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Evaluating the properties of recycled polyethylene films from the construction industry

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Abstract

The construction industry generates tonnes of plastic waste every year and only a small minority of this is recycled. This study looks into possible new film products in the construction industry, if the waste is collected, by evaluating the properties of the mechanically recycled film. The plastic in question is transparent polyethylene (PE) film from a construction specialist shop, sorted into four categories; shrink and stretch films, clean film, dirty film, and thick film. The evaluation of the properties was done through various tests, these were; Fourier transform infrared spectroscopy (FT-IR), differential scanning calorimetry (DSC), melt flow index (MFI), oxidative induction time (OIT), tensile strength test, density and thickness measurements, falling dart, and tear strength and the results were analyzed separately. The results show that it is possible to turn all categories into covering film, hoods, and garbage bags, although the clean film is the only one that does not require any extra measures. The others need to be washed or mixed with virgin material to stabilize some property in order to be made into new products. In addition, an environmental system analysis was performed which revealed that it is environmentally beneficial to recycle PE in terms of carbon dioxide (CO₂) equivalents.

Keywords: recycling, polyethylene, construction industry.

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Abbreviations

CD: Cross direction
CO₂: carbon dioxide
DSC: Differential scanning calorimetry
E-modulus: Elasticity modulus
FT-IR: Fourier transform infrared spectroscopy
HDPE: High density polyethylene
PE: Polyethylene
LDPE: Low density polyethylene
LLDPE: Linear low density polyethylene
MDPE: Medium density polyethylene
MFI: Melt flow index
MD: Machine direction
OIT: Oxidative induction time

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1 Introduction

The invention of plastic has been revolutionary for the society that we live in today. The applications of many different sorts of plastic still continue to widen and one of the largest uses is in the construction industry. It is used as pipes, flooring and different protective films, and a significant part is the packaging of the building materials, to protect them under transport.

In Sweden, the yearly consumption in 2016 of plastic in the construction industry is around 262 000 metric tonnes which is around 20% of the overall consumption of plastic in Sweden [1]. This includes both materials that are used during the construction as well as the packaging. Of these, 150 000 tonnes became the total waste, 62 200 tonnes were sorted out as plastic waste, with a mere 900 tonnes eventually to be recycled. One of the most commonly used types of plastic is polyethylene (PE). In 2016 it represented 29.8% of the demand on the plastic market in Europe.

The Swedish Energy Agency and RE:source has funded a project called CirEm2 where the goal is to develop and evaluate circular recycling systems for plastic packaging films in the construction industry. In CirEm2 there was a large-scale recycling trial performed at Reviva Plastics in October 2021, see appendix A. The project this report is based upon, is performed at RISE and is a part of CirEm2. The major differences between the previous trial at Reviva Plastics and the one performed in this project, is the scale, this project includes only transparent film, and that the film at Reviva Plastics was washed to remove labels and contaminants prior to milling.

1.1 Purpose

This study aims to evaluate the properties of transparent PE packaging films, collected at a construction specialist shop, after mechanical recycling. Thereafter to, with the acquired information, propose suitable new film products for the recycled plastic for use in the construction industry.

1.2 Delimitations

In this study only transparent PE packaging films gathered from construction specialist shops will be studied. No consideration will be taken of additives other than antioxidants.

2 Theoretical Background

2.1 PE in general

PE is a polymer of ethene with the smallest repetitive unit ($\text{CH}_2\text{-CH}_2$). There are three different main types of PE; high density polyethylene (HDPE), low density polyethylene (LDPE), and linear low density polyethylene (LLDPE). These types of PE stem from different types of polymerization [2].

HDPE consists of straight chains which are closely packed together. This makes the material dense and hard, the side chains are short, if there are any [2]. LDPE consists of chains with long side chains. The length of the side chains inhibit the ability of the polymers to align closely together and the result is a tougher material with a lower density. Finally, LLDPE consists of long straight chains but with more short side chains than HDPE. This structure gives the material a low density and makes it stretchy if the material is pulled with a force. This is due to the fact that the chains will stretch out and align themselves making the material more crystalline. A polymer material that is pure and amorphous is transparent, and when the degree of crystallization rises the material becomes more opaque. Depending on the composition, the material can stretch out to 100-400% of its original size [3]. When the force is no longer there, the polymer chains aim to retract to their former amorphous lower energy state. This phenomenon makes the material keep its grip if it is wrapped around an object.

PE is a thermoplastic, which means that it can be melted and reformed [2]. Because of that, the plastic is well suited for the process of mechanical recycling and can be recycled multiple times, although the quality of the plastic will decrease. To prevent degradation of the polymer, antioxidants are added. If the material consists of different types of PE with chains of varying lengths as well as additives, the recyclability is decreased [4]. This is because the differences in the constituent materials generate a heterogeneous melting and solidification temperature profile throughout the recycled material. To stabilize and homogenize the product, virgin material is commonly added to the mix. Further on, there are more parameters that are significant for the quality of the recycled product.

According to RecyClass, a cross-industry initiative for plastic packaging recyclability, the ability to mechanically recycle PE films is high if some requirements are met [5]. For example the film needs to be transparent, the additives can not bring the density above 0.97 g/cm^3 and the labels, if any, need to be made of PE as well. If the labels are instead made out of paper, the ability to recycle is limited and if they are made of polyvinyl chloride it is not recyclable at all unless the labels are removed, either manually or by washing the plastic. In addition, the pieces of film need to be a certain size in order to be sorted. Thus the prospects of recycling depend on many different factors. On the other hand the requirements for recycled products vary as well [4]. Products intended to be a dark colour can have a larger amount of colour changing contaminants than the ones intended to be a light colour. Films of LLDPE intended to stretch can only have a low amount of contaminants due to the fact that these become breaking points when strain is added to the material. Different combinations and compositions of HDPE, LDPE and LLDPE can be recycled together although the properties of the end product will vary [6].

