| | 59 | 58 | 56 | 57.78 |
| | 59 | 60 | 55 | |
| | avg = 58.67 | avg = 59.3 | avg = 55.3 | |
| Recycled - Asia (333) | 56 | 56 | 55 | |
| | 53 | 57 | 56 | 55.78 |
| | 56 | 58 | 55 | |
| | avg = 55 | avg = 57 | avg = 55.33 | |
| Recycled – North America (444) | 60 | 54 | 54 | |
| | 59 | 59 | 58 | 57.44 |
| | 56 | 61 | 56 | |
| | avg = 58.33 | avg = 58 | avg = 56 | |

### 4.3.2 **Melt Flow Index**

The MFI test was performed at a university laboratory in the European country where the producing site of Product Y in Europe is located. The testing was done by the laboratory assistant since this was the most suitable solution due to the geographic location of equipment and testing material.

According to the interview with Anders Sjögren as seen in Section 4.1.6 and Appendix C.6, results of MFI testing can be a good indication of how degraded a recycled material is when compared to virgin material. If the viscosity of a material is lower, the MFI value will be higher, thus the material is more degraded. Moreover, as Anette Munch Elmér explains in the interview, every time a material is heated, molecular chains are getting shorter and it risks degrading, leading to worsened properties. A recycled material has been heated up more times than a virgin and will therefore be more degraded, thus having a higher MFI value. Moreover, the standard MFI range for HDPE is 0.2-3.0 g/10min (Khanam, P.N. and AlMaadeed, M.A.A., 2015). The results of the MFI test can be found below in Table 4.8.

*Table 4.8 Results from MFI tests*

| Specimen Label | PIR/PCR ratio | MFI value (g/10min) |
|---|---|---|
| Virgin HDPE (111B) | N/A | 0.32 |
| Recycled - Europe (222B) | 100% PIR | 0.038; 0.052 |
| Recycled - Asia (333B) | N/A | 0.793 |
| Recycled – North America (444B) | 75% PIR, 25% PCR | 0.192 |

The recycled European material was tested a second time because of the unexpectedly low value, to eliminate possible errors due to human factors.

### 4.3.3 Tensile Test

The tensile test commenced with measuring material thickness on three randomly selected specimens per foil sample, which can be seen in Table 4.9-4.12 below. Later, tensile tests were performed at a university laboratory in collaboration with Company X2 in Europe. The tensile testing was done by the laboratory assistant since this was the most suitable solution due to the geographic location of equipment and testing material.

***Table 4.9 Material thickness of virgin HDPE***

| **Virgin HDPE (111)** | | |
|---|---|---|
| **Specimen** | **Thickness [mm]** | **Average [mm]** |
| 111A-2 | 1.74 mm | 1.733 mm |
| 111A-4 | 1.73 mm | |
| 111A-9 | 1.73 mm | |
| 111B-3 | 1.72 mm | 1.72 mm |
| 111B-7 | 1.70 mm | |
| 111B-10 | 1.74 mm | |

***Table 4.10 Material thickness of European recycled HDPE***

| **Recycled – Europe (222)** | | |
|---|---|---|
| **Specimen** | **Thickness [mm]** | **Average [mm]** |
| 222B-2 | 1.86 mm | 1.863 mm |
| 222B-4 | 1.87 mm | |
| 222B-10 | 1.86 mm | |

***Table 4.11 Material thickness of Asian recycled HDPE***

| **Recycled - Asia (333)** | | |
|---|---|---|
| Specimen | **Thickness [mm]** | **Average [mm]** |
| 333A-3 | 1.79 mm | 1.78 mm |
| 333A-8 | 1.79 mm | |
| 333A-10 | 1.76 mm | |
| 333B-3 | 1.78 mm | 1.78 mm |
| 333B-8 | 1.79 mm | |
| 333B-10 | 1.77 mm | |

*Table 4.12 Material thickness of North American recycled HDPE*

| **Recycled – the Americas (444)** | | |
|---|---|---|
| **Specimen** | **Thickness [mm]** | **Average [mm]** |
| 444A-1 | 1.82 mm | |
| 444A-3 | 1.79 mm | 1.81 mm |
| 444A-10 | 1.82 mm | |
| 444B-2 | 1.84 mm | |
| 444B-7 | 1.81 mm | 1.823 mm |
| 444B-10 | 1.82 mm | |

In Table 4.13 below, the results of the tensile testing are shown as average values for each material and corresponding foil sample-location, which is illustrated further in Figure 4.5. The graphs, along with raw data for each tested specimen, can be found in Appendix E.1.

*Table 4.13 Results of average tensile testing values*

| **Specimen label** | **Modulus at E-modulus** | **Tensile stress at Yield (Zero Slope)** | **Tensile strain at Yield (Zero Slope)** |
|---|---|---|---|
| | (MPa) | (MPa) | (%) |
| 111A | 1168,7 | 25,1 | 7,7 |
| 111B | 1170,3 | 25,4 | 8,0 |
| 222B | 1052,3 | 23,7 | 7,7 |
| 333A | 890,3 | 19,6 | 8,7 |
| 333B | 888,3 | 19,9 | 9,2 |
| 444A | 1264,7 | 26,7 | 7,7 |
| 444B | 1233,7 | 26,5 | 7,7 |

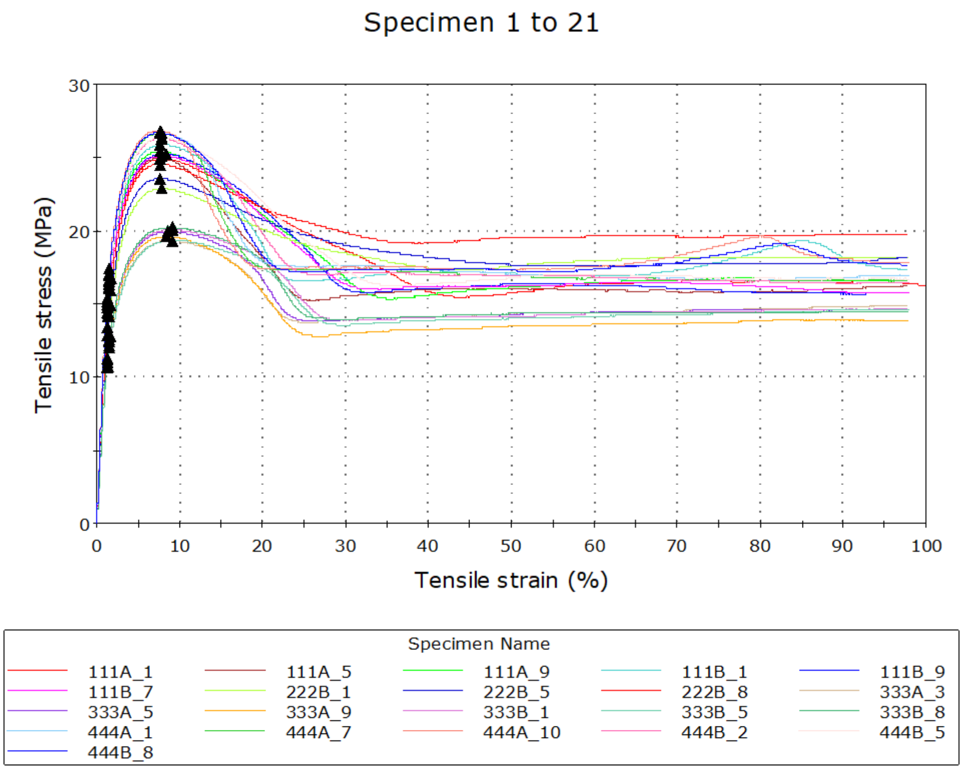


**Figure 4.5 Stress/strain curves for conducted material testing**

Referring to Figure 4.5 above, the laboratory assistant noted that the specimens stretched beyond the equipment's measuring range when testing the first specimen, 111A_1. This resulted in inaccurate presented data for 'Tensile stress and strain at Break', along with 'Tensile stress and strain at Maximum Load', as seen in Appendix E.2. Consequently, the following terminations were recorded as "Fracture", when in reality the specimens did not break. Apart from specimen 111A_1, all 'Tensile stress/Strain at Break'-values were stopped equally, at 97.85% strain, and were recorded at the end of the measurement.

The 'Modulus at E-modulus' defines the stiffness of the material, which is determined by the ratio between tensile stress and tensile strain (Bruder 2015, 60). As seen in Table 4.13 and Appendix E.3, the presented values present Young's modulus at E which was calculated in accordance with the standard ISO 527-1:2023(E). The slope of the stress/strain curve was within the strain interval between 1=0.05, and 2=0.25. This is reflected in the first point from the left in Figure 4.5. The second point from left measures Tensile stress-, and strain at Yield noted in Table 4.13 above.

To clarify using Figure 4.6 below, point C is comparable to the second points from left in Figure 4.5. Point D is not within range. The corresponding values for and to calculate Modulus at E, along with the Modulus value at the peak of the curve (second point in Figure 4.5) are listed in Appendix E.3.

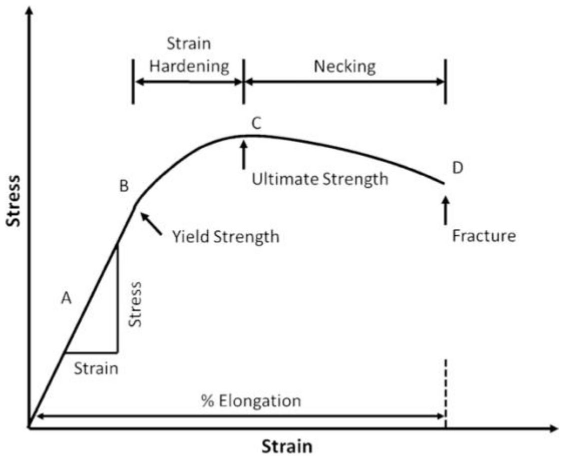


**Figure 4.6 A referential stress/strain curve for a tensile test**

### 4.3.4 **Differential Scanning Calorimetry**

As stated in the interview with Anders Sjögren, the DSC test can show differences in the level of crystallinity of the materials, to investigate possible contamination in the materials. According to A. Singh and M. Kumar Singh (2021), the glass transition temperature ($T_g$) is called the "melting of amorphous material" and second-order transition. Glass transition is an endothermic transition, see Figure 4.7. Moreover, crystallization is the close arrangement of molecular chains in a systematic manner in a long-chain polymeric material. As shown in Figure 4.8, it is an exothermic phenomenon. As can be seen in Figure 4.9, the melting of materials is an endothermic thermal transition or phenomenon in which the molecular chains become free to move at any place in the defined space. Generally, melting takes place at a temperature range. (A. Singh and M. Kumar Singh 2021, 212-213) DSC can be used for studying oxidative degradation of e.g., PE composites, and the crystallization temperature ($T_c$) and melting temperature ($T_m$) can be seen in the resulting DSC curve (Khanam, P.N. and AlMaadeed, M.A.A., 2015).

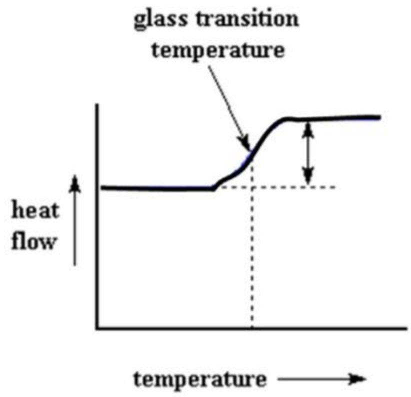


**Figure 4.7 Illustration of $T_g$ (A. Singh and M. Kumar Singh 2021, 213)**

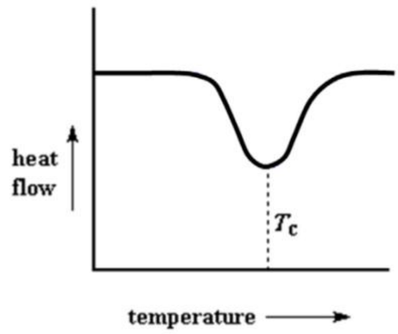


**Figure 4.8 Crystallization (A. Singh and M. Kumar Singh 2021, 213)**

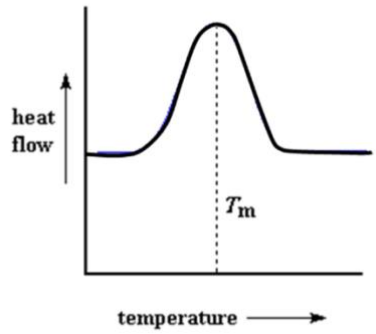


**Figure 4.9 Melting (A. Singh and M. Kumar Singh 2021, 213)**

The result of the DSC test can be found below in Figure 4.10. Graphs showing individual material results can be seen in Appendix E.4. A summary of the melting and crystallization temperatures can be found in Table 4.14 below.

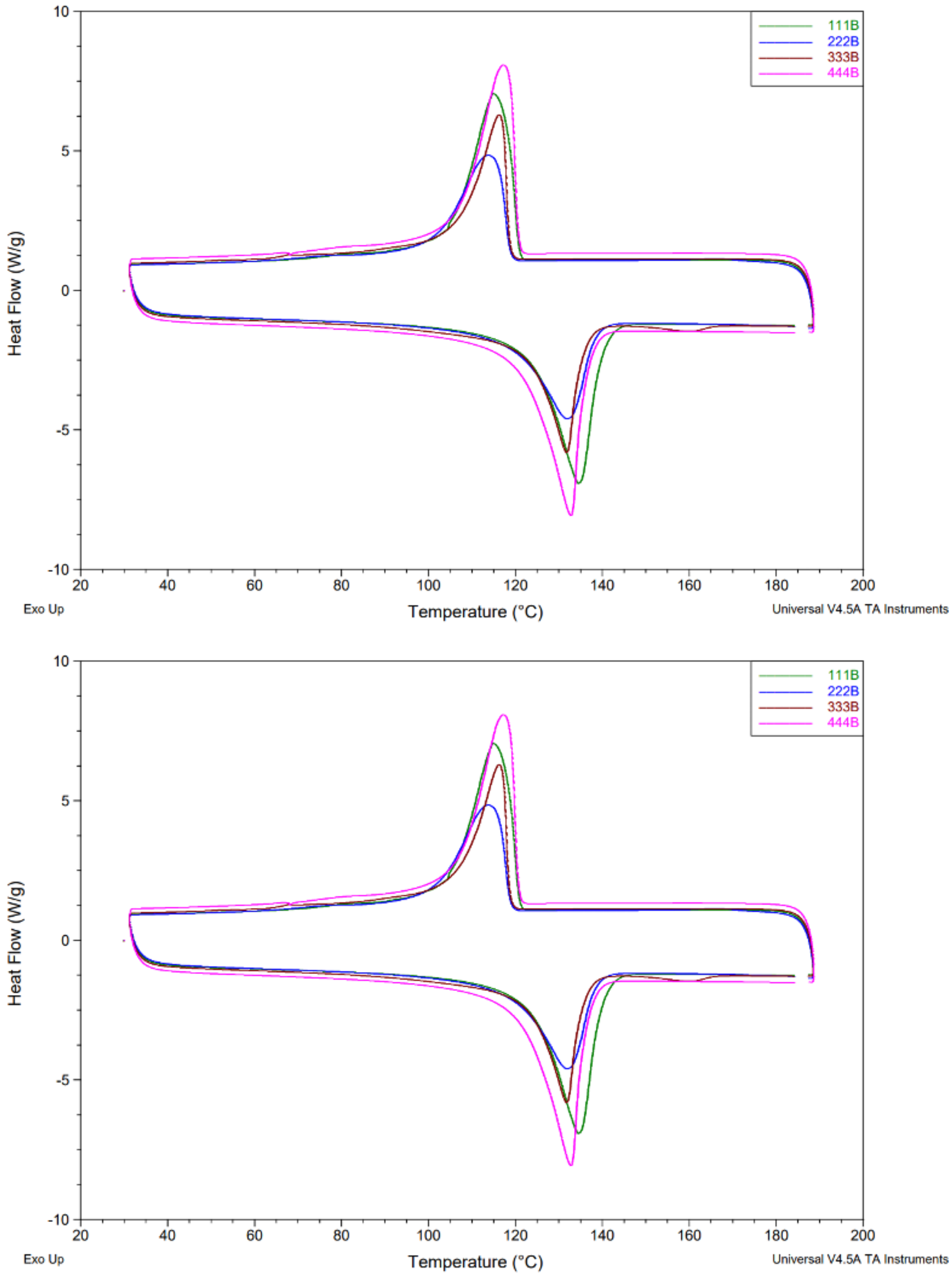


**Figure 4.10 DSC curves of the measured specimens (bottom curve indicating heating, top curve indicating cooling)**

*Table 4.14 Summary of heating and cooling peaks in the graphs in Figure 4.10*

| Material - HDPE | Crystallization temperature, $T_c$ [°C] | Melting temperature, $T_m$ [°C] |
|---|---|---|
| 111B - virgin | 114.82 °C | 134.56 °C |
| 222B - European recycled | 113.75 °C | 131.90 °C |
| 333B - Asian recycled | 116.22 °C | 131.71 °C |
| 444B – North American recycled | 117.18 °C | 132.70 °C |

### 4.3.5 Thermoforming Test

The thermoforming procedure was performed on the rolls, except the North American roll, due to size issues. The North American roll did not fit in the thermoforming machine and could therefore not be tested, because of communication issues between the industrial parties involved.

The first roll to be thermoformed by the machine operator, was the recycled European material, which is the material regularly used at the European producing facility for the production of Product Y. Therefore, the machine operator could perform a thermoforming procedure with a satisfying result, and no issues for the material. Some alterations of machine settings, such as temperature, had to be done by the operator to achieve a flawless result. The outcome of the thermoforming procedure was matte, black finished products with no visible flaws or deviations, once the machine operator had found the suitable machine settings.

After this, the European virgin HDPE was to be thermoformed. This material turned out to not be able to be processed with the same machine settings as the previous material. It showed to soften much quicker than the recycled material, indicating that the material has a lower glass transition temperature, $T_g$. Since HDPE is a semi-crystalline polymer, a lower $T_g$ indicates less crystallinity, since it is the amorphous part of the structure going through the glass transition, as mentioned in Section 3.2: Polymers. This is not a surprising result, since the degree of crystallinity increases when the polymer chains are getting shorter. Recycled material has been through more stages of heating, and is, therefore, more degraded, thus having an increased degree of crystallinity. The machine operator had to alter the forming temperature and speed multiple times, but due to time limitations, the material was not able to thermoform with a satisfactory result before the next material had to be tested. The finished products were matte and black but with many flaws, and no scrap cut off.