The differences in the construction of the material generate different physical properties. Since polymer material consists of polymer chains of different lengths and some different structures, the physical properties depend on this mixture. Although there are some general intervals that can be used to identify and separate the different categories, see table 1 [7, 8].

Table 1: Properties of PE varieties.

	HDPE	LDPE	LLDPE
Melting temperature interval [°C]	120-140	105-115	112-124
Density intervall [g/cm ³]	0.941-0.956	0.910-0.925	0.91-0.94

2.2 Areas of application for PE in packaging in the construction industry

PE can be used for many differing applications, as material in the construction as well as a tool to safely transport other materials. All forms of PE are commonly used as protective packaging film, which come in different thicknesses and designs [2]. Its purpose is to protect goods from moisture, dirt, and dust during transport or if they are kept outside [1]. From the manufacturer to the construction site, all materials are packaged, opened and repackaged, using large amounts of PE film that has a high potential to be recycled.

Shrink and stretch films are commonly made of LDPE or LLDPE or a mixture of both, and these films are used for protective packaging purposes [3]. It is common to find multiple labels on the plastic around one pallet, since it is used for both information about the content as well as the transport details [1]. Due to re-packaging multiple times it is advantageous to use transparent shrink and stretch film with labels since these can be scanned through multiple layers of film. The shrink film is wrapped around the object and shrinks when it is exposed to heat, which makes it a good protective layer around oddly shaped goods [3]. The stretch film is also wrapped tightly around the goods and it is good at stabilizing unstable goods.

Another way to use PE films of different thicknesses is to place them over the goods as a hood [9]. This way no rotation is needed, since there is no wrapping, and the process is quick when dealing with similarly sized goods. The plastic can either be taped down, heated to shrink in order to fit tightly or not fixed at all.

2.3 Identification of PE

A common method for differentiating between different types of PE is differential scanning calorimetry (DSC). In figure 1, the DSC-thermogram graph shows the melting in the heating scans as downward peaks and the cooling scans shows the crystallization as upward peaks, of the three main types of PE as well as medium density PE (MDPE) [10].

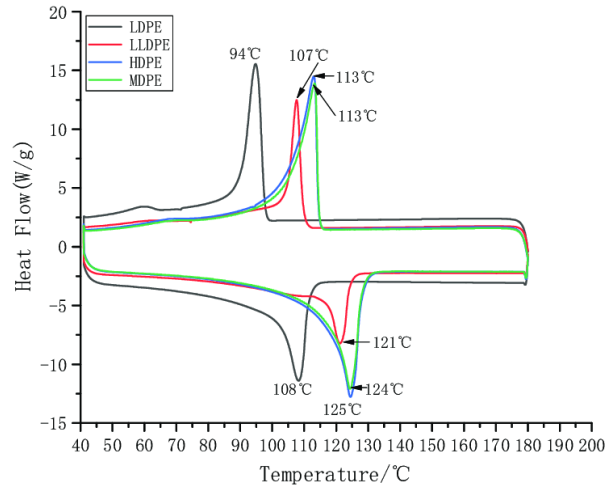


Figure 1: Examples of DSC-curves for common PE varieties. LDPE is the downwards peak at 108 °C, LLDPE at 121 °C, MDPE at 124 °C and HDPE at 125 °C.

3 Methodology

The project was divided into four sections; an environmental system analysis, sorting and investigation of the collected material, reprocessing and characterization of the recycled plastics, and investigation of potential applications for the recycled plastics.

The environmental system analysis was done in order to assess whether the recycling process is environmentally beneficial. It included information on the relative carbon dioxide (CO₂) emissions released by the production of recycled PE and virgin PE, as well as the total amounts released per kg of plastic granulate produced. In addition, comparisons were made between the use of a Swedish electricity mix compared to a European one, in relation to the amount of CO₂ equivalents released.

The sorting consisted of a visual and manual sorting of the collected films into four categories, with the ambition to achieve more homogeneous fractions of material. An investigation of a sample from each category was executed to get information on what the material constituted of before the recycling process. This was done with the test methods Fourier transform infrared spectroscopy (FT-IR) and DSC. With FT-IR the chemical composition of the material can be investigated by measuring the absorbed infrared-light by the material, which allows for the type of polymer to be identified. DSC measures the energy required to keep a test vessel at a specific temperature and provides information about the melting and crystallization temperatures of the material.

The recycling and processing section of the project consisted of milling the material, compounding, pelletizing, film blowing, and injection molding. The milling was done to convert the collected material to a format that was manageable by the compounding machine. The compounding melted and mixed the flakes into one homogenous material and pelletizing made the material into a format suitable for the next process, injection molding and film blowing. The tests performed on the pellets were FT-IR, DSC, melt flow index (MFI), and oxidation induction time (OIT). FT-IR and DSC are explained above and MFI indirectly measures the viscosity, where a higher MFI represents a lower viscosity at a certain temperature. OIT is the time to oxidation of the polymer in an oxygen atmosphere at 200 °C. The OIT is related to the level of antioxidants in the plastic. The pellets were then formed into tensile strength specimens by injection molding at RISE as well as blown into film at Trioworld. Of the tensile strength specimens, five from each category were tested. This trial shows how each material responds when exposed to a tensile force. On the blown film, several trials were performed; density, falling dart, and tear strength. Falling dart shows how resistant each film is to being punctured whereas tear strength is a measure of how much force is required to tear the film once a cut is made. These are important properties for film products.

4 Performance

4.1 Environmental system analysis

The environmental system analysis was performed at RISE by their personnel. This analysis was modeled using data from an industry source as well as from the database Ecoinvent 3.8. It was modeled using SimaPro software and the impact assessment method IPCC 2013 GWP 100a V.1.03. The functional unit used was 1 kg of PE granulate. In order to assess how beneficial recycling is compared to the production of virgin material or incineration, some assumptions had to be made. The transport distance to the recycling site was estimated at 400 km in total and the distance to incineration was assumed to be 30 km in total. In the calculations made, 5% of the plastic waste going into the recycling system is assumed to be incinerated. Only one recycling cycle was considered which may not be representative of the entire life cycle of the material. In addition, the use of a Swedish or European electricity mix affects the results. These mixes are not constant but change depending on the available electricity.

4.2 Investigation

The plastic was sampled over two weeks in the construction specialist shop Optimera in Gothenburg by their personnel, see figure 2. The plastic was sorted into four categories depending on their appearance: shrink and stretch film (A), clean film (B), dirty film (C), and thick film (D). B and C appeared to be the same type of film, only the amount of dirt differentiated them. The packaging film was from pallets stored both inside and outside. In order to verify the identity of the plastics as PE, one sample from each of the categories A, B and D was taken from the bulk material before it was sent to the shredder. These were tested with DSC and FT-IR.

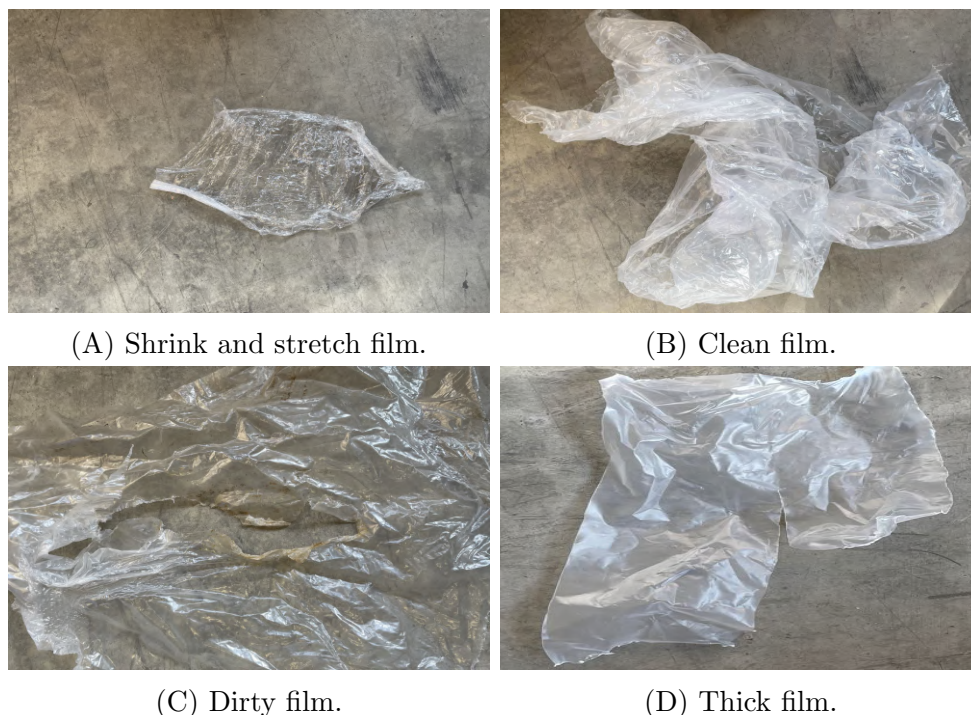


Figure 2: The different film categories. Category C and B are differentiated only by the amount of dirt on the plastic.

4.2.1 FT-IR

In this method a FT-IR machine of brand Bruker and model Tensor 27 was used in conjunction with attenuated total reflectance. The different film samples were placed in the spectrometer and analyzed. The analysis was done at several locations on the specimen to reduce the risk of contaminants affecting the result. The scanning interval used was $4000\text{-}500\text{ cm}^{-1}$.

4.2.2 DSC

The standard method used was ISO 11357 with a Mettler Toledo machine of model DS1 STARe system.

Two tests were taken from each category, in different places on the sample film pieces. These were cut to small pieces and placed in the test vessels so that 5-10 mg of each test

were in separate test vessels.

The test vessels were placed in the DSC-machine. The temperature interval was 25-200 °C and the method was in three steps, meaning the sample was first heated to 200 °C, then cooled to 25 °C and lastly heated to 200 °C again. The first heating allows the sample to release any initial stress caused by tension, the cooling allows the crystallization temperature to be observed, and lastly the second heating gives an accurate reading of the melting temperature. The temperature changed at a rate of 10 °C/min and the measurements were performed in an inert nitrogen atmosphere.

4.3 Reprocessing

4.3.1 Milling

The different categories of films were milled individually and inserted into a big funnel. In the bottom there was a rotating shaft with knives that both cut and tore the pieces apart. This was done at the RISE facility in Borås by their personnel.

The mill was a prototype from the brand Rapid of model G200-48, although it has previously been modified. With this machine the size of the milled material is smaller than 5 mm. Plastic film is a difficult medium to mill, due to the length of the pieces and the stretchy and tough nature of the material. The length makes it easy for the pieces to wrap around the shaft and the material must therefore be loaded in small sections or very slowly to prevent this.

4.3.2 Compounding, melt filtration and pelletizing

Each category was processed individually. The compounder used in the experiment was of the brand Coperion and the model ZSK 26 K 10.6, the melt filtration attachment was of the brand gneußand of model HSM 45 and the pelletiser was of the brand Scheer and of model SGS 50-E4.

The flakes were poured gently into the funnel that led directly down to the first pair of rotating twin-screws, which rotated at 400 rpm. This was done in small batches due to the fluffy nature of the material. The screws pushed the material forward and down to the next pair of twin screws in the compounder, which rotated at 200 rpm. The polymer was melted, mixed and pushed forward towards the melt filtration attachment. The temperature in the compounder was set to 200 °C.