The last material to be tested was the recycled Asian HDPE. This material was put in the thermoforming machine, starting on the same machine settings as the European recycled roll had ended on. This roll performed flawlessly during processing almost immediately, and very few alterations of the machine settings had to be done by the operator. The finished products were shiny and black with no flaws or deviations.

The result can be seen in Figure 4.11 below, where three products are presented for comparison.


**Figure 4.11 Appearance of tested material after thermoforming, illustrating finished products**

Three randomly selected finished products per roll, the Asian and European recycled materials, were measured in product location A, in Figure 1.3: Encrypted drawing of Product Y, for comparison in wall thickness. The results can be seen in Table 4.15-4.16 below. Finished products of the North American material (444) could not be measured since this material was not thermoformed, as well as products of the virgin material (111) due to the scrap not being properly cut off, as seen in Figure 4.11 above. The cutting could not be performed due to the material still being soft coming out of the mold, due to a lower glass transition temperature, thus being overheated during the thermoforming procedure.

***Table 4.15 Wall thickness of European finished products in location A***

| **Recycled - European** | **Product piece 1** | **Product piece 2** | **Product piece 3** |
|---|---|---|---|
| Wall thickness [mm] | 0,8636 | 0,9144 | 0,9144 |
| Wall thickness | 0,8636 | 0,7620 | 0,9144 |
| Wall thickness | 0,8636 | 0,9144 | 0,8636 |
| Wall thickness | 0,9144 | 0,9144 | 0,8636 |

***Table 4.16 Wall thickness of Asian finished products in location A***

| **Recycled – Asian** | **Product piece 1** | **Product piece 2** | **Product piece 3** |
|---|---|---|---|
| Wall thickness [mm] | 0.8129 | 0.8636 | 0.7874 |
| Wall thickness | 0.8382 | 0.7620 | 0.7620 |
| Wall thickness | 0.7874 | 0.9144 | 0.8636 |
| Wall thickness | 0.8128 | 1.0414 | 0.8128 |

# 5 Analysis of Material Testing

*In this section, an analysis will be done on the results from the material testing, with further discussion.*

## 5.1 Analysis of Shore D Hardness Test

The standard value of Shore D-hardness provided by the Company X handbook on HDPE properties, is set to a range between 55-64. All materials tested were within this range, with the recycled Asian HDPE at the lowest average value at 55.78, along with the virgin HDPE showing the highest average value at 58.55. However, there is not a significant difference between the materials, and referring to the interview with Anders Sjögren, it is difficult to draw conclusions on material behavior just by testing the Shore D hardness.

There is a small, observed difference in hardness between the Asian (55.78) and European (57.78) recycled HDPE. This did not seem to have any impact on the performance of the material in the thermoforming machine. These two materials were behaving similarly during thermoforming with the same machine settings, with the same outcome on finished products, except for the surface gloss finish.

## 5.2 Analysis of MFI

The testing of MFI showed some unexpected results. Based on the theory of MFI, linked to the degradation of recycled materials as mentioned in the interview with Anders Sjögren, the European virgin HDPE (111) should have the lowest MFI value, since this material is not degraded at all, thus the 111-material is the reference value in this test. However, the MFI testing showed that the recycled European HDPE (222) has a radically lower MFI value than the other materials. Also, the recycled North American HDPE (444) showed a lower MFI value than the virgin material. Based on these results, both the European and North American recycled material is supposedly less degraded than the virgin HDPE, based on the theory that a higher MFI value indicates more degradation. However, this is not possible since virgin material is not degraded at all.

This indicates that the content of the 222- and 444-materials should be further investigated i.e., the ratio between PCR and PIR, the PCR content, and the source, together with possible additives and fillers in each material. For PCR materials, especially HDPE, there is often contamination of other polymers like LDPE or PP, as mentioned in the interview with Rickard Jansson.

For the TDS provided by the Asian producing site, the MFI value of HDPE is set to ≤ 3, which the 333-material achieves. However, compared to the standard MFI range of 0.2-3.0 g/10min provided by the North American TDS, neither the 222- nor the 444-material is within range.

The 222-material is significantly far from the minimum MFI value for HDPE which raises the suspicion of it being a mix with another material, e.g., a type of LDPE. The MFI range of very-low-density polyethylene (VLDPE) is set between 0.026-0.1 g/10min (Khanam, P.N. and AlMaadeed, M.A.A., 2015). Thus, this MFI range is better matched with the resulting MFI values received for the 222-material.

However, the Shore D testing did not show any significant difference between the 222-material compared to the others. For an LDPE material, the Shore D value should be lower than the other tested HDPE materials, which it is not. The standard Shore D range for LDPE is between 40-50 (SpecialChem SA, 2023).

Since the 444-material does also provide a lower result than the set range, it is likely that there is another polymer or filler mixed in this material. This is not a surprising result, since this material is a mix between PIR and PCR materials, and many times the PCR material is not pure HDPE due to the sorting process, as also mentioned in the interview with Rickard Jansson.

## 5.3 Analysis of Tensile Test

Referring to the results presented in Table 4.13, the specimens made of recycled North American material, from Company X1 in the Americas, showed to be the stiffest and the strongest, whereas the Asian material was the least stiff among all specimens.

In accordance with Company X's Handbook viewed in Table 3.3 in Section 3.2.1.3, the average tensile modulus for HDPE ought to range between 1000-1200 MPa, along with yield stress between 20-25 MPa. As seen in Table 4.13, all specimens are within the defined range for tensile modulus, except for the specimen labeled 333A and 333B from Company X1 in Asia, which present lower values in material stiffness. Additionally, in regard to the defined range for yield stress from the handbook, only the European plastic was within the range, along with the virgin material being slightly above the range.

The results show that the Asian specimens have the lowest values for both tensile stress at yield and modulus at E-modulus, while the North American specimens 444A and 444B present the largest values.

Looking into the Asian specimens on the other performed tests, alignment can be observed in the Shore D hardness results, as the Asian material also shows a lower hardness value. The North American material is however not reflecting a higher Shore D, inhibiting a potential pattern.

Reflecting the MFI results of the European material, with the suspicion of it being another type of material, or a mix with some type of LDPE, the tensile results would reflect the material to be more similar to a HDPE-material, by observing the graphs in Appendix E.1. Further, if the specimen were to be of VLDPE-material, Young's modulus and tensile stress for LDPE would be 90.22 ± 4.25 MPa and 32.07 ± 1,85 MPa respectively, which is significantly lower than the presented results. (Awad, S.A. 2020, 1328)

All specimens stretched beyond the measuring range of the equipment, resulting in no breaking during the tensile testing. Hence, the results from "Tensile strain at Break" and "Tensile strain at Maximum Load" are not representing the real breakpoint of the specimens. The fact that the specimens did not break could be an indication of the material being suitable for its purpose with the Product Y-production. It would however be of interest to obtain data on when these specimens would eventually break with another tensile testing machine.

Investigating further on the results of the North American tensile specimens, it is interesting to compare the provided TDS from Company E1 in the Americas. The 444 samples present a lower tensile stress at yield than in the specification of 27.58 MPa (4000 psi). It is also interesting how this specification is defining a value that is significantly higher than the given range in Company X's handbook for internal use.

## 5.4 Analysis of DSC

The melting temperature for HDPE according to the Company X handbook is set to 150-170°C. The DSC results show a significantly lower melting temperature for all the materials compared to the standard range as seen in Table 4.14, which is something the company should look into.

It is shown that the melting temperatures and the crystallization temperatures of the materials are very close in range. However, the sizes of the peaks are different, as seen in Figure 4.10. The upper peaks show how much the materials have crystallized, where the recycled 444-material shows to have crystallized the most, with 222 crystallizing the least. Although there is not a significant difference, it is hard to determine whether the lower degree of crystallization for the 222-material is due to it possibly being another material than HDPE, or a HDPE mix with some type of LDPE, or other fillers. Especially since the melting temperature does not deviate for the 222-material. This would have to be investigated further with the supplier to get knowledge on what the material actually contains. Especially since the tensile-, and hardness tests do not show a significant difference in results for the 222-material, while the MFI for 222 is distinctively lower than the other materials.

## 5.5 Analysis of Thermoforming Test

The outcome of the thermoforming testing showed good results for the 222- and 333-materials, which could be thermoformed with similar machine settings and had a flawless outcome of finished products. The only difference was the surface finish which was glossier for the 333-material and matte for the 222-material, however, Company C has not set any requirements for this type of aesthetic factor. The glossier surface for the 333-material can possibly be connected to it being a softer material, shown in the Shore D hardness test, making it form easier in the mold resulting in a shinier surface.

The North American material did not fit the thermoforming machine, which was unfortunate since it was the material from the producing line with aesthetic issues on the final products. Due to the time limitations in this project, the roll did not manage to be cut into the correct dimensions in time for the thermoforming testing. However, this material could still be used in the polymer laboratory for property comparison through tensile-, MFI- and DSC testing.

The European virgin HDPE (111) did not perform well in the thermoforming machine and started to sag significantly during heating, which led to it not being able to thermoform properly within the time frame. The sagging could be explained by the semi-crystalline nature of HDPE, where a lower glass transition temperature caused the sagging for this material, since this material is closer to melting. It is difficult to know why this material showed this type of behavior, and the issue would have to be investigated further with the material supplier, together with Company X2 in Europe.

After thermoforming, the wall thickness was measured on three randomly selected samples of the finished products for the 333- and 222-materials. It was measured in product location A, which in the drawing of Product Y is set to be 0.889 mm; +0.508; -0.127 (0.035 inches +0.020; -0.005). All measured wall thicknesses were within the set range, some leaning towards the lower limit, which is generally a good result considering the aim of thermoforming is using as little amount of material as possible, while still fulfilling all necessary criteria for the product. However, since the measuring of the wall thickness was measured by hand with a caliper, it could be a possible source of error.

# 6 Discussion

*In this section, the methodology covering a literature study, interviews, and material testing will be discussed, together with the results and findings.*

The methodology applied for this thesis can be divided into three parts; a literature study to gain necessary background knowledge on the subject, conducted interviews with internal and external industry representatives to gain insights on how the industry works today, and material testing to compare if the results are corresponding to expected results. Overall, the chosen methodology provided a clear and structured approach to working, following a logical order to gradually gain more knowledge on the subject. However, improvements could be made, which will be discussed further in this section.

The testing methodology included Shore D hardness test, measuring of material thickness, tensile test, MFI, DSC, and thermoforming test with a following visual inspection of the finished thermoformed products.

For the MFI and DSC tests, it would be of interest to perform more than one test for each material, to gain broader insights into possible deviations along the roll. For tensile testing it would be of value to utilize a machine with the properties allowing the specimens to break, to acquire a more exact result.

The sample pieces created for the tensile tests with a punching tool showed to be successful. Furthermore, despite the differences in material thickness between standard injection molded tensile specimens (4mm) and the specimens for this project (1.8mm), the specimens are similar enough to be comparable with standard values for virgin HDPE, provided by the Company X Handbook and the technical data sheets.

It would be of interest to investigate even further on PCR materials, to gain a more general understanding of the quality of recycled materials. None of the tested rolls were of pure PCR material, which would be of value for comparison.

Lastly, it would be interesting to conduct a wider variety of tests, considering mechanical, rheological, and thermal properties. For example, the Charpy impact test was previously considered to be of relevance for the project but had to be excluded due to material availability, and the material being too thin to create suitable testing specimens. Hence, potential solutions could be looked into for future studies.

Focusing on thermoforming, the aim was to test materials as close to production reality as possible. In order to facilitate testing, the decision was however to make customized, smaller batches of the rolls for the testing procedure, which was decided by the company representatives involved in the project. For a result closer to reality and to make comparisons between production lines more accurate, rolls used in the normal production of Product Y would be preferable to test, along with the ability to do material testing along the extruded roll.

While being at the testing site receiving the material rolls from each production site, there were two main bottlenecks faced. One being a dimensional issue with the North American roll, the other being a thermoforming issue with the virgin roll.

The dimensional issue was enlightened prior to testing, and possible solutions were looked into beforehand. One discussed option would be sawing the roll to the right dimension, which later was concluded to risk layers melting together, ruining the material structure. The other discussed option would be to send the roll to an external extruder for unrolling of the material, cutting the material into the correct width, to later be re-rolled. Due to longer lead time, this could however not be done within the time frame of this thesis. However, it could be of interest for Company X to proceed with this option for further investigation of the material.

Regarding the thermoforming issue of the virgin roll, the material demonstrated abnormal behavior compared to the recycled materials by sagging, due to the material's lower $T_g$. It was later concluded by Company X2 in Europe to potentially be an extrusion issue, which is currently being monitored.

Based on the thermoforming results during material testing, compared to the other test results in this thesis, it was shown that all the materials were performing rather similarly in each test, with some smaller deviations. Even if the MFI value for the 222 material (recycled European HDPE) was significantly lower than the other materials, the 222 material still performed well in the thermoforming machine with a satisfactory result. The reason for the very low MFI value would have to be investigated further with the material supplier together with Company X2 in Europe but is likely due to an HDPE material mixed with a type of LDPE. Overall, the materials used in this project are performing well, and although there were some unexpected findings, the materials seem to perform according to customer demand.

The interviews conducted for this thesis had a wide range of participants from various fields of interest for this thesis. Since Company X is a company operating globally, the opportunity to interview people, both externally and internally about the issues regarding quality assurance of recycled plastics, provided a comprehensive picture of the global situation. Furthermore, the opportunity to visit plastic processing sites in two different European countries for further insights was a beneficial way of gaining knowledge in the plastic packaging production processes. These visits involved witnessing production processes in person, along with interviewing involved people on site. Reviewing the project on a general level, these visits have become a main pillar for the pursuit of answering this thesis' research questions. The conversations with employees at the three producing sites generally all revealed the difficulty of balancing costs, quality, and sustainability when producing plastic packaging of recycled material. Moreover, the visits provided insights into how the global differences related to legislation provide different baselines for the producing sites to work from.

Due to the global production of Product Y, differences between both producing sites and vendors have continuously been observed throughout the project. Studying the differences in vendor relationships, along with working routines, differences can be targeted between the producing sites. Some producing sites can access more details about the material content than others. While the pellet suppliers for Company X1 in Asia are working under business secrets, the suppliers for the North American production provide disclaiming letters, along with material specifications and certifications that occasionally are experienced to be inaccurate. Considering this viewpoint, one could argue that there perhaps are more similarities in vendor relationships between sites, but that the similarities are established in a different way.

Referring to the interview with Company T1, part of the North American production, it was highlighted how the differences in working methods at extruding companies affect thermoformers in quality assurance. Additionally, Company T2 in Europe claims that it is hard to assure quality when the material content differs the way it currently does when working with recycled materials. Both Company T1 and Company T2 in Europe further claim that thermoformers have to characterize the material content throughout production, to assure the quality of recycled products due to the unpredictability, e.g., shrinkage percentage. This not only exhausts thermoformers' resources but also creates unnecessary scrap which is a claimed main bottleneck in production.

When reviewing the interviews with the extrusion company, Company E1, the main challenge was with the recycler's efficiency, and how dependent extruders generally are on the outcome of mechanical recycling. Perhaps this could be the reason behind Company E1's 'Recycled Products Letter', disclaiming the difficulty of specifying material content to clients.

Looking at how impactful the utilized certifications and ISO standards are in the production of Product Y, in bridging the observed differences between sites, some of the producing sites have claimed to use ISO standards mainly as a utility when sourcing for new collaborators. All producing sites have stated to utilize specifications, some as acting certifications valid between 3-5 years *"if nothing changes"*. A raised question is whether these administrational initiatives are currently achieving the task on a global level for the production of Product Y.

Furthermore, Company T2 in Europe described that some of the observed changes in the material content were not specified in a specification or certification from extruding companies, raising the discussion about what the definition of *"if nothing changes"* is in regard to material content. The employee at Company T1 also mentioned that it would go under the radar if a specification is not heavily demanded.

Despite how the arguments go with observed differences between sites, there are counterarguments claiming that processes for recycled materials can be similar globally and that it is not necessarily that hard. Referring to the interview with Anette Munch Elmér at Polykemi, it is explained that maintaining a uniform quality level between global production lines is possible to achieve and that potential differences would not necessarily make it harder to achieve a uniform quality level. Instead, much of the responsibility lies on the companies to make sure that a uniform quality level is maintained globally. On the other hand, Company T2 in Europe argues that since every country has its own challenges and prerequisites based on different business cultures, national-, and corporate prerequisites, and further safety precautions, it is hard to assure a uniform quality standard globally. It was further argued that global collaborations are complex and could therefore adventure quality assurance when working globally. Perhaps the production lines for Polykemi and Product Y are not comparable, but it evokes the question of what the norm is.

Commencing with reviewing the results from the question bank, it illustrates how details like the machines with corresponding settings, vendor routines, and further relationships are different between sites. E.g., while Company X1 in Asia cannot see the forming-, and molding tool temperature, due to using a machine with no probe. Moreover, neither Company X1 in the Americas nor Company X2 in Europe can see the cooling temperatures. Additionally, both Company X1 in Asia and Company X2 in Europe are thermoforming Product Y in-house, while Company X1 in the Americas outsources the production completely. Lastly, Company X2 in Europe is the only producing site working with 100% PIR material, while both Company X1 in Asia and in the Americas are working with a mix of PIR and PCR materials. Company X1 in Asia is unable to trace the ratio, while the North American production has a set ratio.

Narrating the discussion to the traceability at the producing sites, it was shown to differ. Referring to the two Asian trading companies with claimed business secrets, supplying pellets to Company X1 in Asia, it is currently inhibiting Company X1 to trace the material history and establishing what material is being delivered. This puts Company X1 in Asia in a complex position, where much of the quality assurance is based on trust in the traders to deliver what is asked for. Moreover, the company will not know if the material is actually PCR, PIR, or virgin. Even less knowing the ratio if it is a mix between the three.

Furthermore, a similar situation is experienced in the production line for Company X1 in the Americas. As previously mentioned, the employee at Company T1 explains how adding virgin material to the material mix can easily go under the radar. As long as the material runs well in the extrusion- and thermoforming machines, the quality will most likely not be questioned nor tested, which makes it easy for the granulators to upcycle the recycled materials in a way that would benefit the granulating company but adventures the material traceability. Another aspect that can be taken into consideration is the routines around the technical data sheets for each material. Referring to Company E1's 'Recycled Products Letter', it could somewhat illustrate the unpredictability in assuring material properties of recycled material.