The end of the compounder was connected to a melt filtration attachment which separated possible debris from the polymer. From this attachment the final recycle was extruded in the form of two long strings. These were then cooled with water and a fan before being cut up into pellets. From all categories a small sample of the extruded material was extracted before pelleting.

The filter was changed when the pressure reached around 120 bar, which was around every five minutes. The size of the filter and the mass flow through the extruder was different for each category.

Category A

There was first an attempt made to use a 125 μm filter and a mass flow of 4 kg/h. The pressure increased rapidly and the settings were changed to 160 μm and 3 kg/h.

Category B

The first settings were 160 μm filter and 3 kg/h flow. There was a pressure drop when category B was introduced to the system. The filter was changed and the problem did not return. The time to reach the desired pressure was too long so the filter size was decreased to 125 μm . The time was still too long and the filter was thereafter changed to 80 μm . The pellets that were filtered with 160 and 125 μm were collected as one batch and 80 μm as one.

Category C

The filter used was 125 μm and at first a mass flow of 3 kg/h. The flow was then changed to 3.5 kg/h, as the extruded strings were too thin to cut in the pelletizer.

Category D

The first settings were a 125 μm filter and 3 kg/h flow. The time to reach the desired pressure was too long and the flow was therefore changed to 3.5 kg/h. The change did not alter the pressure development considerably and the filter was then changed to 80 μm . The pellets that were filtered with 125 μm were collected as one batch and 80 μm as one.

4.3.3 Preparing the pellets

The pellets were dried in an oven for four hours at 65 °C. The material was stirred in the vessel after 1 hour and as well as after 3 hours. The larger pieces or strings of pellets still attached were removed from the material.

4.3.4 Injection molding

Injection molding was not done on all batches due to a lack of pellets.

When making the tensile strength specimens an Engel ES200&110 HL/V machine was used. The mold temperature was 30 °C and the cooling time was 20 seconds. The screw in the machine was 30 mm in diameter and was heated to 190 °C at the back and to 220 °C in the front. The first samples from each category were discarded until the system

reached equilibrium and all the old material had been removed from the system. The lock pressure was set to 800 bar except for C125 where it was increased to 900 bar. The other pressures in the process were the lowest functional pressures for each batch, see table 2 .

Table 2: Category specific pressures for injection molding.

	Injection pressure, hydraulic [bar]	Injection pressure, specific [bar]
A125/160	96	1059
B80	92	1015
C125	92	1015
D80	113	1246

4.3.5 Film blowing

Film blowing was not done on all batches due to a lack of pellets.

Film was blown at Trioworld in Smålandsstenar using machines from Labtech. The compounding section was of the model LF-250 and the extruder LE 20-30/C. The pellets were inserted into a funnel which led them down to the heating section of the machine. The first part where the pellets entered was 170 °C and the rest was kept at 180 °C. The melted material was pushed upward to the nozzle where air was blown into the material, producing a hollow cylinder. The cylinder was led to and pressed in between two rollers above that directed it forward and to a new pair of rollers with a speed of 4.3 rpm. The film was rolled up on a roller with the speed of 4.7 rpm.

The process went smoothly with the exception of D80. When air was blown into the material a cylinder with multiple bulges was created, although this later stabilized and film was able to be collected.

4.4 Characterization of the recycled material

The following tests were performed on the recycled plastic in order to evaluate what products it could be used to manufacture.

4.4.1 FT-IR and DSC

The same method was used as during the investigation, see section 4.2.1 and 4.2.2, however individual pellets were used instead of film.

4.4.2 MFI

The standard method used was ISO 1133 with a CEAST machine of model 7024.0000.

The machine was preheated to 190 °C and the pellets were then packed into the barrel and compressed manually to help the polymer melt evenly as well as to prevent air bubbles. The pellets were then allowed to melt compressed only by the test piston. After 2 minutes a load of 5 kg was applied. When the test piston was 50 mm above the top of the barrel, the previously extruded polymer was cut and the test began. After 10 or 30 seconds, depending on the batch, the extruded polymer was cut and weighed. When the test piston reached 20 mm above the barrel the test was stopped. The MFI was then calculated in g/10 min.

4.4.3 OIT

The standard method used was ISO 11357-6 with a Mettler Toledo machine of model DS1 STARe system.

Two tests were taken from each batch. The pellets were placed in the test vessels so that between 1-2 mg of each test were in separate test vessels. If needed the pellets were cut into smaller pieces to fit the weight requirement.

The test vessels were then placed in the DSC-machine. The temperature interval was 25-200 °C in an inert nitrogen atmosphere. When 200 °C was reached, the atmosphere was automatically changed to oxygen. The time was measured until an initiation of an exothermic reaction was detected.

4.4.4 Tensile strength test

The standard method used was ISO 527 with a MTS machine of the brand 20-M from 2014.

Five tensile strength specimens were tested from each batch. The specimens were pulled apart at 1 mm/min until the elasticity modulus (e-modulus) was measured and thereafter automatically changed to 50 mm/min. A separate strain measuring device of brand MTS was placed on the specimen and manually removed once the strain reached 50%. Thereafter the strain was measured solely on the length between the two holders, which generated data with lower accuracy. The load cell was of the magnitude 1 kN.

4.4.5 Density and thickness

Density measurements on the film were performed at Trioworld by their personnel and the standard method used was SS-EN ISO 1183-1. The thickness was calculated from the density and weight of a specific size of a piece of film.

4.4.6 Falling dart

The machine used for the tests was from the brand Davenport Ltd of model 50. The film was cut into a long strip, which was then placed over a vacuum and clamped down. The dart was then placed in the dart holder and subsequently released. If the film did not fail, i.e. the dart did not penetrate the film, weight was added to the dart and the experiment was tried again. If the film did fail, the weight of the dart was decreased and the experiment tried again. This practice was continued until the highest weight where the film did not fail was found.