It has been noticed during the project that it is difficult for all involved parties, in the plastic packaging supply chain, to take concrete actions for quality assurance. Using recycled plastics for the production of new products is such a complex field and there are no global standards to follow on how to act and accountability in each part of the process; from raw materials to finished products. Therefore, it is easy for the plastic processors to blame possible issues on the other involved parties in the supply chain. The thermoformer will blame the extruding company, who will blame the raw material supplier, and so on. However, it has been evident that the causes of issues can be prevented early on in the process. Referring to the interview with Company T1, the employee stated that a maintained dialogue between industrial parties is crucial for preventative purposes. Additionally, Anette Munch Elmér states in the interview that it is of high importance for the plastic processing company to choose suppliers carefully and maintain a good relationship and dialogue with chosen suppliers, to contribute to quality assurance. This is also supported by the interview with Company E1 in the USA which is careful when choosing suppliers for the PCR material, focusing on the larger suppliers. By taking these actions it will be easier to assure quality since the larger suppliers hold new, more advanced sorting and cleaning technology.

When it comes to appropriate testing methods for quality assurance of recycled plastics throughout the supply chain, including raw material, semi-finished products as well as finished products, it has been found out during the project that this is largely dependent on customer demands and needs. As Anette Munch Elmér explains in the interview, multiple tests can be executed in order to assure quality, but it is up to the customer to set requirements on what the critical factors are on the specific product.

During the start of this thesis, Product Y had some aesthetic issues occurring as small holes and wrinkles in the corners of the finished thermoformed product, at both producing sites in the Americas. When interviewing Company X1 in the Americas about the issue it was discovered that the aesthetics of the finished product had not been set as a critical factor by the customer, Company C. Since the products, according to the employee at Company X1 in the Americas, were functioning well, and *"even better than prototypes"*, the aesthetic issues had not been taken into consideration when delivering the finished products to Company C, therefore the product-return from the customer being a surprise. This illustrates the importance of clear communication and setting mutual criteria from the beginning between parties.

Referring to the interview with Company T1, the aesthetic issue is currently assumed to be resolved. It was resolved by a change of mold design inspired by the used design at the European Company X2 in Europe.

Throughout the interviewing process, it has been evident that one of the main issues with recycled materials is the degradation of materials, affecting its properties, after repeated heating through the recycling- and forming processes. As Henrik Eriksson mentioned in the interview, recyclers want to maximize profits by using higher process temperatures leading to a negative impact on the outcoming material quality. It was further discussed in the interviews with Anette Munch Elmér and Lars Josefsson how the heating of material will cause the polymer chains to break, leading to difficulty in further material processing and worse mechanical properties for each heating cycle.

Due to the unpredictability of properties and behavior of recycled materials, the importance of having a skilled machine operator throughout the processes is of high importance. This was evident during the thermoforming testing procedure of this project. The ability to adjust the settings throughout the forming process, in case of differing or unexpected material behavior, is crucial and will require experience and knowledge.

As previously mentioned, the extrusion process will affect the thermoforming procedure negatively if it is not executed properly, inhibiting thermoforming machine operators from predicting how the extruded material will behave when being formed. Moreover, as mentioned by Company T2 in Europe, is it important that the size of the regrinded flakes is kept at as homogeneous size as possible when extruding. Thus, enhancing the material flow into the extrusion screw, and possibly achieving a higher-quality extruded material. Different size flakes can cause a non-homogeneous polymer to melt due to an irregular flow of flakes being added into the machine, since plastics are insulating materials, and do not transfer heat very well.

One solution mentioned by Company T2 in Europe regarding different-sized flakes is to re-melt the material and shape it into new granules, and Company T2 in Europe states that this is something thermoformers would encourage extruders to do, despite it being a matter of cost. However, based on what is said by i.e., Lars Josefsson and Anette Munch Elmér, every time a polymer is heated the molecular chains will break, leading to a degraded material with poorer material properties. With this knowledge in mind, the recommendation on re-melting the flakes and making new granules is not a preferred solution, since this will add another heating step to the polymer life cycle, degrading the material further.

Due to repeated heating creating a lacking performance in material properties, Henrik Eriksson at Baerlocher stated in the interview that additives can be a solution for this issue. Additives like hindered phenols and phosphites, in combination with acid scavengers, can be applicable to a material like HDPE to inhibit the degradation of mechanical properties. The need for additives in recycled material was also supported by Anette Munch Elmér, stating that adding antioxidants for each cycle is preferable in order to protect the plastic, illustrating it as ‘acting vitamins’. By doing this, the plastic will then be more durable and last for a longer period of time.

However, not all additives or fillers should be added to the material mix from a recycling point of view. Talc is an example of an undesirable filler as it is viewed as contamination. This is also mentioned in the interview with Company E1, which states to test incoming material through burning samples in order to look for talc particularly. This is also something Henrik Eriksson mentioned in the interview, recommending doing a measurement of ash content to check for excessive mineral filler. However, one surprising outcome of the interview with Company T2 in Europe was that adding talc is one of Company T2 in Europe’s applied solutions for making the material heavier. This finding shows the importance of all involved parties having the necessary knowledge regarding what should and should not be added to a material mix and avoiding working in different directions.

Recurring through all the conducted interviews was the importance of sorting and washing related to PCR materials. To make improvements, more investment needs to be put into building the necessary infrastructure and facilities with advanced sorting and washing technology. This is a matter of cost but is a crucial step to achieve clean material streams and thus high-quality recycled plastics. As both Rickard Jansson and Lars Josefsson state, for sorting- and washing facilities to be able to provide the advanced technology needed to make sorting more precise, investment needs to be increased in this field. Rickard explained how an increased number of NIR scanners in the new sorting facility in Motala will make the number of sorted plastic fractions go from 5 to 12, i.e., more than double.

This can be related to what was said by Henrik Eriksson, regarding the specifications of recycled polymer materials related to cost. Eriksson states that the cost of the polymer will increase with the number of set specifications and requirements, which can possibly be explained by the increased cost of the sorting technology needed to deliver a high-quality recycled PCR material. Furthermore, according to Henrik Eriksson and Rickard Jansson, sorting and washing technology might be the most important step in the quality assurance of PCR material since it will determine the purity of the recycled materials. What is shown through all the interviews is the fact that mixing of materials, as a result of a less precise sorting process, will provide an outcome of a lower quality recycled plastic material.

An important part of the plastic packaging industry, mentioned both by Lars Josefsson and Rickard Jansson, is the approach of *Design for recycling*. For the recycling process, especially the sorting step, to be as efficient and precise as possible, it is crucial that the packaging companies are making the plastic products able to be recycled. The manual with guidelines, created by Svensk Plaståtervinning, on how to design for recycling is as of now not mandatory for plastic packaging companies to follow.

Since mechanical recycling is the primary recycling method applied in the industry today, it has been the main focus of this thesis. However, the interview with Lars Josefsson showed an interesting point of view on chemical recycling. According to Josefsson, the only way to get virgin polymers with virgin properties out of recycled materials is through chemical recycling. Hence, chemical recycling will provide virgin polymers but is not a feasible option today. It is a matter of cost for the plastic packaging companies and also getting acceptance from society on this being an official recycling method. Moreover, the infrastructure would need to be developed further.

It has been shown during the project that the cost- and quality trade-off, when handling recycled material, is a recurring issue. At the moment, mechanical recycling is the only feasible option for the plastic industry, hence the reason for using mostly PIR materials rather than PCR. The PIR materials are not contaminated like PCR materials, and many times only processed once before, i.e., the quality is almost as high as for a virgin material, which explains why many of the producing sites in this project are prioritizing PIR materials in the production.

# 7 Conclusions

*In this section, the conclusions of the project will be presented.*

The aim of this project was to, together with Company X, research how to quality assure Product Y, made of recycled HDPE material, due to occurring aesthetic issues with the finished product at the producing lines in the Americas.

This was done by initially interviewing the three involved producing sites for Product Y, to gain insights on the differences and similarities in the way of working at each site, facilitating comparison. It soon became clear that there are many differences, both regarding the choice of material supply, as well as the production process, connected to having completely different baselines. Variations in machine settings, vendor routines, and relationships between the producing sites and vendors, are resulting in different prerequisites in the production of Product Y. Additionally, the differences in material content and specifications create a challenge to assure quality and maintain a uniform standard globally. This is mainly because of geographical reasons, with societies handling recycled materials differently, along with a lack of legislation or global standards. Furthermore, the challenges faced by extruders and recyclers in specifying material content to the customers have been discussed, which raises questions about the most suitable way of working when production is not centralized and how to approach global differences in quality standards.

There are a wide variety of tests that can be done to investigate the properties of recycled plastic, depending on the purpose. In this project the selection of tests was chosen based on time restrictions and material availability while looking at different types of properties; rheological, mechanical, and thermal. The material test resulting in the most unexpected and interesting outcome for this project was the MFI, melt flow index, which indicates that this test could be of interest for Company X to perform throughout the supply chain for verification of material content.

Based on the material testing result performing MFI together with DSC and tensile testing, a conclusion can be drawn that a combination of tests, for different types of material properties, is to be recommended for verification of what type of content the material consists of. Only performing one test, e.g., only MFI, is not preferable since comparison with the other test results is necessary to provide a broader insight in the material properties. The results should thereafter be compared with provided

TDS for material for verification. If the test results do not coincide with the material’s TDS, dialogue with the supplier should be carried out for clarification.

Testing procedures for quality assurance have shown to be highly individualized, depending on the customer and what criteria have been determined for the specific product. An appropriate testing procedure should be conceived by the customer, in agreement with the plastic processing company, to fulfill the customer's demands for the product.

Moreover, the choice of suppliers is of high importance when assuring quality of recycled plastics, along with maintaining a transparent relationship and communication. If there are uncertainties regarding suppliers' way of working when producing the material, it should be investigated further to improve quality control.

When working with recycled plastics, insight into the traceability of the material history is of high importance. Without knowing what type of content is added to the material mix, or how it has been handled previously, it is hard to predict the material performance when forming the finished products. For PCR materials, the sorting- and washing process will highly determine the quality of the outcoming recycled material. For PIR materials, the handling of the material in the previous processing step is what will influence the material performance after being recycled. High processing temperatures will cause degradation of the material for each cycle, and for PIR materials, such as scrap, it is hard to trace how many recycling cycles the material has been through.

Through a comprehensive analysis of the plastic industry and the societal and global differences that influence recycled material practices, it has been found that there are several challenges that hinder plastic recycling processes. These challenges include different technological limitations, lack of infrastructure, and lack of consistent regulations and policies. Furthermore, societal and global differences, such as varying levels of material awareness, also contribute to the difficulty in achieving effective plastic recycling practices.

Additionally, this analysis has revealed that the relationship between industrial parties also affects recycling processes. These relationships include those between producers, customers, policymakers, and waste management companies. It was found that proper communication and collaboration between these parties are essential to address the challenges and issues facing plastic recycling processes. Without all parties taking equal responsibility for the quality assurance of recycled plastics it will be hard to achieve uniformity globally.

Overall, these findings suggest the need for a more integrated and coordinated approach to plastic recycling and quality assurance, involving all stakeholders in the industry throughout the supply chain. This could include increased investment in infrastructure and technology, such as chemical recycling, implementation of consistent regulations and policies including follow-ups, and lastly greater education and awareness industrially and publicly. Only through such a collaborative effort can an efficient and sustainable plastic recycling process on a global level be achieved.

Based on the findings of this study, several areas raising further research in the field of plastic recycling are highlighted. Firstly, further research and initiatives are needed to establish global standards and legislations on a political level, to address the issues related to production of plastic waste and recycling. Such research could help explore the development of policies and regulations that promote the circular economy and incentivize the implementation of sustainable and efficient recycling practices.

Secondly, there is a need for improvements in the characterization of recycled plastic materials, mainly through testing. This could involve the development of new and more accurate methods for assessing the properties of recycled materials including their mechanical, thermal, and rheological properties. Such research could also explore the use of advanced analytical techniques to gain a deeper understanding of the composition and structure of recycled materials.

Thirdly, there is a need for more research on chemical recycling, which has the potential to overcome many of the current limitations of mechanical recycling.

Finally, research is needed to improve the material sorting process through the technical aspect of mechanical recycling. This could include investigations into the use of new and innovative sorting technologies to improve the accuracy and efficiency of sorting processes. Additionally, research could explore the possibilities of working more with PCR materials and identify ways to implement the use of PCR materials in the production of new plastic packaging products.

In summary, future research should be focused on the areas of global standards and legislations, sorting technologies together with material testing, and chemical recycling. Together this will lead to improved recycling processes globally that can help to overcome the challenges regarding quality assurance of recycled plastics today.

Based on the delivered conclusions, the following topics could be general guidelines applicable for Company X, and the plastic industry, to take into consideration for further work regarding assuring quality of recycled plastics:

1. Understanding the differences and similarities in the way of working at each producing site for Product Y, to facilitate comparison.
2. Performing a combination of material tests, to test different types of material properties, in order to verify material content and material composition. Moreover, comparing the results with the provided TDS of the material to clarify any inconsistencies with suppliers.

3. Implementing an appropriate testing procedure, by the customer in agreement with the plastic processing company with involved industrial parties, to fulfill customer demands on the product.
4. Carefully choosing suppliers and maintaining transparent relationships with clear communication.
5. Gaining insights into the traceability of the material history for recycled plastics in order to predict material performance when thermoforming the finished products.
6. Establishing consistent policies and regulations on a political level in order to promote a circular economy, encouraging implementations of sustainable and efficient recycling practices.
7. Improving material sorting and cleaning processes through the technical aspect of mechanical recycling
8. Exploring the potential of chemical recycling, to overcome current limitations of mechanical recycling

Generally, there is a need for a more coordinated and integrated approach to plastic recycling and quality assurance, involving all stakeholders within the industry, throughout the supply chain. This can include implementation of consistent regulations and policies including follow-ups, increased investments in infrastructure and technology, i.a., chemical recycling, and greater awareness and education both publicly and industrially.

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# Appendix A Work Distribution and Time Plan

## A.1 Work Distribution

The two authors of this master thesis have, throughout the entire project, been collaborating and equally contributed to the work. Some tasks have been divided between the authors, but always discussed beforehand and reviewed afterwards. All decisions have been made together as a team. Both the authors have participated in the interviewing, the material testing and in the writing of the report.

## A.2 Project Plan and Outcome

In the beginning of this project an indicative timeline was made, which can be seen in Figure A.1. This was made in order to facilitate the planning of the project together with the collaborating company, since the visits and the material testing abroad had to be booked in advance. The actual timeline can be found in Figure A.1, and corresponds relatively well to the initial time plan. It can be seen that the material testing was done in the last week of this planned segment, which made the analysis of the results move forward almost three weeks. This was due to the fact that a part of the material testing was done at an external lab, by a laboratory assistant, and that the Easter weekend occurred at this time, prolonging the waiting time for receiving the results.

Initial project timeline

| Month | December | January | | | | February | | | | March | | | | April | | | | May | | | | June |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Week | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| Tasks | Internal Master thesis application | Exams/work | Exams/work | Project start | Project plan | Project plan | Execution phase, start prepping for practical work | Execution phase | Execution phase | Do practical work and testing | Do practical work and testing | Do practical work and testing | Do practical work and testing | Analyzing results | Report | Report | Report | Finish up report | Finish up report | Concluding phase + presentation | Concluding phase + presentation | Presentation 1st or 2nd of June |

Actual project timeline

| Month | December | January | | | | February | | | | March | | | | April | | | | May | | | | June |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Week | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| Tasks | Internal Master thesis application | Exams/work | Exams/work | Project start | Project plan | Project plan | Execution phase, start prepping for practical work | Execution phase | Execution phase | Do practical work | Do practical work | Do practical work | Do material testing | Do material testing | Report | Report | Analyzing results | Finish up report | Finish up report | Concluding phase + presentation | Concluding phase + presentation | Presentation June 2nd |

**Figure A.1 Initial and actual project timeline**

# Appendix B Specification Checklist

***Table B Example of sheet purchasing specification checklist (T = thermoformer, X = extruder, T/X=both) (Throne 2008, 214)***

| **Specifications** | **Certifier/tester** | **Comments** |
|---|---|---|
| Degree of orientation allowed | T | |
| Sheet sag characteristics | T | Material consideration but extrusion characteristics considered as well |
| Use of regrind, trim, selvedge | T | |
| Gauge tolerance | T | Sheet-to-sheet accuracy may require extruder input as well |
| Width, length, flatness tolerance | T | Extruder input useful |
| Impact strength, drop ball, dart, Izod, Charpy | T | a priori decision on who runs test |
| Moisture level | T/X | Specific drying level required for moisture-sensitive materials |
| Foreign matter, agglomerations, type, frequency | T/X | Important for polymers that burn, discolor, processing aids, fillers, fire retardants, cross linking |
| Gel count | T/X | See comments above |
| Finish surface required,<br>Texture<br>Smoothness<br>Gloss<br>Pits, dimples, waves, air entrapment, bumps | T/X<br>T/X<br>T/X<br>T | Good products made from quality sheet |
| Optics | T | |
| Mechanical properties | T | Translation of polymer properties into sheet is thermoformer responsibility |
| Pigment distribution | T/X | Type of test must be made a priori |
| Filler condition | T/X | Particle size, drying conditions |
| Fire retardant condition | T/X | Method of addition, determination of loss of effectiveness |
| Odor | T/X | |

| | | |
|---|---|---|
| Laminate properties<br>Moisture transmission<br>Oxygen permeability | T/X<br>T/X | Type of test must be made a priority<br>Type of test must be made a priority |
| Packaging, shipping | T/X | Roll diameter, core size, method of palletizing, protective wrap, moisture protection |

# Appendix C External Interviews

## C.1 Rickard Jansson – Svensk Plaståtervinning

### C.1.1 Interview Questions

- Can you tell us a bit about yourself and about Svensk Plaståtervinning i Motala?
- Can you tell us about the facility in Motala, the strengths and what is unique about it?
- What does the future look like with SiteZero?
- How do you plan on achieving high quality final products?
- What steps in the recycling process do you think has the largest impact on the final material properties and quality?
- Can you tell us about the plastic recycling processes globally, what is it like outside of Europe?

### C.1.2 Summary

Rickard Jansson is a development engineer and a material expert at Svensk Plaståtervinning in Motala, Sweden. After studying engineering, Rickard Jansson has worked with material technologies and material science during the past 15 years. Previously working within the automotive-, aviation- and military defense industry, Jansson started at Svensk Plaståtervinning three years ago, focusing on environmental- and sustainability issues.

Svensk Plaståtervinning is owned by large parts of the Swedish business community through the Plastbranschens Informationsråd (IKEM and SPIF), the Swedish Association of Consumer Goods Suppliers, the Swedish Trade Federation along with the Swedish Retail Federation. The company offers a national system for circular recycling and collection of plastic packaging for producers and businesses and is now building the world’s largest and most efficient plastic recycling facility, Site Zero. (FTI 2023)

Rickard Jansson explains that the purpose of Svensk Plaståtervinning is to handle all plastic packaging waste from Swedish households, sort it into fractions and send it to their recycling partners for further processing. According to Swedish law, a packaging producer is obliged to provide a collecting-, and recycling system for the packaging material put on the market. This is called extended producer responsibility, Jansson explains, i.e., a type of producer responsibility. Similar laws also exist in other EU countries.

Furthermore, all plastic packaging companies in Sweden need to report to Förpackningsinsamlingen, FTI, on how much packaging material is put into the market. Based on the reported data, a differentiated packaging fee needs to be paid depending on what type of packaging material is used, which will help fund collecting and recycling of the material. The fee will be higher if the material is hard or impossible to recycle, Rickard Jansson says. Moreover, as a consumer in Sweden, one is obliged to recycle at source and ensure that the plastic packaging ends up in the vessel for plastic waste. This can be done at a recycling station or curbside collection.

When the plastic is sorted in Motala it is sent to the recycling partners to go through the recycling process. For HDPE, these are located in Finland, Denmark, Germany, and the Netherlands. The reason why recycling processes are not being executed in Sweden is due to the lack of recycling capacity for this type of plastic waste, according to Rickard Jansson. In Sweden there are no facilities built for handling this type of contaminated plastic waste containing residues of e.g., food or cosmetics, which demands a thorough washing process.

Recycling facilities demand a continuous stream of material to recycle and have therefore been built close to the sorting facilities, Rickard Jansson explains. Up until 2019 when the facility in Motala was built, the Swedish plastic packaging waste was sent to e.g Germany for sorting, where the required facilities are more accessible. Jansson states the current situation is very well functioning with the sorting facility built in Motala. To enable the whole process being done in Sweden, the long-term plan is to further build a recycling facility.

At Svensk Plaståtervinning, the plastic packaging waste is sorted into fractions based on plastic type. At the moment, there are five different types of plastic fractions managed to be sorted out. However, a new facility, Site Zero, has been built and is a part of the development towards a circular recycling process, rather than a linear one. A circular recycling process, according to Rickard Jansson, will enable replacement of virgin plastic, thus producing a recycled material with the same properties and quality as virgin plastics. However, building a fully circular recycling system is not feasible at the moment, explaining that there will always be some fractions with mixed materials.

The purpose of the new Site Zero facility in Motala, Rickard Jansson explains, is to sort as much plastic packaging waste to circular recycling as possible. To achieve this, a technology called near infrared spectroscopy, NIR, is used. This technology is scanning the plastic packaging, which is travelling on a conveyor, with infrared light and makes it possible to detect what type of plastic the packaging is made of. This is possible since infrared light is interacting with the chemical bonds in the different plastics. The plastics will reflect back a light, specific for each material and indicate what material the packaging is made of. Based on this indication, the packaging on the conveyor will be sorted into fractions with the help from compressed air and blown in different directions depending on material type.

According to Jansson, a facility with a higher number of NIR equipment will result in a more precise sorting process, thus a higher number of different material streams. While a standard European sorting facility has around 5-10 NIR units, Site Zero will have 60 NIR equipment. Rickard Jansson further states this to be probably the most crucial part for achieving a high-quality sorting process, thus a circular recycling process. Moreover, it is common for the plastic packaging on the conveyor to be wrapped up in each other and therefore accidentally sorted wrongly by the compressed air. The solution for this is to have a following conveyor leading to another NIR equipment, a so-called NIR cleaner, performing one more sorting procedure of the packaging flow. For this reason, Svensk Plaståtervinning always has at least two steps of sorting procedures in sequence, and the risk of wrapping will therefore decrease, Rickard states. In this way it is possible to sort out impurities and thus achieve a higher sorting quality. Furthermore, by using only one NIR equipment in the sorting line will result in a sorting quality of about 70-80%, but with using a following NIR-cleaner in sequence, the end result will be 95% sorting quality with less mixing of materials.

As previously mentioned, the old facility in Motala can sort five fractions of plastic for recycling, but Site Zero will have the possibility to sort 12 fractions leading to less plastic waste being burned instead of recycled. Rickard Jansson explains that the plastic packaging is sorted based on the main polymer, thus a shampoo bottle made of HDPE with a cap made of PP will end up in the HDPE fraction, contaminating this material stream. To avoid this, Jansson argues that it is important that the following step in the recycling process is designed to remove impurities from the 95% sorted fraction, in addition to the 5% wrongly sorted materials. Of the 95% correctly sorted HDPE, there will be about 5% PP due to bottles with caps or similar. To increase the quality of the HDPE material stream, an additional sorting process can be done on the washed and shredded material. This can be done by using flake sorting equipment, which will sort the flakes into correct fractions by using the same technology as the initial sorting step. However, this enables an even more precise sorting process, thus a purer material stream and higher sorting quality. Rickard Jansson explains that this will require a lot of investment by the recyclers.

Jansson further argues the washing step in the recycling process to be crucial for the resulting quality. Appropriate chemicals should be used to remove grease and other residues for a clean material. Therefore, it is important that the washer knows what type of application the recycled material is going to be used for in the future, together with the source of the sorted material. Based on these two aspects, the washer will know what type of investment is needed to achieve the desired material cleanliness. A lower investment with a simpler washing process and no flake sorting step will result in a less clean and less pure material stream. For making new plastic packaging, and a circular recycling process, Rickard Jansson explains that there needs to be more investment in all the different steps to increase the quality of the recycled material.

Rickard Jansson argues that correct and precise sorting is the key to a high-quality recycled material, and to have many different separation steps. Both before the recycling step and during the recycling processes. In the end this will determine the final quality of the recycled material, together with the design of the plastic packaging.

Design for recycling is a concept regarding in what way the plastic packaging producers are designing their products. According to Jansson, the current market of packaging material contains multiple types of design features, making it difficult to recycle. For a facilitated recycling process, Svensk Plaståtervinning has created a manual with design guidelines for plastic packaging manufacturers, including e.g., avoiding print, glue, and mixing materials which will make it harder to recycle into a high-quality material.

According to Rickard Jansson, the global challenge is to achieve high quality recycled materials. Meaning, creating and implementing well-functioning collecting-, sorting-, and recycling processes. In Sweden there is a well working system for sorting at source, but in for example southeast Asia, there is no existing system for collecting household waste, and it will end up in dumpsites and landfill. Jansson further explains that some people will live at these dumpsites making a living out of collecting and sorting the different materials. This will lead to a well sorted and pure material source since it is done manually and can be very selective. However, this is not a sustainable or healthy way of living for the people doing this every day, Rickard Jansson argues.

In the USA, the existence of recycling infrastructure is yet limited, which has led to exportation of waste to other countries. Before China introduced the waste import ban, a lot of American waste was exported there. Currently, the American waste ends up in e.g., Malaysia instead, according to Rickard Jansson. Further, Jansson explains that there are European waste streams going in the same direction as in the USA. However, Svensk Plaståtervinning keeps all material within the EU.

# C.2 Henrik Eriksson - Baerlocher

### C.2.1 Interview Questions

- Tell us about you and about the company, Baerlocher.
- What are the pros and cons of adding additives to the recyclate?
- Besides up-cycling with additives, what possibilities are there for ensuring quality of the recycled plastic?
- What are the possible issues regarding sorting techniques?
- The sorting and recycling processes are different depending on geographical location globally, can you tell us about this, and possible solutions for traceability?
- What are the main factors affecting the finished product’s quality and properties?

### C.2.2 Summary

Henrik Eriksson is an LTH alumni in the field of chemistry and has later worked at Polykemi in Ystad for about 15 years. At Polykemi Henrik Eriksson worked with recycled plastics, gaining experience on how the plastic recycling industry works and expectations. Now Eriksson works at Baerlocher, as a technical product manager, responsible for the technical aspects in the polymer products. Throughout time, this field has gradually started to involve recycling procedures.

Baerlocher produces so called pastilles, containing stabilizers and additives with 100% active content. This pastille is added as a granule with the grinded polymer flakes before being regranulated into raw material. The pastille-concept simplifies the handling of the additives for the recyclers. The additive formulations are compounded to contribute to reaching best possible properties on the plastic materials.

Discussing additives, Henrik Eriksson expresses how the use of stabilizers can help maintain polymer chains’ chemical structure of recycled HDPE. According to Eriksson, stabilizers are reliable tools for inhibiting degradation of mechanical properties when recycling plastics, e.g., in HDPE by acting to maintain the linear structure of the polymer, as far as possible. This would not only contribute to consistency in practical processing but would also prevent the need for over-dimensioning designs, according to Henrik Eriksson. Moreover, the use of stabilizers could help improve crystallization behavior, as an indirect effect of keeping as much linear structure as possible in the recyclate. This would result in shorter cycle times with more predictable results in the thermoforming process. Even the risk of post-crystallization over time, leading to deformations, can thus be indirectly mitigated through the use of stabilizers. For HDPE, applicable stabilizers include hindered phenols (primary antioxidant) and phosphites (secondary antioxidant), in combination with acid scavengers. Notable however, Henrik Eriksson addresses that an excessive usage of phosphite can result in formation of deposits around nozzles, meaning the added amount ought to be monitored.

Discussing further possibilities for ensuring quality of plastic recycling, Eriksson touches upon several methods. To check processability, Eriksson recommends performing MFI. For an estimation of the amount of e.g., PP content mixed in the plastic Henrik Eriksson suggests conducting a DSC. Further suggestions would be tensile testing and performing a measurement of ash content to check for excessive mineral filler. Eriksson also discusses the possibilities with the use of stabilizers, and how oxygen induction time (OIT) can be measured with DSC to ensure that enough stabilizer has been added. This can be a way of ensuring that the recycler has actually added the requested stabilizer. Henrik Eriksson also emphasizes that the end use of the product determines whether further long-term properties/stabilizations are needed.

Focusing on potential issues in sorting techniques, Henrik Eriksson believes that type of sorting technique determines the quality level of recycled plastics of post-consumer waste. Continuing, a contributing factor could be when in time sorting equipment was purchased. On average, a purchased sorting facility carries a life expectancy between 10-15 years. Since it is a substantial investment to make, investors become tied up to the purchased technique to make profit, inhibiting technique developments to be applied. Further, the efficiency is also connected to when the sorting facility was built. Eriksson states that modern facilities can achieve higher purity than older facilities, and that the cleaner and purer the material is, the better. However, it is also more expensive.

Connecting the matter to HDPE, Henrik Eriksson explains that a consumer of recycled HDPE must qualify different recyclers for its use, which is done by discussing a basic specification with each supplier. Further, it must validate that the recycler meets the set requirements. The HDPE-business is quite tight according to Eriksson and claims that the harder the specification of a polymer, the higher the cost.

*"The harder a polymer is specified, the higher the cost."*

When it comes to HDPE, the market is quite tight, so one must be careful about over-specifying a product. Over-specification can lead to a decreased availability of raw materials and higher costs, which is disadvantageous as the big companies operate production all over the world. E.g., the cleaner it is, the more must be paid for it to be achieved.

Discussing the global differences on sorting-, and recycling processes, Henrik Eriksson agrees to the significant differences to be a fact and emphasizes it to be the perfect example for how important it is to know the material source. There are international players such as Veolia, and PreZero offering global standards for recycling, but it is uncertain whether it is possible to standardize the processes regarding recycled material globally. The source of the recycled material and the sorting technology are the two main factors affecting both quality, and further properties on a finished product. According to Eriksson, sorting technology is perhaps the most important step since it determines how pure the recycled material will be.

After sorting, the regranulation process is crucial and involves melt filtration to remove non-melting impurities along with plastics with different melting temperatures. This process puts a strain on the polymer, causing degradation during this stage of the recycling process. Recyclers also tend to maximize their profits by forcing the melt filter to its maximum capacity, which results in higher process temperatures and pressures causing degradation of the polymer, and therefore adventuring the material quality.

According to Henrik Eriksson, a way to avoid the issue is to add a stabilizer into the mix, claiming that it could play an important role in the melt processing stage. Additionally, the recycler's expertise in choosing appropriate processing settings can also impact material quality.

## C.3 Anette Munch Elmér - Polykemi

### C.3.1 Interview Questions

- Tell us about you and about the company, Polykemi.
- What are the critical factors in the recycling process to be able to deliver a high-quality recycled material?
- How do you ensure that the plastic you buy from suppliers for regranulation is of high quality?
- How do you test the quality of the outcoming product to be delivered to customers?
- Since you are operating in China, do you have any insights on possible differences in recycling processes globally, and how it potentially could affect material quality?

- What can affect final material quality on a continent like e.g., Asia?
- What do you consider to be the main influence on final properties and quality of recycled material?

### C.3.2 Summary

Anette Munch Elmér is an LTH alumni with a Ph.D. in the field of chemistry. At the moment Anette Munch Elmér is the head of development at Polykemi in Ystad, working with frequently developing new materials.

Polykemi is a company with more than 250 employees, making customized thermoplastic raw materials, mainly to be used for interior details within the automotive industry. Besides Sweden, Polykemi has production in China and the USA. Rondo is an affiliate to Polykemi, handling the production of recycled material, which is PIR material only. Rondo mechanically recycles the PIR material and upcycle it to be used again.

Discussing critical factors in enabling high quality recycled material, Anette Munch Elmér commences with the differences noted between PIR and PCR materials. Further Munch Elmér suggests that while PCR plastic material currently falls short of quality standards compared to primary material, this will improve as better sorting technology for PCR material is developed. Regarding the critical steps in the recycling process, the plastic waste is roughly sorted into fractions based on polymer type using NIR technology. Additionally, heating of plastic material causes polymer chains to degrade, leading to difficulty in further material processing and worsened mechanical properties. However, cleaning and sorting are critical stages in the recycling process, and while Germany is performing this well, Sweden lacks the capacity to clean the amount of plastic waste produced.

Based on Polykemi's way of working, the company is managing PIR materials and no PCR. Anette Munch Elmér primarily highlights the importance of maintaining a good relationship with the suppliers. It is all about the exchange between the parties, and maintaining a proper dialogue contributes to the quality assurance. When receiving purchased material, it needs to be tested for unwanted chemicals, e.g., pigment containing heavy metals and so on. Munch Elmér further refers to legal requirements covering the matter that easily can be monitored. Furthermore, the mechanical and rheological properties of the plastics ought to be tested. MFI is mostly used to test the behavior of the plastic melt and will indicate how easy to process the material is. For mechanical properties standardized testing methods using injection molded specimens are recommended to observe the behavior of the polymer, if requested by the customer.

The previously mentioned tests done on the incoming material can also be done on the finished products, which is something Anette Munch Elmér highly recommends.

However, here is no standard procedure for testing finished products today. There are multiple tests that can be conducted to assess various polymeric properties. Munch Elmér concludes further that the choice of polymer tests mainly depends on the customer's stated need and requirements. E.g., if a customer wants high impact strength, the material should be tested for this property.

Discussing how material quality assurance can differ globally, Anette Munch Elmér explains that it mainly depends on the type of plastic being used. For Polykemi and Rondo's case, it is more based on the organization, than the region. Anette Munch Elmér further explains that when Polykemi and Rondo buy PIR material, the organization takes responsibility for finding the sources, processing, conducting quality control and appropriate use. This process is the same regardless of whether the company is working in Asia or elsewhere. Therefore, Anette Munch Elmér assumes that there would be no difference for an individual operator when purchasing PIR material.

Regarding PCR materials, the quality depends on how well the plastics can be sorted in the region where the company is operating. In this field, Europe is ahead of Asia and USA, but there is still no proper coordination on the issue within Europe. Hence, obtaining good PCR material in Asia depends on finding the right partner. One might have access to great material in Asia, but the partners may not be making sufficient efforts in sorting the materials, Anette Munch Elmér states.

Envisioning the future, Munch Elmér can see more washing facilities along with better sorting facilities being introduced to the industry. Furthermore, the current difficulty of recyclability of black plastic, anticipating it to be more feasible in the future, with the use of better sensors than the ones being used today. Additionally, Anette Munch Elmér predicts that future policy incentives will optimize sorting throughout the entire chain, although specific incentives are hard to estimate. A suggestion would be to focus on the consumer's waste behavior by introducing higher costs for consumers to throw plastic away at dumpsites, to encourage better waste disposal practices.

Munch Elmér explains that recycled plastic is increasing in demand, hence expecting it to be more expensive than virgin plastic, since this would require high costs of establishing necessary recycling streams and washing facilities. In fact, recycled plastic is already being sold at a premium cost in some cases, possibly due to the growing demand for environmentally friendly products – "the pulse of the green heart." As an example, Anette Munch Elmér refers to furniture companies facing a challenge in sourcing enough high-quality PCR materials for their products due to the increased demand of PCR materials for their products.

Anette Munch Elmér emphasizes that the final properties and quality of recycled material is primarily determined by three factors: the production process, the shape of the desired part, and the material used. Thus, setting requirements for a desired product demands setting requirements for all three factors, which are interrelated. For example, setting material requirements alone is insufficient, as having no knowledge of the process or final product shape would result in an incomplete overview of the overall quality. This is critical since delivering the same material to different processors could allow entirely different properties. Making a comprehensive quality overview is necessary to ensure consistency and meet desired product specifications. In regard to the material, one wants to look at how it is constructed, especially if it contains dirt or impurities from previous cycles. Furthermore, the content of minerals or other organic matter that has not been washed off properly should be investigated. This can be measured relatively easily by checking the density of the material, but also by burning the material to see how much non-organic material it contains. At a material processing facility, these tests should be relatively easy to perform, Anette Munch Elmér states.

In regard to testing, executing the simple form of rheological investigation, like MFI, is beneficial for quality assurance. Extrusion is a relatively unique process as it stresses the material significantly, Munch Elmér states. Depending on the molecular weight of the polymer chains, the material can behave differently. In this way, it is useful to set a specification on what MFI the material should be within. For example, for the problem of voids in product-corners, it mainly indicates that it is a material with low viscosity that has been processed. This is a typical source of error, as one should ideally have fairly viscous material when extruding.

Regarding additives and the impact of these on quality of material, Anette Munch Elmér refers to what was previously mentioned; every time a plastic material is heated and molded, it risks degrading. Further, when the plastic starts to degrade, it will happen fast. This is why antioxidants are preferable to add to the material, to protect the plastic. Munch Elmér describes it like ‘vitamins’ for the plastic, and agrees with Henrik Eriksson at Baerlocher, that if the plastic is going to be durable and last for a long time, additives should be added for each cycle i.e., upcycling.