4.4.7 Tear strength

Eight pieces were punched out of the film for each category in both the machine direction (MD), the direction the film was blown, and cross direction (CD), perpendicular to the direction the film was blown. The pieces were then individually clamped down in the equipment and a slit was cut before it was torn apart. The equipment used was of the brand Lorentzen & Wettre Tensile tester of model 09ED.

5 Results and discussion

After the recycling process the different categories are referred to as A-D in combination with the filter size used for melt filtration for each batch, e.g A125/160.

5.1 Environmental system analysis

PE has a great potential to be recycled and doing so can be beneficial from an environmental standpoint, see appendix B. If the proper systems for collecting and sorting PE are put in place, there is potential to save between 2.6-2.9 kg of CO₂ equivalents for every kg of recycled plastic that is not incinerated. The recycling process uses between 12-28% of the energy compared to manufacturing virgin PE depending on whether a Swedish or European electricity mix is used.

5.2 Investigation

5.2.1 Manual inspection

The film samples are visually quite different. Sample A is transparent, stretchy. Sample B is transparent and not as stretchy as sample A. Sample D is milky white in colour, stiffer and is not stretchy. A is the thinnest film, B in the middle and D is considerably thicker, see figure 2 section 4.2.

5.2.2 FT-IR of film samples

The film samples are in general very similar, and their spectra confirm this, see figure 3. The clear similarities between the spectra and their references show that all samples are PE. The matches to the references for A, B and D are 930, 922 and 952 out of 1000, respectively, which is a measure of accuracy. For the spectra of the samples in comparison with their references, see appendix C.

There are, however, a few significant differences. Sample B has an additional peak at around 1100 cm^{-1} which most likely is an additive. Furthermore, the peak at around 720 cm^{-1} is different for each sample. These peaks are related to the carbon—carbon bonds of PE and a double peak indicates a crystalline PE. If there is a single peak, the type of PE is more amorphous. A has a single peak, whereas B has a slight double peak indicating a smaller degree of crystallinity compared to D which has a double peak indicating a substantial amount of crystallinity. This is consistent with the manual inspections of the films, whereas D is whiter in colour. The samples were tested at different locations and the same results were found.

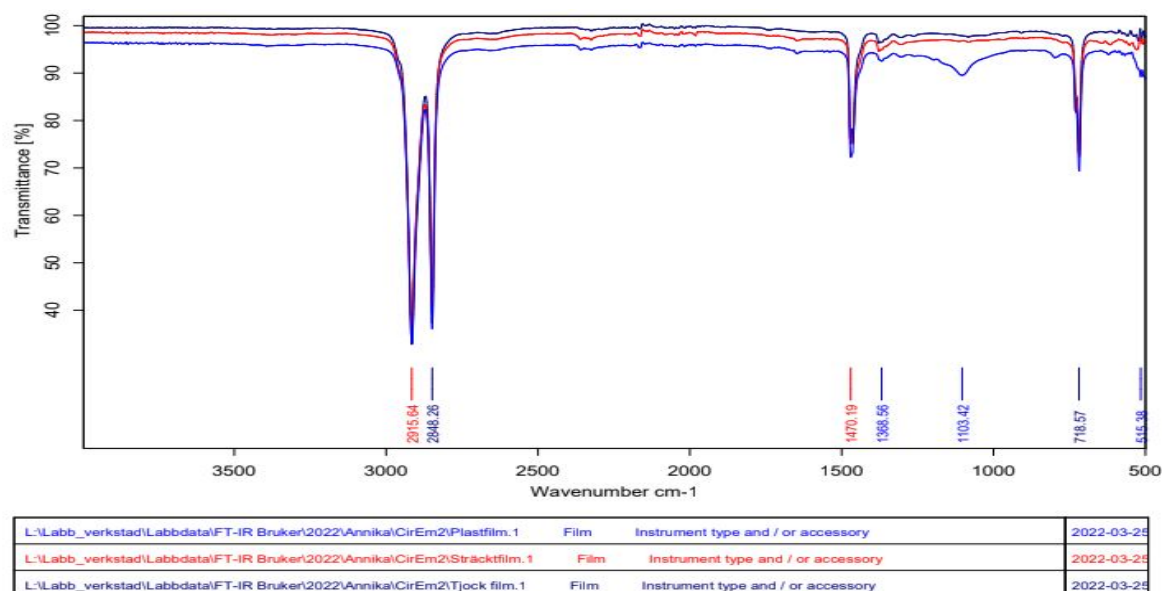


Figure 3: The FT-IR spectra of the measured transmittance at different wavenumbers. Sample A is illustrated in red in the middle, B in bright blue at the bottom and D in dark blue at the top.

5.2.3 DSC of film samples

The main peaks for all specimens are different, showing differing melting temperatures for the films, see figure 4. In the second heating process, for sample A, the melting temperature for the crystalline part is $121\text{ }^{\circ}\text{C}$, which is typical of LLDPE. For B, the melting temperature is $112\text{ }^{\circ}\text{C}$ which is more common in LDPE. However, the appearance of the curves, with a small peak before the main peak, indicates that for A, there is a small amount of LDPE mixed in, and vice versa for B. The melting temperature for D at $130\text{ }^{\circ}\text{C}$ is common in HDPE. This agrees well with the distinct double peak seen in the first melting process, and the large area of the peak in the second melting process, which are indicative of a more crystalline polymer. In addition, during the first heating

process, for samples A and B, there is a small depression around 45 °C, this could be due to stress in the material. It is not likely an additive as it would then be seen in both heating processes. For the individual thermograms of the two specimens of each sample, see appendix D.