Regarding pigment additives, Anette Munch Elmér concludes that black pigment should not impact the material in regard to quality. However, emphasizing the need to have an uncolored or light plastic from the start. *“If red, blue or yellow pigments are added, it can play a pretty big role in how the plastic behaves. “*

Munch Elmér further highlighted certain parameters to consider for the thesis’ material testing procedure. Firstly, when a roll is to be thermoformed, it is important to monitor the material thickness throughout the roll. Depending on the extrusion site, there are cases where the material thickness can vary significantly along the roll, even if there is a set thickness. Additionally, it is a simple parameter to test, and there are conclusions that can be drawn if it would show thickness differentialities along the roll.

Concerning Charpy Impact testing, Anette Munch Elmér believes it to be a relevant test to perform but highlights the test to include a rather fast deformation. Since the material thickness of the testing material available is thinner than a standard Charpy specimen, thus performing an impact test would risk the material to bend instead of breaking properly. If it would bend, Munch Elmér recommends performing a tensile test instead.

Regarding DSC, Munch Elmér states it to be a polymer engineer's favorite instrument, as it can target the thermal properties in a material. By performing this test, it can be investigated if there are impurities in the material. As HDPE has a given melting point, it will show whether the material actually melts at this temperature or not. Regarding hardness testing, Anette Munch Elmér explains that it is a very simple test, possibly too simple to actually get relevant information regarding the material out of it.

## C.4 Lars Josefsson – Chemical Recycling

### C.4.1 Interview Questions

- Tell us about yourself and your background within the plastic industry.
- What are the pros and the cons of mechanical plastic recycling?
- What are the pros and the cons of chemical plastic recycling?
- What are the critical factors within plastic recycling to ensure the material quality outcome?

### C.4.2 Summary

Lars Josefsson has worked over 30 years at one of the big chemical companies in Stenungsund, Inovyn, that manufactures a wide range of chemicals used as raw materials in industrial processes (Inovyn 2023). Josefsson has had 12 different roles at the company and was the CEO between the years 2001-2009. Since 2011 Lars Josefsson has worked within the field of sustainability and plastic recycling.

Today, mechanical recycling is relatively easy and available for practice, Josefsson explains. It is also the most affordable way of recycling plastics today. However, it demands so-called “clean streams”, meaning the polymers should not be mixed together, but carefully sorted by type for the outcome quality to be ensured. Mixed materials, according to Lars Josefsson, will affect the quality negatively. Furthermore, every time the material is heated, the molecular chain deteriorates, thus the plastic quality will be affected negatively each time and for each recycling cycle the polymer chain will degrade.

However, during chemical recycling, Lars Josefsson explains that the polymers will go through pyrolysis, i.e., polymers are broken down to molecules by heat and can therefore be mixed into already existing infrastructure streams built for fossil fuels. By doing this, the polymers can be recycled to achieve the same quality as virgin material, Josefsson states. However, if this is done in already existing infrastructure there will not be pure streams of only molecules from recycled polymers, explaining the society's hesitation in accepting chemical recycling as an official recycling method, according to Lars Josefsson. However, due to the high quality of chemically recycled polymers, the finished products will be virgin, which is the benefit. Josefsson also concludes chemical recycling being the way to go in the future.

Regarding what the critical factors are within plastic recycling, and how to ensure an outcome of a high-quality material, the first step, according to Lars Josefsson, is for consumers to sort at source, i.e., put the used plastic packaging to plastic recycling instead of trash to be burned. Secondly, it is of high importance that the sorting process of post-consumer plastics at the sorting facilities is precise to ensure clean streams of the different polymer fractions. The precision of the sorting process is what will in the end affect the quality of the finished recycled product. This requires a demand for recycled polymer materials from the packaging companies. For the sorting facilities it requires a lot of investment to upgrade their sorting technology to be more precise.

Josefsson further emphasizes the importance for plastic packaging companies to implement the concept 'Design for recycling', i.e., no mixing of different materials, and that the design should be done to facilitate recycling at end of life. Lastly, certificates and standards should be implemented to ensure quality internationally, Lars Josefsson states.

## C.5 Company T2 – Thermoforming Company

### C.5.1 Interview Questions

- How do you ensure that the incoming rolls of extruded material (semi-finished products) are of good quality?
- Do you have a procedure of testing the incoming materials, to ensure high quality material? (with recycled content) PCR & PIR?
- What quality control and quality assurance do you perform before, during, and after processing?

- What is the procedure of testing finished products to ensure quality?
- What are the most common issues you have experienced when using recycled plastics for thermoforming?
    - How can they be avoided?
- What are the main causes for lacking quality when using recycled materials?
    - How can this be avoided?

### C.5.2 Summary

Company T2 has been working with one of the companies that got acquired by Company X in 2022, and mainly produces to European customers. Company T2 focuses on producing products within consumer markets, food sector, pharmaceutical sector along with the industrial sector, hence having insights on the utilization of recycled materials when thermoforming. Since Company T2 does not have a direct involvement to the focused product of this thesis, Company T2 could carry a somewhat objective perspective to how global collaborations can affect quality assurance. There were two candidates present for this interview – one being the operational manager of Company T2, the other being the former owner of Company T2. Working with both PIR-, and PCR-materials, Company T2 described its way of working, and explained about the thermoforming industry in this interview.

Company T2 has two vendors supplying material, located in Belgium and the Netherlands. Company T2 performs rough inspections defined primarily from customer requirements, and how it would work in the machine. Primarily, deviations can be noticed when receiving incoming rolls. A rough inspection would initially involve visual checks. This would include checking how the pallet is packet and what kind of pallet is underneath. Further, checking of the width of the material as well as thickness is done. For materials purposed for food packaging, degradation of the material is also inspected, however only a couple of times a year. If Company T2 targets error potentials, rejects, incoming inspections would be performed more frequently and notified to the vendor about the matter. If Company T2 does not find any rejects, the pallet proceeds to production.

Company T2 has a long-term relationship with the vendors, for about 16-17 years. However, if a vendor is to be chosen, the price, service, and quality would be considered as the most important factors. Company T2 does however emphasize that the material's compatibility with its machines is also of importance and would consider paying more for that reason. The type of machine used will also make a difference, making this important when selecting a vendor. When considering a new vendor, a visit would take place and sample batches (around 1000 kg) would be tested. Apart from Company T2's set criterias in material properties i.e., melt flow, impact, and temperature ranges, the suppliers are free to choose the flow of material sources.

To maintain consistency, Company T2 performs regular inspections of the material in production, taking sample pieces of the machine rolls every 1-2 hours. The company follows a list of certain checkpoints that can differ based on product purpose and further customer requirements. Most commonly, it is inspections of cuttings, fittings, moldings and/or presence of dirt etc. Any noted issues will be documented and regularly checked afterwards.

To avoid cooling down the machine when performing sample inspections, Company T2 does not shut the machine down when targeting an issue with a sample product but would instead adjust or reject all products on the active batch. This is not primarily motivated by the costs for down-hours, but mainly due to the quality aspect. If the machine is stopped it will start to cool down. When it is started up again, it will have to be heated up again. These temperature changes would differentiate the material flow, which would adventure the quality of the treated material.

Concluding, instead of stopping the machine when targeting errors with a sample product, the company either adjusts settings, or rejects all the products on the active batch. The goal is to maintain consistency in the production, so by focusing on the mold tool, creating the designed thermoforming moldings, adjusting the temperature on machines and pre-stretchers is required to maintain a consistent temperature distribution and producing products with consistent properties.

To further assure quality, Company T2 follows a specific principle when managing rolls of extruded HDPE material regarding in what order the rolls should be put into the thermoforming process. When the material arrives from the extruder the extruded material has been rolled up like spirals and cut into uniform rolls. This is illustrated in Figure C.5.1. Roll number one is the first section of the extruded material, and the ending of this roll will be connected to the inner starting material of roll number two, etc. Normally, a thermoformer will start thermoforming roll number one, and finish with roll number three.

However, by doing this the company will be starting the thermoforming process on material from the middle of the extrusion process. Instead, the last roll from the extruder, in this case roll number three, should be the first roll going into production at the thermoformer, for a more uniform process, since the inner end of roll three has been connected to the outer end of roll two, during the extrusion process before the cutting. By doing this, the machine operator will be able to perform the thermoforming process with a more uniform result since the material going into the machine will have uniform properties and performance.

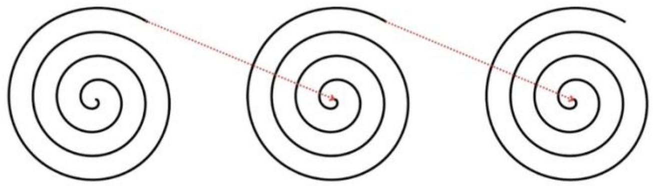



**Figure C.5.1 Illustration of the connection between extruded, rolled material**

Regarding the testing procedure of the finished goods to ensure quality, Company T2 usually applies similar testing procedures as with the incoming material, i.e, sample checks every 1-2 h.

*"Roughly, we say if the fine distribution is visually correct, no holes in it, etc, we accept these parts."*

Apart from the normal way of working, the inspection routine of finished products is mainly based on customer requirements, potential suspicions on certain processes, and if the product is new to production.

For new products, Company T2 must sign it off more frequently to the customer. Usually, a salesperson is available to tell if the product is of good quality or should be brought for further inspection. This would be performed via a provided Technical Data Sheet (TDS).

For Company T2, frequently observed issues when using recycled plastic for thermoforming are mainly challenges in estimating shrinkage percentages of the material, with further effects based on the extruding process. When extruding recycled material, the shrinkage percentage ranges more compared to virgin material, making it hard to gain a reasonable shrinking estimate when thermoforming. To tackle the issue, Company T2 decided to only focus on the individuality of the materials from the suppliers. I.e, instead of basing on the given theoretical range, focus is more on what range the specific materials used in the corresponding production line are providing. This gives Company T2 a more reliable shrinkage estimate, resulting in the design of the thermoforming tool being more accurate. Sometimes, modifying the material mix can also be an applied solution for Company T2, e.g., adding talc to make the material heavier. These methods are claimed to work most of the time, but that there are batches that will not reach the required dimensions anyway, making this one of the main challenges in thermoforming.

*"If the shrinkage is not correct, then the fit is not correct resulting the product to be scrap."*

Furthermore, Company T2 emphasizes how events during extrusion can cause common issues when thermoforming, one being fluctuations when managing a lot of flakes. Thermoformers can tell when a roll has been extruded with flakes of very different sizes. It is important that the material, i.e., the flakes, are kept in homogeneous sizing during extrusion as this would enhance the material flow into the screw, and thus create extruded material of higher quality. Also, re-melting the material to shape new granules is something thermoformers would encourage extruders to do, as this would provide material of uniform size. Company T2 is aware of the suggestion being costly, but that it would help quality assurance of recycled material long-term.

Covering the main causes for lacking quality when utilizing recycled materials, Company T2 mainly highlights administrational parameters such as certifications, the definition of recycled material, and differing work ethic to be main root causes. Starting with certifications, Company T2 explains that it basically manages and monitors standards of industrial parties, and of material-, and production standards. Company T2 continues stating that the format can vary, but that it usually would originate from customers as specifications. Company T2 further concludes that the utilization of these certifications differs substantially, and that it could enable quality issues.

Company T2 is working with ISO standards covering both food packaging, and other packaging solutions, and can/will only work with suppliers who carry the same certifications. The certifications also include auditing criteria for suppliers to gain traceability, that the machines are safe, and that the factory is 'clean'. Due to this, Company T2 is audited every 12 months.

Focusing on HDPE, the specifications that are usually valid between three to five years – *if nothing changes*. When asked about what the definition of change would be, Company T2 said that it would differ depending on who is asked, and that this is a risk in the industry. Company T2 further explains about witnessing situations where specifications have been bent, and that it is hard to notice if an agreed material content is being fulfilled when follow-ups are not performed frequently. E.g., if virgin material has been added into a mix agreed to be of 100% recycled content, it would easily go unnoticed if the finished product is of good quality.

Continuing on diffuse definitions, Company T2 claims the definition of ‘recycled’ to be diffuse and that the word can be used for various types of circumstances. There is no uniform definition of what a recycled material is in the plastics- and thermoforming industry. E.g., a virgin material that has been extruded once to be grinded up again would be considered as recycled material. Even if the material has been heated up once up to 10-15 times, both are considered to be recycled, which can be misleading for consumers and for industrial parties. Hence, the definition does not cover mechanical differences, nor the material traceability in a sense, which is considered to be risky according to Company T2.

*“So basically, it really falls down to what one would define as changes and what would be defined as recycled.”*

Lastly, Company T2 brings up how the differences in regional-, national- and business cultures could affect material quality. Since every country has their own challenges and prerequisites, it is hard to assure a uniform quality standard globally. Both candidates portray further about a factory visit made on another continent, and how the parameters are completely different. From machine setup and safety precautions to business cultures. Some business cultures contain less transparency than e.g., Europe, which makes collaborations complex and could therefore adventure quality assurance when working globally.

## C.6 Anders Sjögren – Faculty of Engineering at Lund University

### C.6.1 Discussed Testing Methods Available for Use:

- Charpy hammer – Impact strength
- Tensile modulus
- Shore A and Shore D hardness
- Melt Flow Index
- HDT (Heat Deflection Temperature) and Vicat softening temperatures
- Capillary rheometer
- Thermogravimetric device
- Differential Scanning Calorimetry

- Dynamic Mechanical Thermal Analysis
- Electric microscope

### C.6.2 Summary

Dr Anders Sjögren, teacher at LTH and founder of Ad Manus Materialteknik AB, is an expert within the material testing field. Ad Manus Materialteknik is an independent company offering testing and analysis of materials and components, specializing in testing and analysis of plastic and composite materials (Ad Manus 2020). Dr Anders Sjögren was consulted regarding the material testing part of this thesis. The list of testing equipment available, together with the problem statement of this master thesis, was presented to him and discussed thoroughly.

Sjögren argues that the Charpy Impact Test could be of interest but highlights a risk with the material thickness (1.8mm) being an issue since the material available is extruded on a roll, instead of the standardized specimen with correct dimensions. The risk would be that the material will bend rather than break due to its low thickness.

Anders Sjögren considers the Tensile Test to be relevant to perform. By doing this, the elongation at break can be evaluated. Normally, injection molded specimens with a dogbone shape are used in tensile testing. If required equipment and resources are available, Sjögren suggests looking into making a dogbone of the roll material by punching, especially since injection molding is not an option in this case.

Company X producing sites are performing the Shore D Hardness Test during quality control, which Sjögren believes to be an easy, quick, and cheap method to evaluate the material. However, Anders Sjögren is doubtful regarding how true to reality this test-result would be. According to him, the Shore D Hardness Test is not a test showing very relevant data when material properties for recycled materials are compared with properties for virgin materials, but Sjögren still suggests it to be done, since it is an easily accessible test.

Testing the Melt Flow Index (MFI), Sjögren claims it would be more accurate to check when handling material used for injection molding, but that it could be of interest in this case too. Sjögren further explains that if the molecular chains are shorter, the viscosity of the material will be lower and thus the MFI value will be higher, meaning the material is more degraded. By doing this on all the recycled materials and doing a comparison with the virgin HDPE, differences will be shown regarding degradation. Another test similar to MFI is the capillary rheometer which can be used to see how degraded the material is. It will show differences in molecular chain length and could be of interest to test according to Anders Sjögren. Due to time constraints, Sjögren suggested testing either MFI or capillary rheometer for this project.

The last test recommended by Anders Sjögren to be performed is Differential Scanning Calorimetry (DSC). This test can show differences in levels of crystallinity of the materials, which can be linked to the results of the other tests performed to find possible connections. It is a good test to perform as a complement to tensile- and/or impact tests, Sjögren states. Further it is suggested performing two identical DSC tests on each material to verify the measuring's accuracy. If something unusual occurs, it is desirable to have an additional test result of the same material for comparison.

# Appendix D Producing Sites

## D.1 Question Bank

### D.1.1 Current Status and Processing

- What are the issues with the product results of Product Y at your site, if there are any? Please explain.
    - Aesthetic/mechanical properties/other?
    - Where on the Product Y are the issues/deviations located? (Images to show us if available)
        - Are the issues always located in the same area on Product Y?
- Which are your suppliers?
    - Please specify their names, and what type of supplier they are.
    - What is the procedure of choosing different kinds of suppliers?
        - Explain the procedures for selecting new suppliers.
    - What tests do the suppliers do on the recycled HDPE before sending it to you?
        - Please present the given/set critical values they have for these test results
- What is the procedure of testing the incoming material from the suppliers before going into production of Product Y, to ensure quality? Both for bits and/or sheets/rolls
    - Please present the given/set critical values you have for these test results
- What is the testing procedure for the finished product to ensure quality?
    - Please present the given/set critical values you have for these test results
- What is the wall thickness in Product Y? (both thickest and thinnest points. If possible, attach an illustrating image)
- Do you use thin- or heavy gauge when thermoforming?
    - What size/dimension?
- What tool do you use? Please present its name.
    - Does this tool use vacuum or pressure forming?

    - Does this tool use positive or negative forming?
    - Do you do pre-forming before final forming?
        - If yes; in what form/how?
    - Does this tool manage rolls or sheets?
        - If sheets: Does this tool have a permanent format frame or adjustable clamping frame?
    - What dimensions on rolls/sheets does this tool use?
    - What is the forming temperature?
    - What is the mold tool temperature?
    - What is the vacuum and/or air pressure?
    - What is the liquid and/or cooling temperature?
    - What is the cycle time?

### D.1.2 Plastic Recycling Process

- What sorting/separating technique do you/suppliers use for post-consumer HDPE used in Product Y?
- Please explain the cleaning procedure of the recycled HDPE.
- What colors do the recycled plastic in Product Y contain?
    - Do you/the supplier add any pigment to make it black?
    - Do you/the supplier add any other upcycling additives?
- Is the HDPE for Product Y post-industrial or post-consumer? (Or mixed?)
- What percentage of recycled material do you use when producing Product Y?
    - Is it always the same percentage of recycled material, or can it differ?
        - If it's different, why?

### D.1.3 Critical Values

We want to know all critical values/intervals set by Company X/Company C regarding the following properties (for Product Y):

#### *D.1.3.1 Foil Rolls for Product Y*

Please explain:

- Which ones are critical of the following properties below?
- What are the requirements on the following properties below?
    1. Tensile modulus
    2. Yield stress
    3. Impact strength

4. Elongation at break
5. Hardness
6. Material thickness

*D.1.3.2 Finished Product, Product Y*

Please explain:

- Which ones are critical of the following properties below?
- What are the requirements on the following properties below?
    1. Tensile modulus
    2. Yield stress
    3. Impact strength
    4. Elongation at break
    5. Hardness
    6. Service temperature
    7. Flammability
    8. Electrical resistance
    9. UV resistance
    10. Chemical resistance
    11. Water absorption
    12. Wall thickness on finished Product Y – max & min

## D.2 Encrypted Version of 'Recycled Products Letter' from Company E1

[DATE]

[Customer Address]

RE: [Product]

Dear Valued Costumer,

**ReCycled Products**

Products manufactured by Company E1 as 'ReCycled' are made with reprocessed materials and are produced without guarantees relative to the physical properties. Company E1 can only guarantee the physical dimensions and that the base material is of the polymer family desired for products sold as 'ReCycled'. Materials used in the manufacture of these products are materials that at some point have either lost their original identity or integrity and may contain contaminates, such as UVI, fillers, additives or other polymers, not conducive to consistent performance or aesthetic properties. These materials may be inconsistent in nature from order to order and even within individual orders.

As a result of the unpredictable nature of the materials used, Physical Property sheets (Technical Data sheets) are not typically available. Base polymer Safety Data Sheets for ReCycled products are available to communicate expected material hazards and meet requirements to 29 CFR 1910.1200.

ReCycled materials cannot be certified to FDA, NSF, UL, RoHS, REACH, Prop 65 or other regulatory specifications. Although on a lot-by-lot basis the materials may be able to successfully pass testing to these kinds of standards, the unpredictability of the material prevents it from being able to consistently comply.

Discretion should be used whenever electing to purchase a ReCycled product for a particular application. It is the sole responsibility of the purchaser to determine the suitability of use, based on their application, for ReCycled materials.

Each user bears full responsibility for making its own determination as to the suitability of each material, product, recommendation or advice set forth by Company E1. Each user must identify and perform all tests and analyses necessary to assure that its finished parts incorporating Company E1's materials or product will be safe and suitable for use under end-use conditions. Nothing in this or any other document, nor any oral recommendation or advice, shall be deemed to alter, vary, supersede, or waive any provision of Company E1's Standard Condition of Sale or this Disclaimer, unless any such modification is specifically agreed to in writing signed by Company E1. No statement contained herein concerning a possible or suggested use of any material, product or design is intended, or should be construed, to grant any license under any patent or other intellectual property right of Company E1 or any of its subsidiaries or affiliates covering such use or design, or as a recommendation for the use of such material, product or design in the infringement of any patent or other intellectual property right.

## D.3 Company E1 – Interview Questions

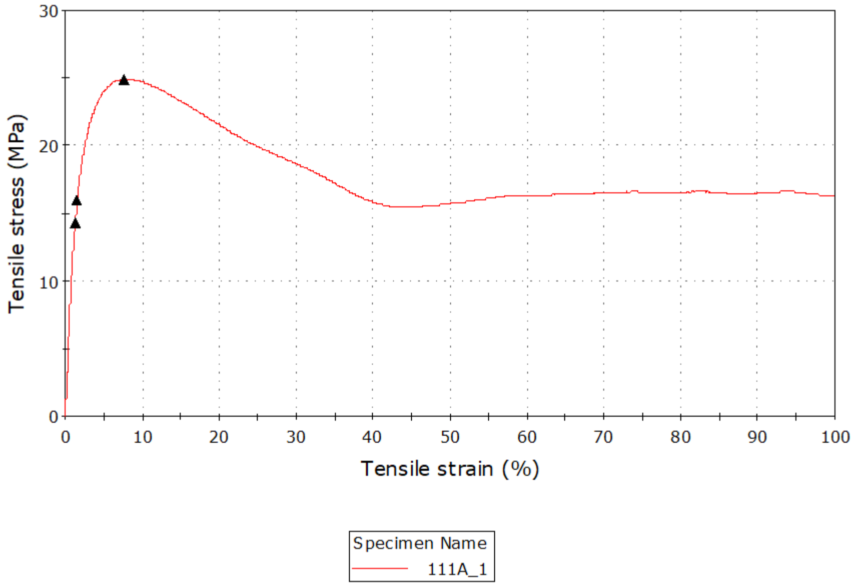
1. What is the procedure of choosing suppliers of the recycled HDPE, to be used in Product Y?
    a. Regarding traceability of the material (post-consumer); how is it gathered, sorted, cleaned, etc., before grinded and re-granulated?
2. What is the procedure of testing incoming material (both post-industrial & post-consumer) from suppliers to ensure high quality recycled material?
3. What is the procedure of testing finished products to ensure quality?
4. What are the most common issues you have experienced when using recycled plastics for extrusion? How can they be avoided?

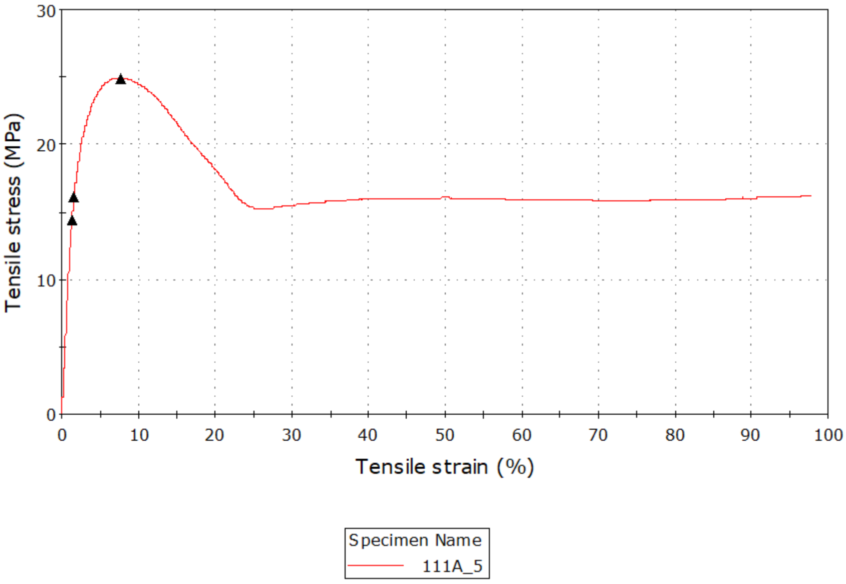
## D.4 Company T1 – Interview Questions

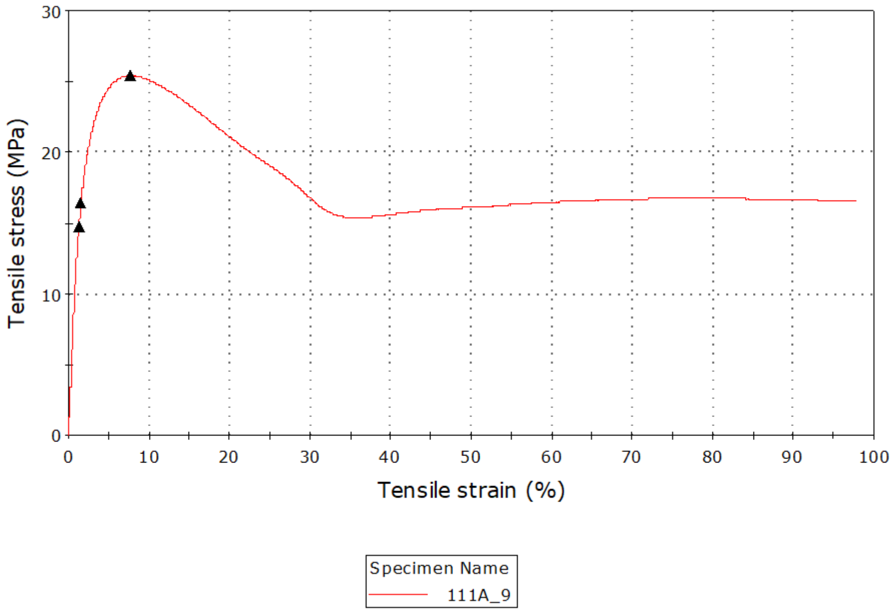
1. How do you ensure that the incoming rolls of extruded HDPE are of good quality?
2. What is the procedure of testing the incoming rolls from Company E1, to ensure high quality recycled material?
    a. It is stated that this product is produced with 25% post-consumer materials, and 75% post-industrial material. In your experience, have you seen this ratio differing, or is it properly followed?
3. What effect will the processing/machine settings have on the finished product?
    a. What is your way of working regarding this? Speed, temperature etc
4. What is the procedure of testing finished products (Product Y) to ensure quality?
5. What are the most common issues you have experienced when using recycled plastics for thermoforming? How can they be avoided?
6. What do you think is the cause of the previous aesthetic issues occurring in the same location on Product Y, even though produced in different producing sites with different recycled content (post industrial vs. post-consumer)?

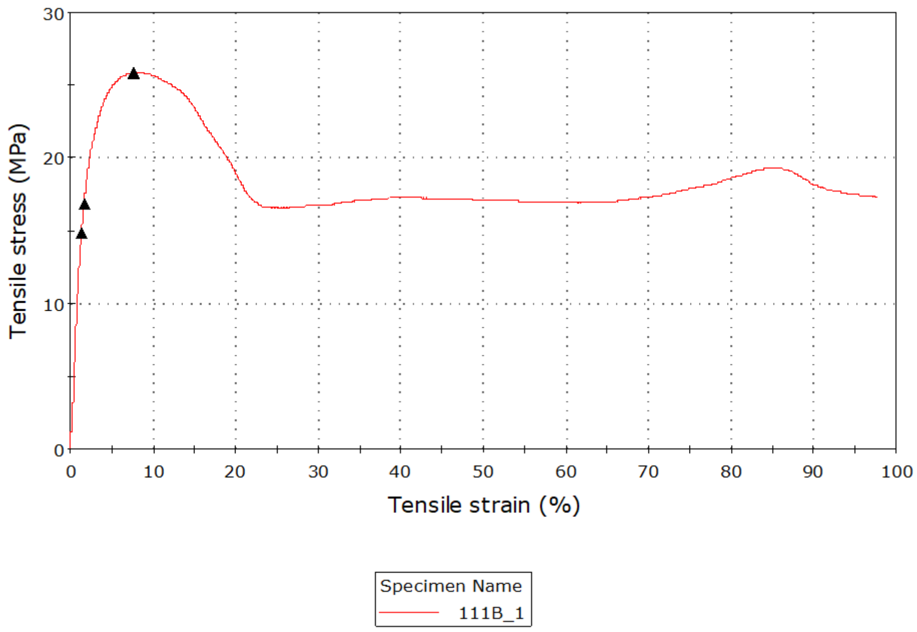
# Appendix E Material Testing

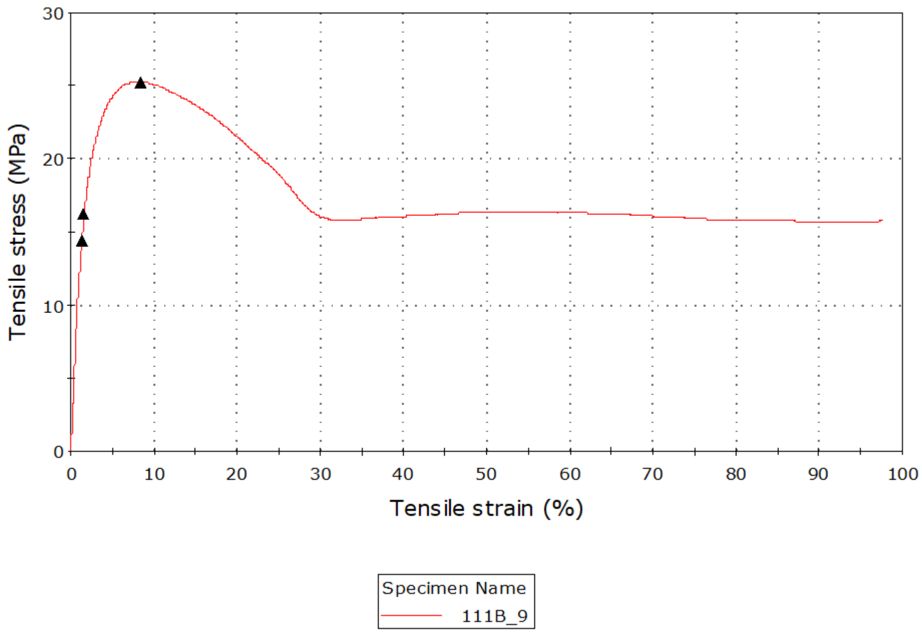
## E.1 Tensile Test – Raw Data for Each Tested Specimen