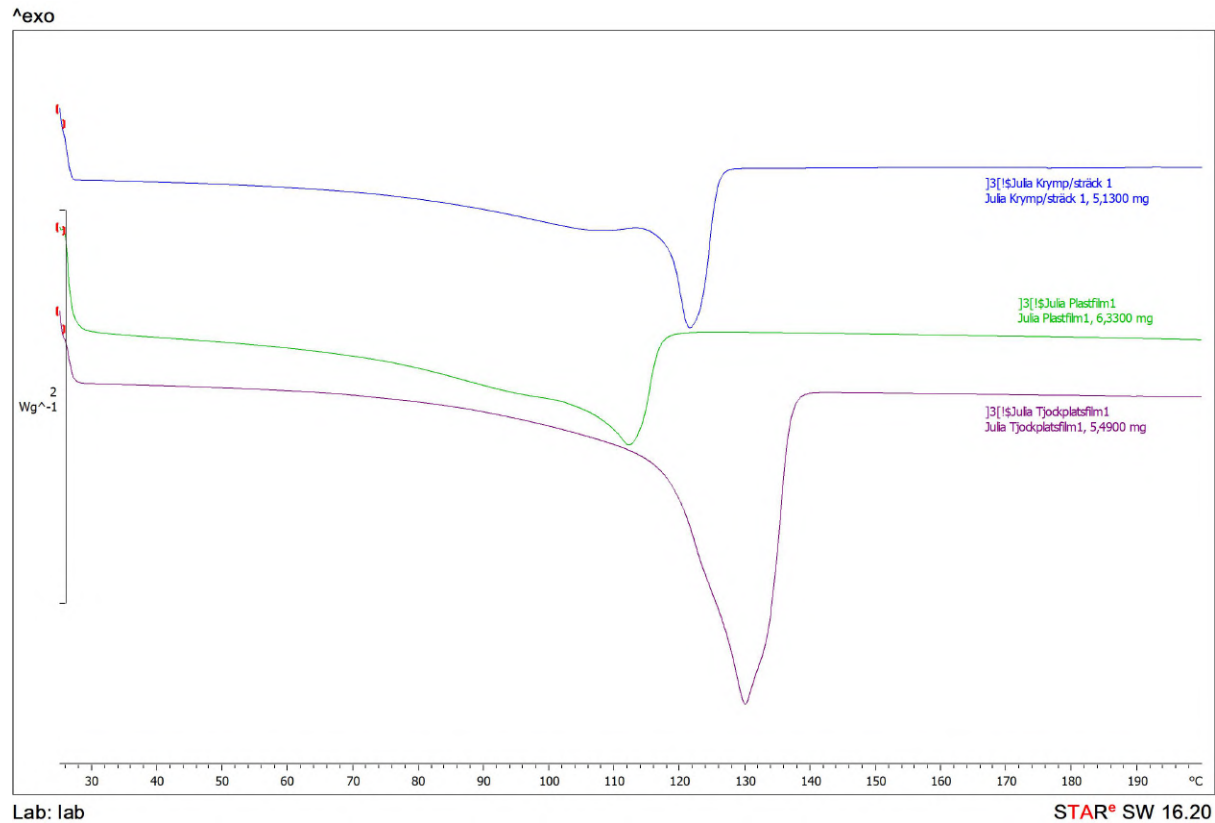


Figure 4: DSC thermogram of the second heating process of the first specimen of each sample. Sample A is in blue at the top, B is in green in the middle, and D in purple at the bottom.

5.3 Milling

5.3.1 Manual Inspection

The categories post milling are still visibly different, see figure 5. The flakes of category A are more irregular in shape than the others whereas category C clearly has more dirt in it than category B. Category D retains its stiffness and is more sharp to the touch.

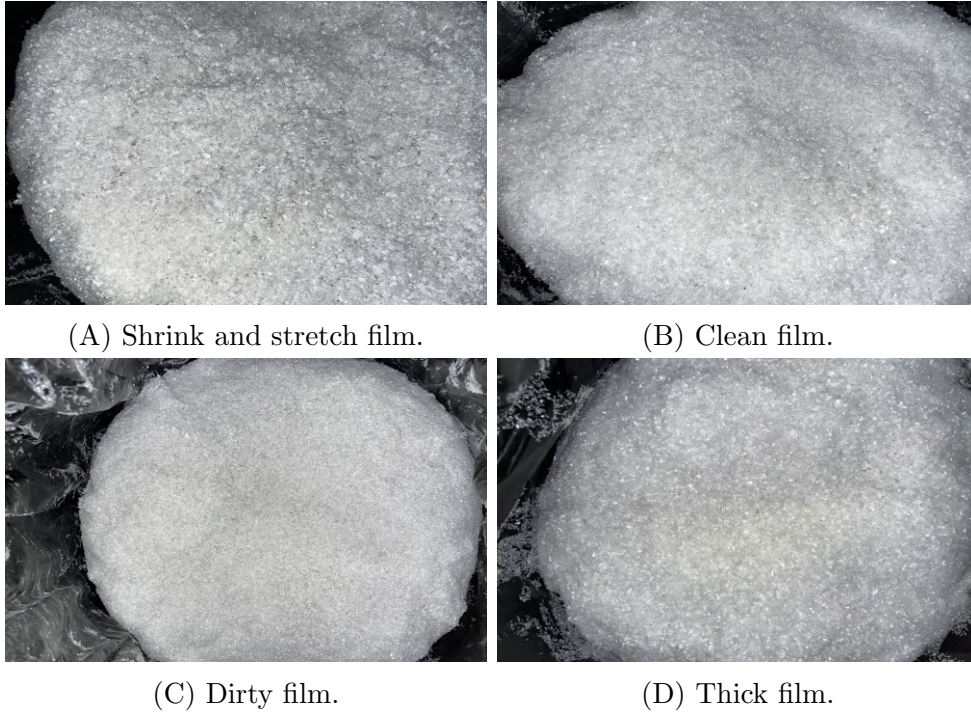


Figure 5: The flakes of the milled films. A is more irregular in shape and D is stiffer than B and C.

5.4 Reprocessing

5.4.1 Compounding and melt filtration

The overall results of the compounding agrees well with the theoretical background and the results from the investigation tests. There is a distinct variety in colour between the samples of extruded material, where both batches of D are the whitest, indicating a larger amount of crystallinity and C125 is the darkest due to the large amount of contaminants. A125/160 is shiny and quite flexible, surpassed only in flexibility by C125. This is most likely because the large amount of contaminants inhibit the polymer chains from creating as many intermolecular bonds. Sample D of the extruded material, due to its crystallinity is the stiffest, with B between categories D and A.

All categories emit a smell of burnt cellulose and adhesive, although this is most prominent in category A. This is most likely due to a high amount of labels, which corresponds well with the previous knowledge about the advantages of using labels on shrink and stretch film. This is further substantiated by the fact that category A could not be filtered with a finer filter than 160 μm . The categories filtered with an 80 μm filter have little to no visible impurities, whereas the 125 μm and 160 μm filters resulted in visible impurities in all categories.

A likely source of the sudden pressure drop in the beginning of compounding category B is air in the system from the material change, although this did not occur for any other categories.

5.5 Characterization of the recycled material

5.5.1 FT-IR of the recycled material

The spectra of the pellets are similar, although there are some differences. One of them is the amount of noise in between the large peaks around 720 cm^{-1} and 1200 cm^{-1} , see figure 6. Noise can occur because of various things, but a likely reason is contaminants in the material. The contaminants are likely inorganic compounds as they are commonly found in this region. A125/160 has the smallest amount of noise, which is notable since the batch was filtered with the coarsest filter. C125 has the most amount of noise, which corresponds well with expectations since it was the most contaminated.

Another significant difference is that C125, D80 and D125 have an additional peak just to the left of the big peak around 3000 cm^{-1} that does not appear in the other batches or in the references. For the spectra of the samples in comparison with their references, see appendix E. It is not likely cellulose from the labels since it does not appear in this region. The accuracy score is high for all the samples and it varies between 909-986 of 1000, where D80 has the lowest score and A125/160 the highest.

The peak at around 720 cm^{-1} indicates the degree of crystallinity. Both batches of D have a proper double peak, which aligns well with the manual inspection, more specifically with the opacity and the stiffness of the material, both of which are indicative of crystallinity. For both batches of B as well as for A125/160, there is a slight double peak, although it is more pronounced in A125/160. However, for C125 there is a single peak, a reason for that could be that the large amount of contaminants obstructs the intermolecular

bonds between the polymer chains. This has shifted from the investigation FT-IR where A125/160 had a single peak and B had a slight double peak.

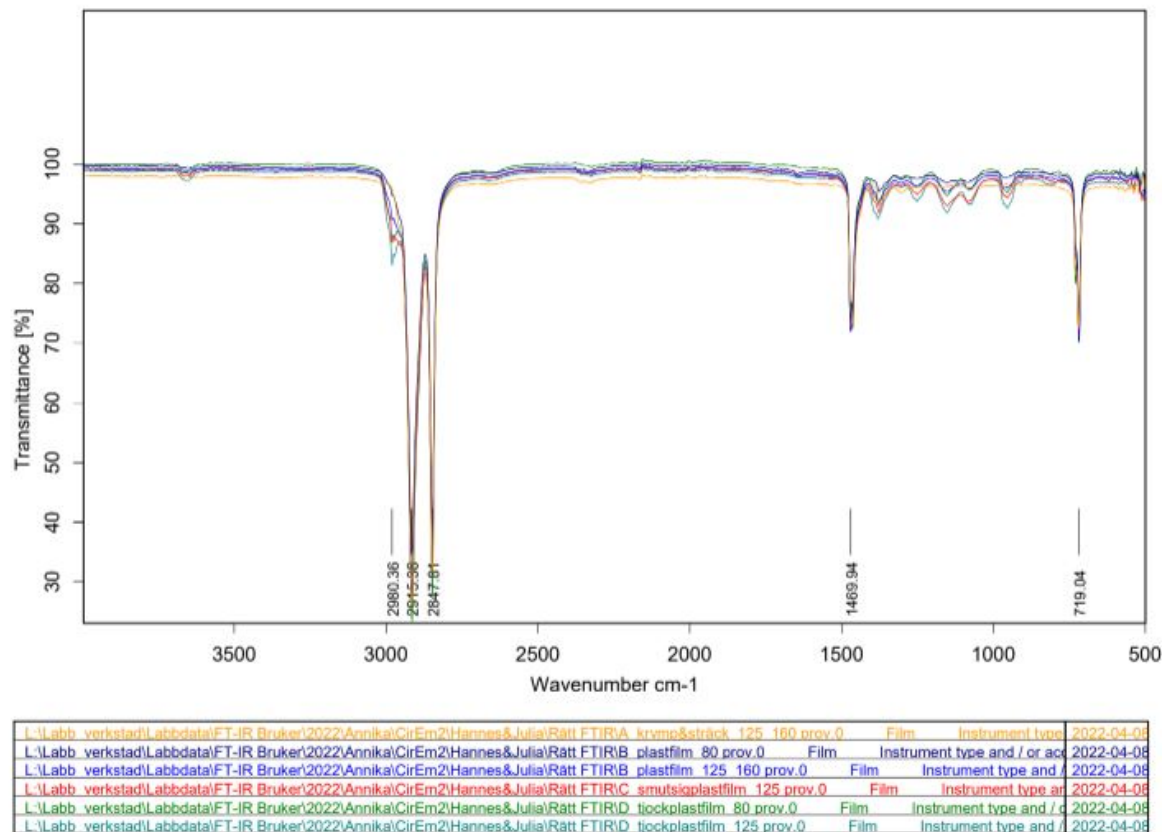


Figure 6: The FT-IR spectra of the measured transmittance at different wavenumbers. Sample A125/160 is illustrated in Orange, B80 in black, B125/160 in blue, C125 in red, D80 in green and D125 in turquoise.