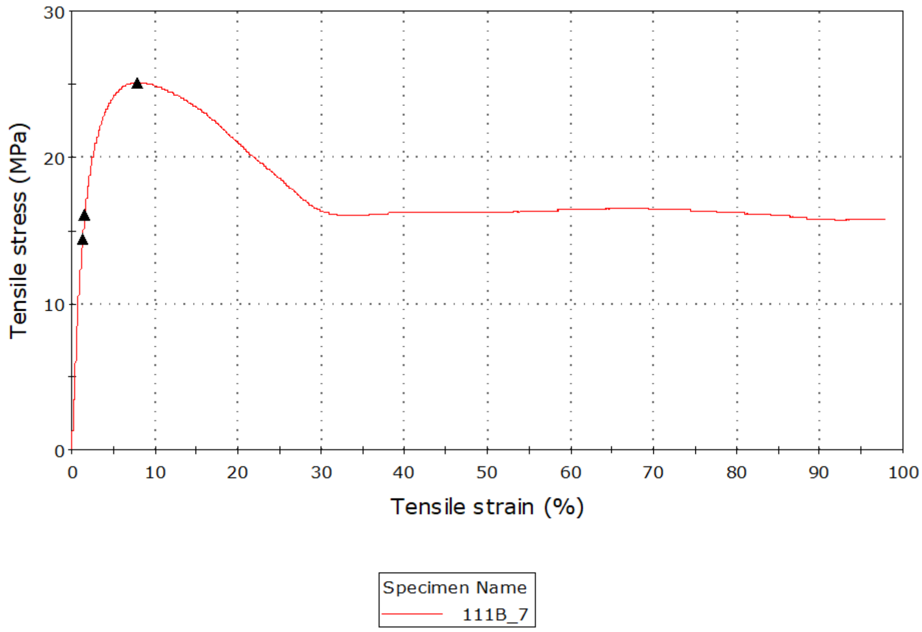


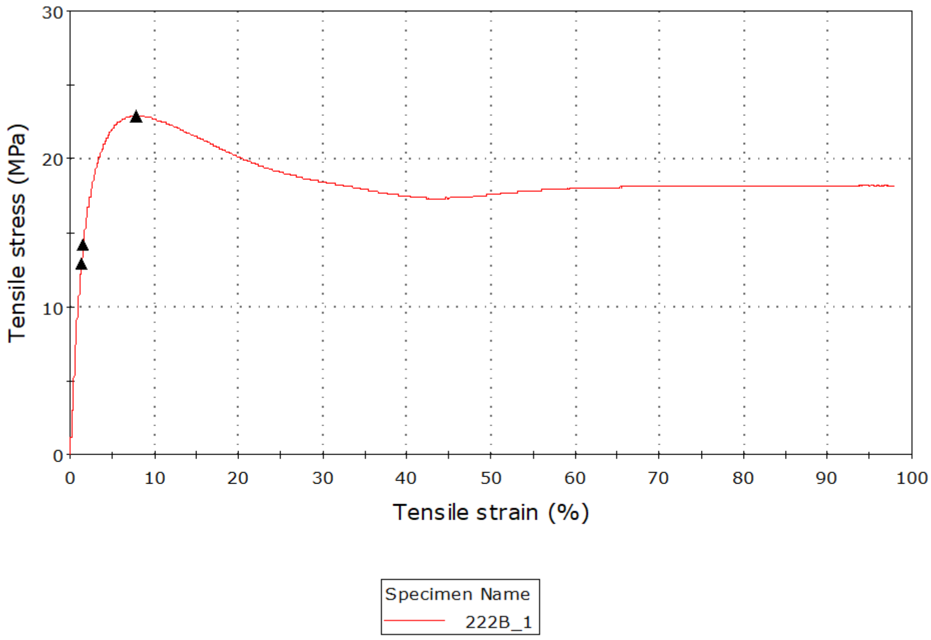

30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
111A_5

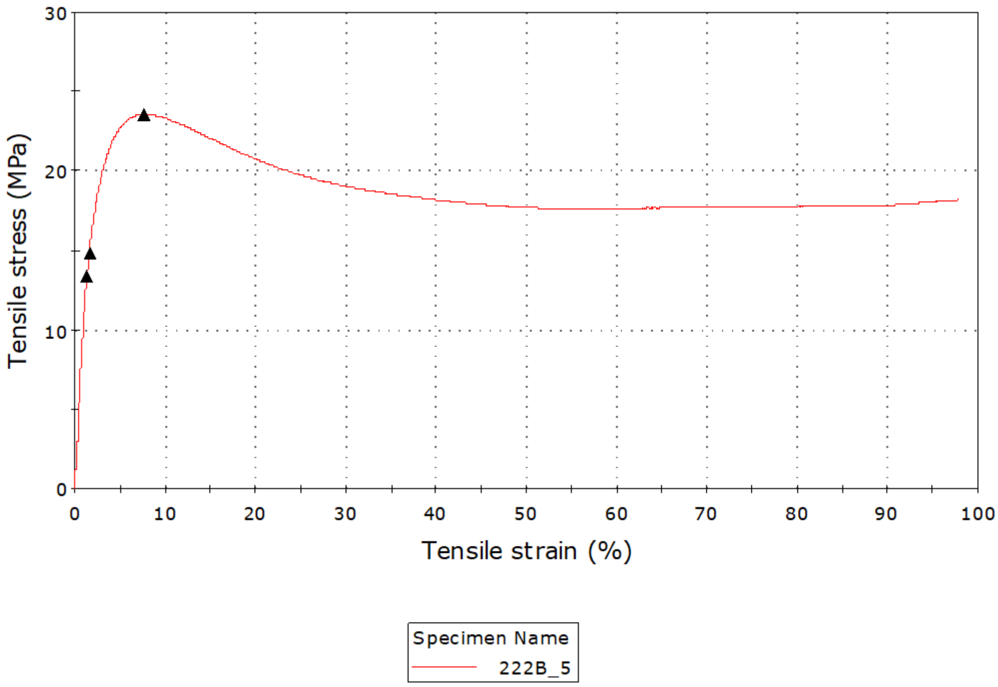

30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
111A_9


30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
111B_1

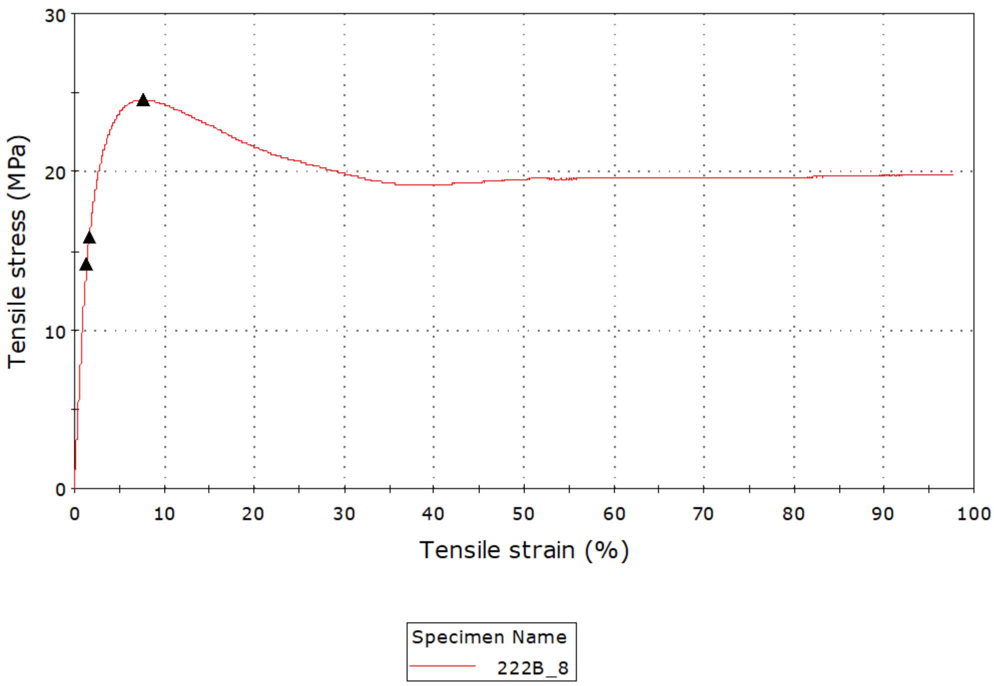

30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
111B_9


Tensile stress (MPa)
Tensile strain (%)
Specimen Name
111B_7

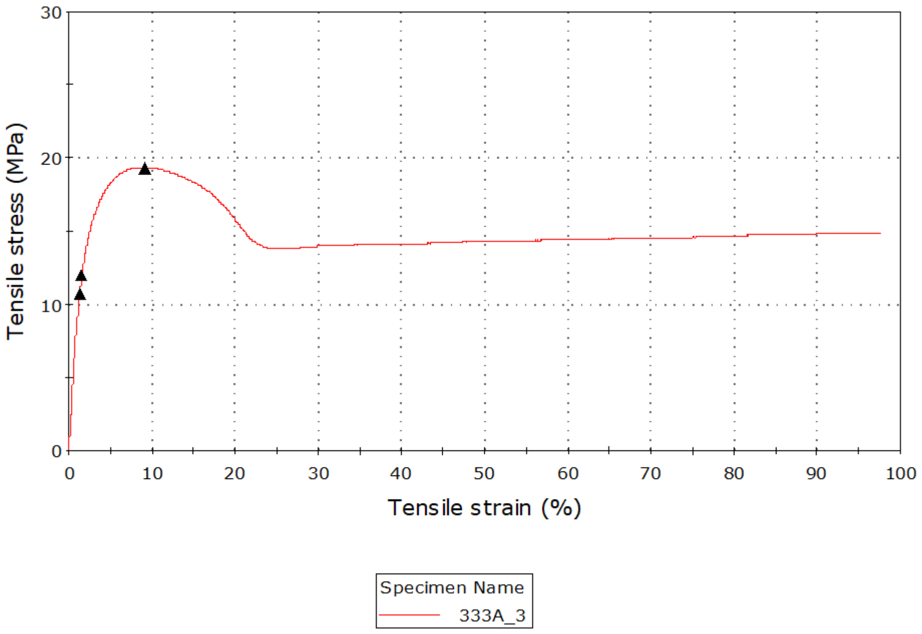

Tensile stress (MPa)
Tensile strain (%)
Specimen Name
222B_1



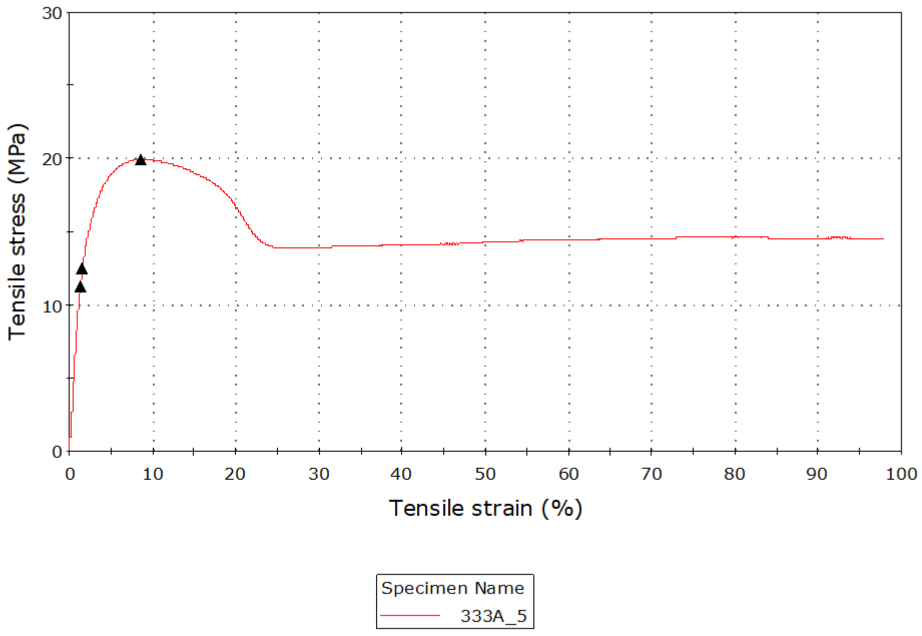
Tensile stress (MPa)
Tensile strain (%)
Specimen Name
222B_5

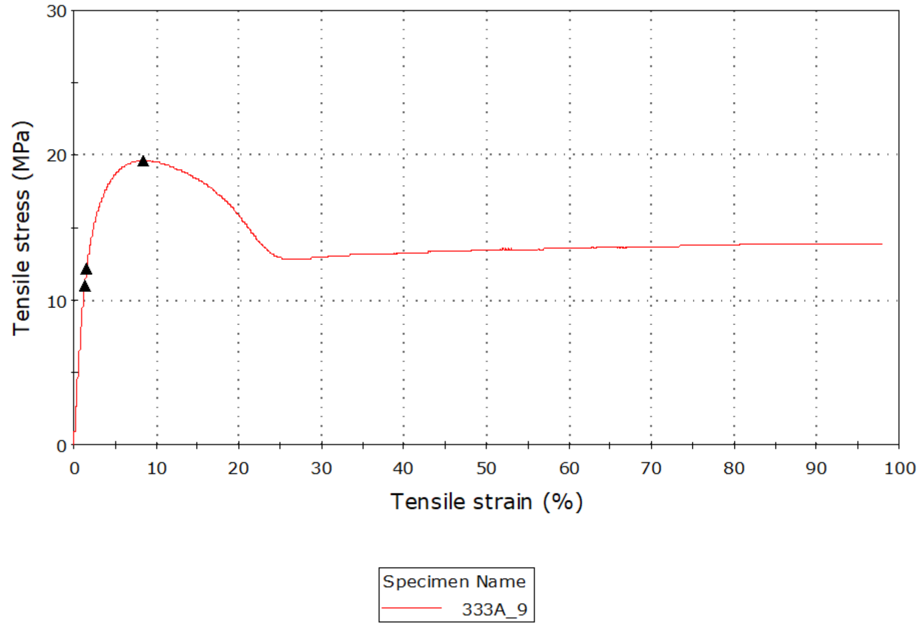
Tensile stress (MPa)
Tensile strain (%)
Specimen Name
222B_8

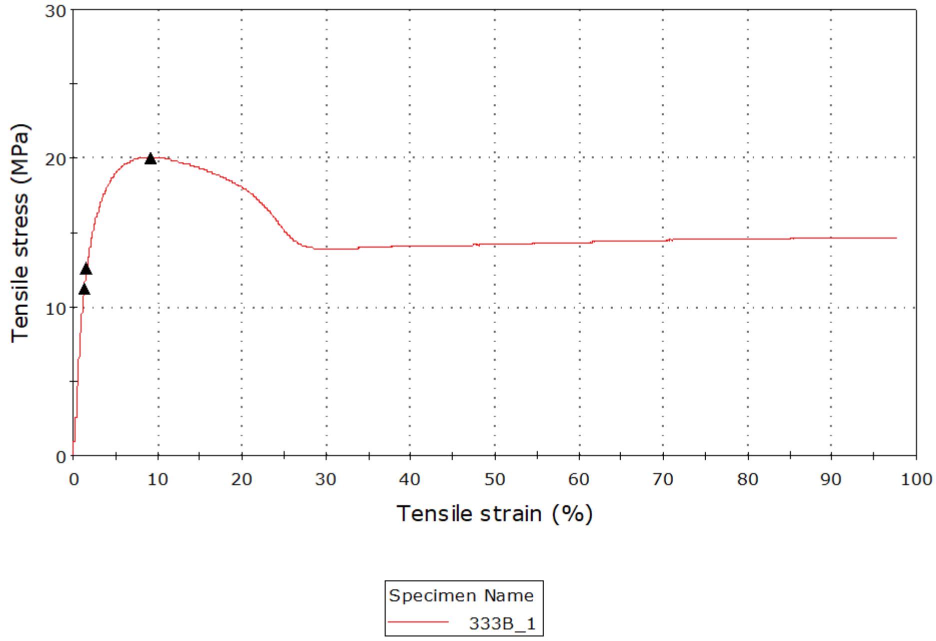


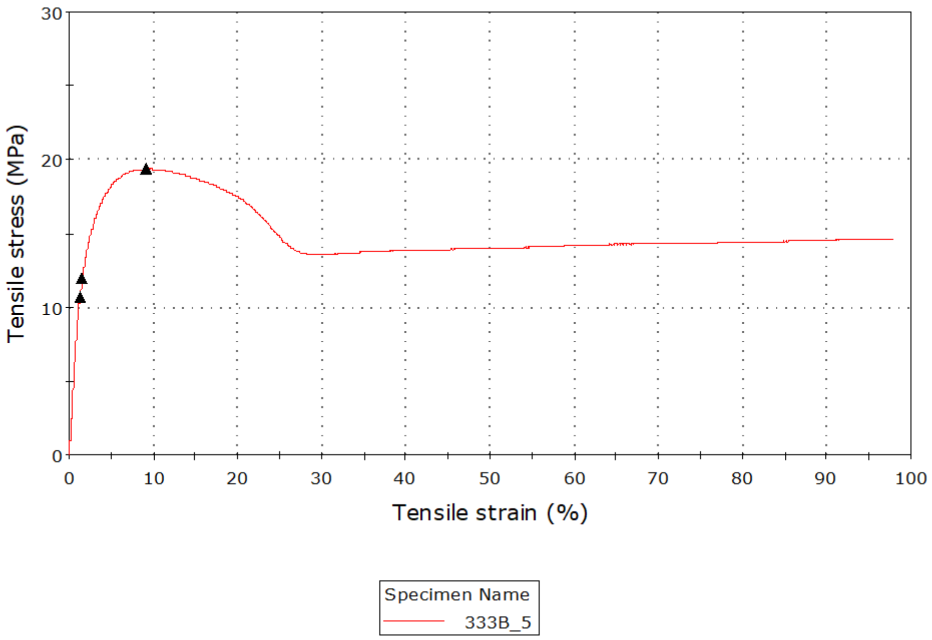
30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
333A_3

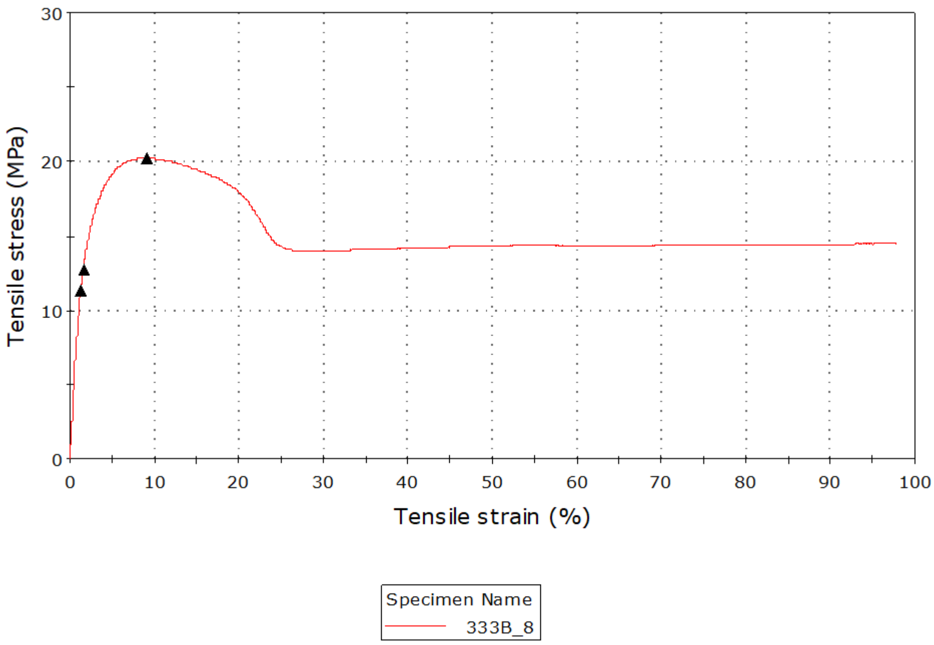



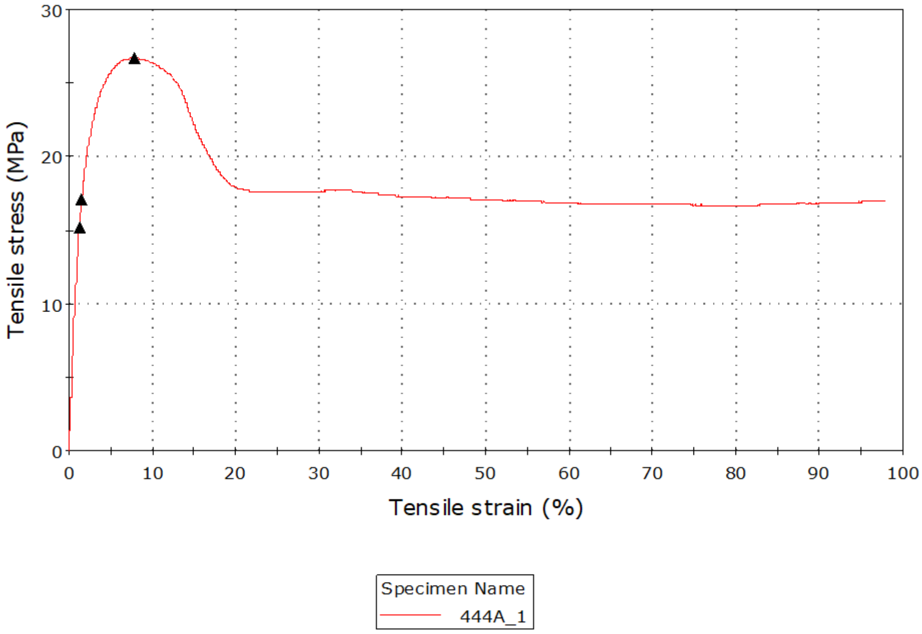
30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
333A_5

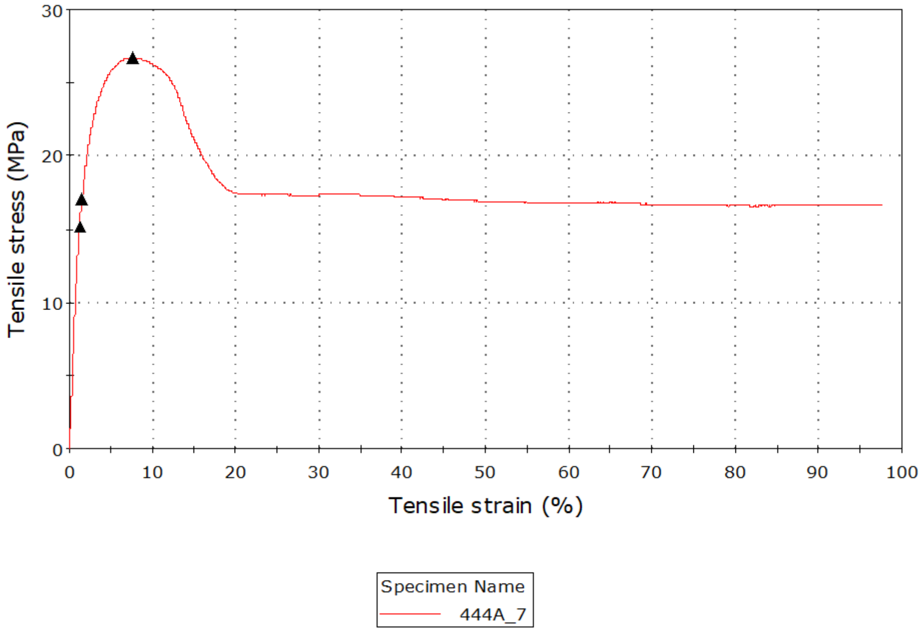

30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
333A_9

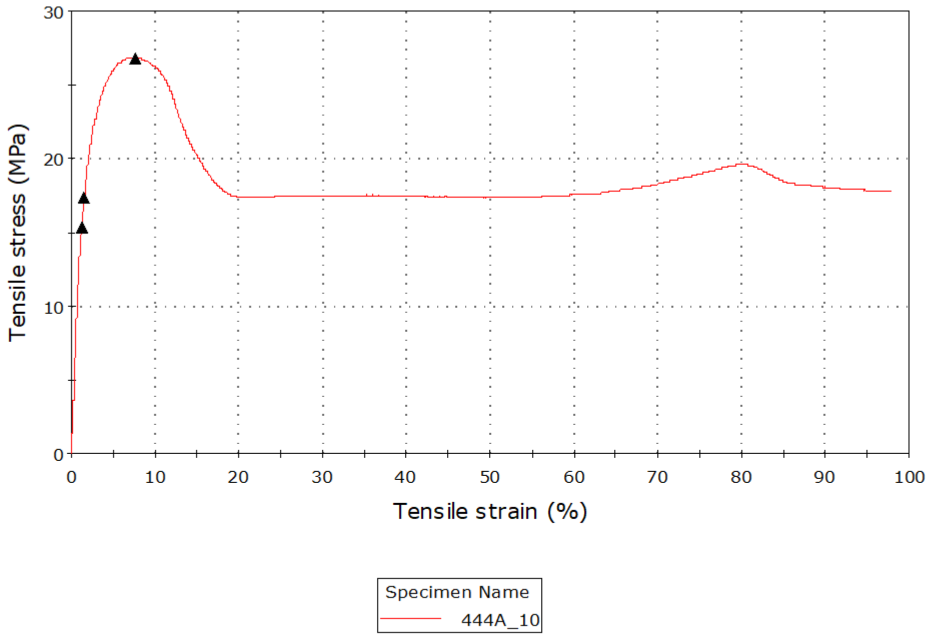

30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
333B_1

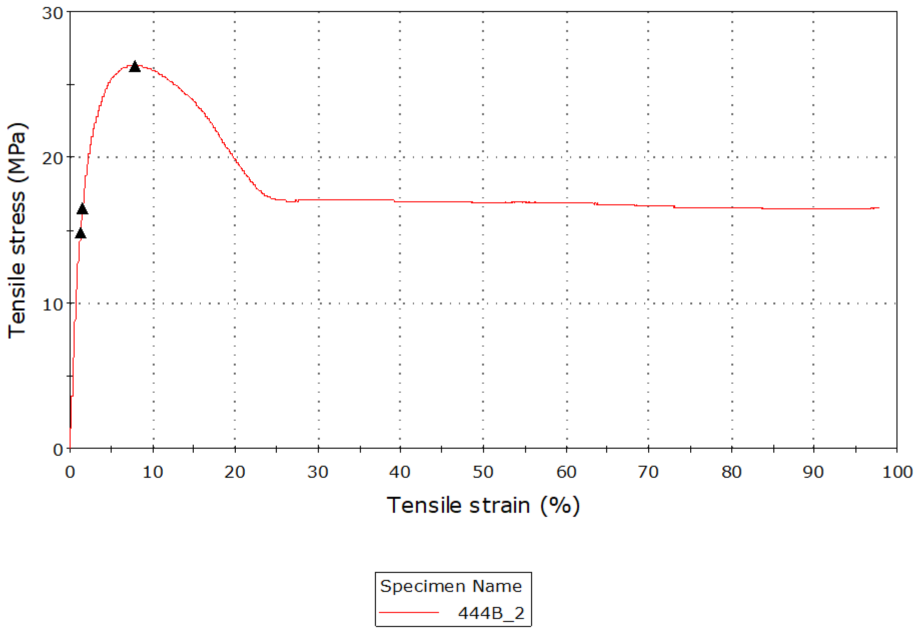

Tensile stress (MPa)
Tensile strain (%)
Specimen Name
333B_5

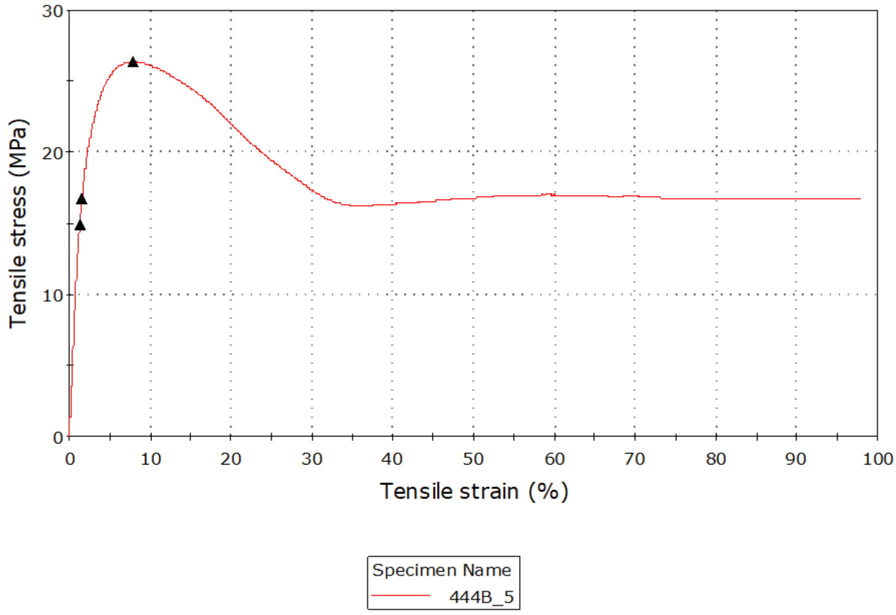

Tensile stress (MPa)
Tensile strain (%)
Specimen Name
333B_8


Tensile stress (MPa)
Tensile strain (%)
Specimen Name
444A_1

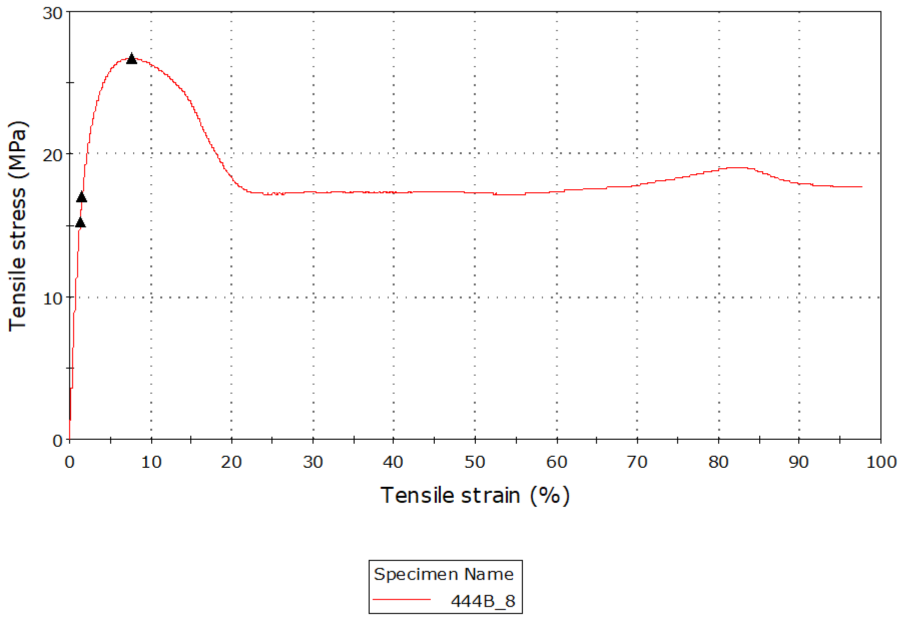

Tensile stress (MPa)
Tensile strain (%)
Specimen Name
444A_7


30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Tensile stress (MPa)
Tensile strain (%)
Specimen Name
444A_10


30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Tensile stress (MPa)
Tensile strain (%)
Specimen Name
444B_2



30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
444B_5

30
20
10
0
Tensile stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Tensile strain (%)
Specimen Name
444B_8

| | Specimen label | Modulus at E - modulus (MPa) | Tensile stress at Yield (Zero Slope) (MPa) | Tensile strain at Yield (Zero Slope) (%) |
|---|---|---|---|---|
| **1** | 111A_1 | 1152 | 24.92 | 7.67 |
| **2** | 111A_5 | 1166 | 24.96 | 7.66 |
| **3** | 111A_9 | 1188 | 25.42 | 7.66 |
| **4** | 111B_1 | 1180 | 25.87 | 7.67 |
| **5** | 111B_9 | 1164 | 25.26 | 8.41 |
| **6** | 111B_7 | 1167 | 25.13 | 7.78 |
| **7** | 222B_1 | 1030 | 22.89 | 7.76 |
| **8** | 222B_5 | 1052 | 23.57 | 7.70 |
| **9** | 222B_8 | 1075 | 24.55 | 7.60 |
| **10** | 333A_3 | 869 | 19.34 | 9.12 |
| **11** | 333A_5 | 903 | 19.93 | 8.52 |
| **12** | 333A_9 | 899 | 19.61 | 8.37 |
| **13** | 333B_1 | 904 | 20.07 | 9.14 |
| **14** | 333B_5 | 858 | 19.36 | 9.17 |
| **15** | 333B_8 | 903 | 20.24 | 9.17 |
| **16** | 444A_1 | 1259 | 26.69 | 7.78 |
| **17** | 444A_7 | 1264 | 26.68 | 7.63 |
| **18** | 444A_10 | 1271 | 26.85 | 7.60 |
| **19** | 444B_2 | 1220 | 26.32 | 7.79 |
| **20** | 444B_5 | 1224 | 26.37 | 7.79 |
| **21** | 444B_8 | 1257 | 26.72 | 7.62 |

## E.2 Tensile Test – Recorded Values at Testing Termination

| | Tensile stress at Break (Standard) (MPa) | Tensile strain at Break (Standard) (%) | Tensile stress at Maximum Load (MPa) | Tensile strain at Maximum Load (%) |
|---|---|---|---|---|
| **1** | 17.22 | 191.39 | 24.92 | 7.67 |
| **2** | 16.25 | 97.83 | 24.96 | 7.66 |
| **3** | 16.51 | 97.85 | 25.42 | 7.66 |
| **4** | 17.32 | 97.79 | 25.87 | 7.67 |
| **5** | 15.77 | 97.84 | 25.26 | 8.41 |
| **6** | 15.79 | 97.87 | 25.13 | 7.78 |

| | | | | |
|---|---|---|---|---|
| **7** | 18.17 | 97.79 | 22.89 | 7.76 |
| **8** | 18.18 | 97.82 | 23.57 | 7.70 |
| **9** | 19.80 | 97.77 | 24.55 | 7.60 |
| **10** | 14.89 | 97.84 | 19.34 | 9.12 |
| **11** | 14.54 | 97.80 | 19.93 | 8.52 |
| **12** | 13.88 | 97.84 | 19.61 | 8.37 |
| **13** | 14.68 | 97.84 | 20.07 | 9.14 |
| **14** | 14.61 | 97.86 | 19.36 | 9.17 |
| **15** | 14.47 | 97.84 | 20.24 | 9.17 |
| **16** | 16.95 | 97.86 | 26.69 | 7.78 |
| **17** | 16.62 | 97.80 | 26.68 | 7.63 |
| **18** | 17.84 | 97.86 | 26.85 | 7.60 |
| **19** | 16.49 | 97.89 | 26.32 | 7.79 |
| **20** | 16.74 | 97.84 | 26.37 | 7.79 |
| **21** | 17.66 | 97.82 | 26.72 | 7.62 |

## E.3 Tensile Test – Corresponding Values for ε and σ to Modulus E

| | **Specimen label** | **Modulus at E-Modulus (MPa)** | **X-Intercept at E-Modulus (%)** | **Y-Intercept at E-Modulus (MPa)** |
|---|---|---|---|---|
| **1** | 111A_1 | 1152 | 1.574 | 16.01 |
| **2** | 111A_5 | 1166 | 1.562 | 16.07 |
| **3** | 111A_9 | 1188 | 1.565 | 16.41 |
| **4** | 111B_1 | 1180 | 1.623 | 16.82 |
| **5** | 111B_9 | 1164 | 1.582 | 16.17 |
| **6** | 111B_7 | 1167 | 1.561 | 16.11 |
| **7** | 222B_1 | 1030 | 1.559 | 14.2 |
| **8** | 222B_5 | 1052 | 1.6 | 14.89 |
| **9** | 222B_8 | 1075 | 1.663 | 15.9 |
| **10** | 333A_3 | 869 | 1.571 | 12.01 |
| **11** | 333A_5 | 903 | 1.568 | 12.5 |
| **12** | 333A_9 | 889 | 1.54 | 12.2 |
| **13** | 333B_1 | 904 | 1.577 | 12.57 |
| **14** | 333B_5 | 858 | 1.585 | 12 |
| **15** | 333B_8 | 903 | 1.6 | 12.74 |
| **16** | 444A_1 | 1259 | 1.535 | 17.04 |
| **17** | 444A_7 | 1264 | 1.533 | 17.05 |

| | | | | |
|---|---|---|---|---|
| **18** | 444A_10 | 1271 | 1.553 | 17.38 |
| **19** | 444B_2 | 1220 | 1.534 | 16.54 |
| **20** | 444B_5 | 1224 | 1.548 | 16.72 |
| **21** | 444B_8 | 1257 | 1.543 | 17.09 |

# E.4 DSC – Graphs

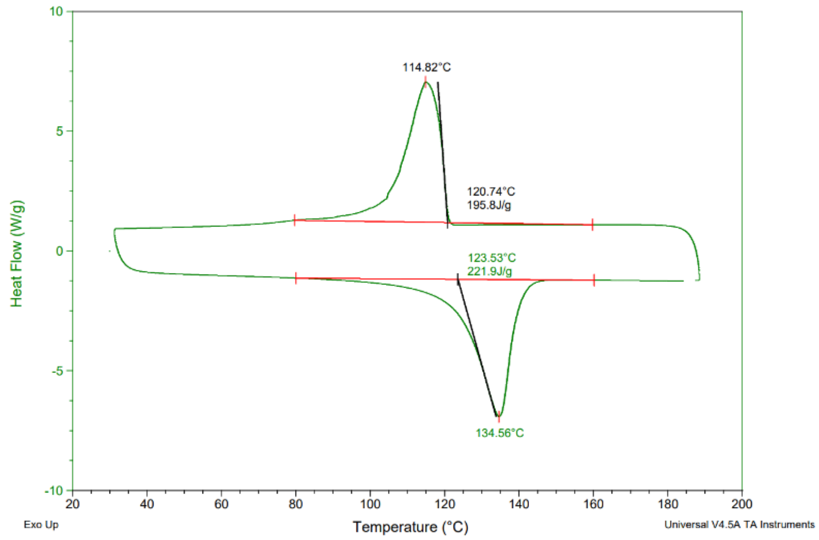



**Figure D.4.1 Heating (bottom) and cooling (top) curves of specimen 111B (virgin HDPE-Europe)**

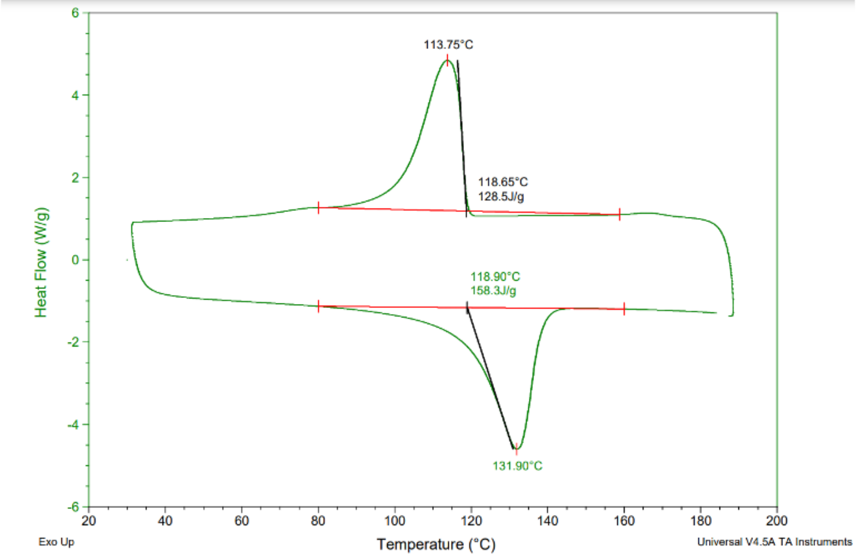



**Figure D.4.2 Heating and cooling curves of specimen 222B (recycled HDPE - Europe)**

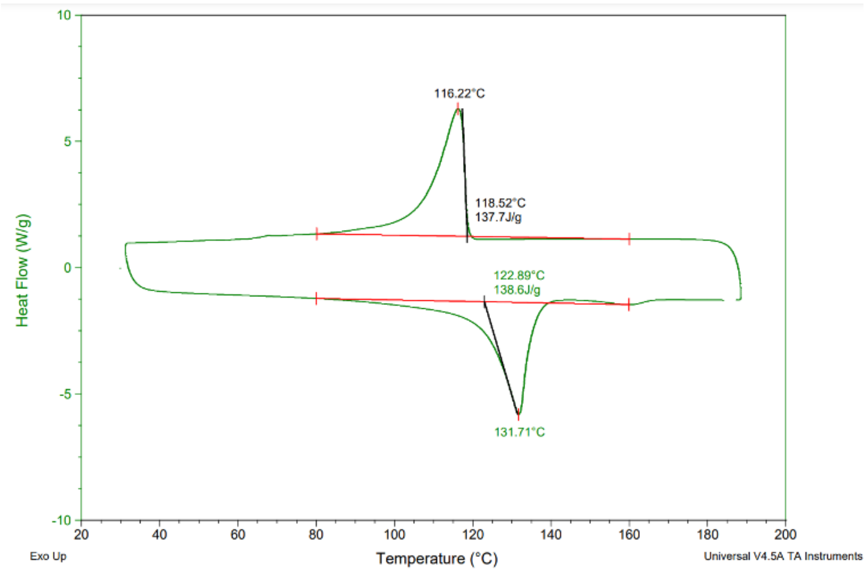



**Figure D.4.3 Heating and cooling curves of specimen 333B (recycled HDPE - Asia)**

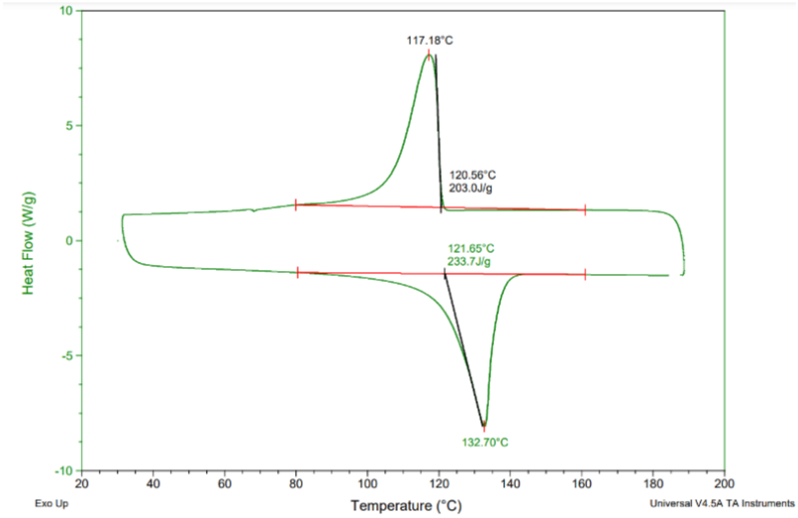



**Figure D.4.4 Heating and cooling curves of specimen 444B (recycled HDPE – the Americas)**