5.5.2 DSC of the recycled material

The thermograms of the pellets with the main peaks of B80, B125/160, C125 show similar melting temperatures of around 110 °C in the second melting process, which is common in LDPE, see figure 7. For A125/160 the melting temperature of 120 °C is representative of LLDPE. For both batches of D, the melting temperature of 130 °C in the second melting process indicates that it is HDPE. Although there is, in the first heating process, only a double peak in one of the specimens, which was not the case before recycling, it is still likely HDPE. For the thermograms of the individual samples, see appendix F. In both specimens for A125/160, B80, B125/160 and C125 there is a slight depression around 45 °C in the first heating process. This was also there before recycling and could be due to stress in the material.

As before the recycling, the appearance of the curves, with a small peak before the main peak, indicate that for A125/160, there is a small amount of LDPE mixed in, and vice versa for both batches of B and C125. In addition, the appearance of the curves for B80 and B125/160 is almost identical. The same can be said for D80 and D125.

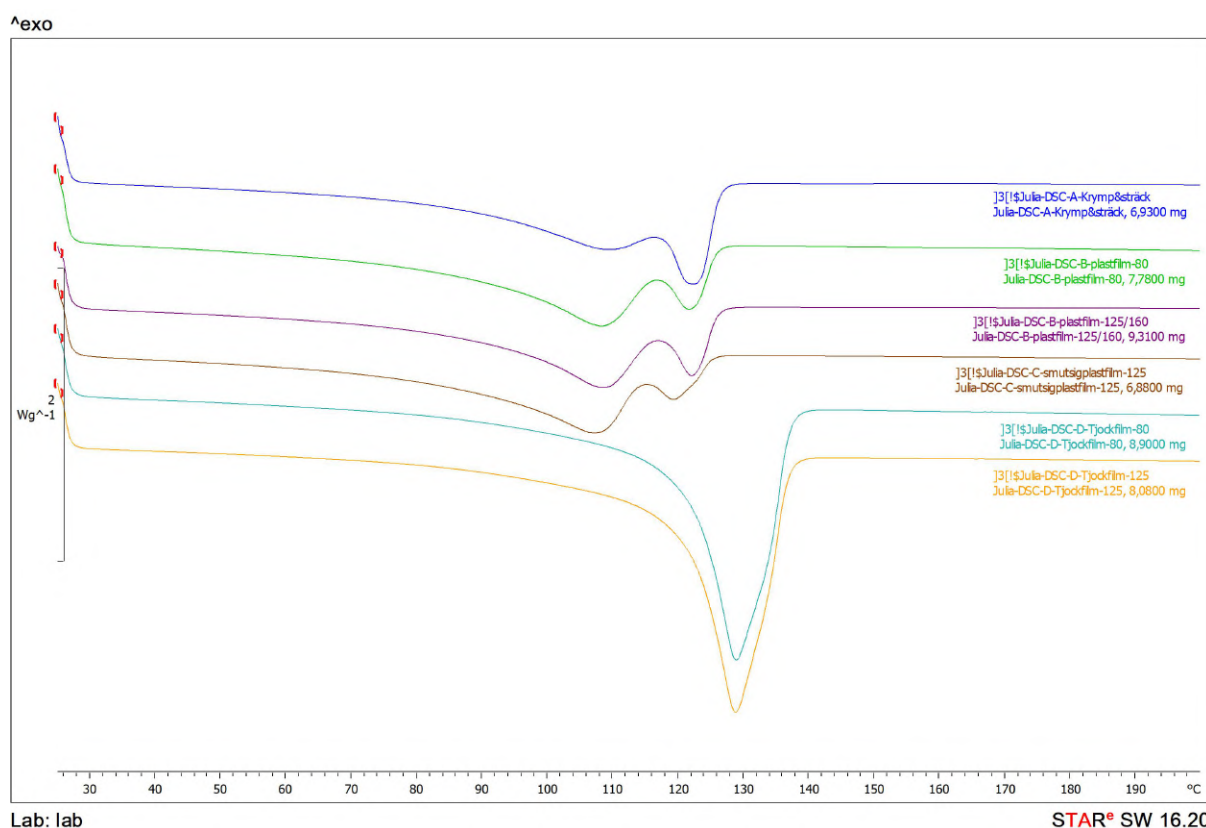


Figure 7: DSC thermogram of the second heating process of the first specimen of each sample. In order from top to bottom, A125/160 is in blue, B80 in green, B125/160 in purple, C125 in brown, D80 in turquoise, and D125 in orange.

5.5.3 MFI of the recycled material

A higher value of MFI means that the melted pellets have a lower viscosity at a certain temperature, which is an important property that influences the processing of the material.

A low value is advantageous when blowing film as the bladder can otherwise become unstable. A125/160 has the highest value at 7.26 g/10 min with a 5 kg weight at 190 °C, see figure 8, which means it is unsuitable to blowing film in its current state and virgin material should be mixed in to stabilize this property [4]. However, the desired value is higher for extruded film at 2-3 g/10 min with a 2.16 kg weight at 190 °C which includes A125/160 which had an MFI of 2.7 g/10 min when re-analyzed with that weight. Thus, making the batch suitable for extruding film.

On the other hand, an MFI below 0.7 g/10 min with a 2.16 kg weight is also undesirable for film blowing. This means that both batches of D with an MFI of around 0.5 g/10 min with a 5 kg weight are unsuitable, unless mixed with virgin material. In the middle are both batches of B and C125 at 1.93-2.57 g/10 min with a 5 kg weight, which most likely corresponds to a MFI of 0.7 or slightly above with a 2.16 kg weight and are therefore classified as suitable. The fact that the batches are quite similar is an indication that the extra debris in C does not affect the MFI considerably although it has been raised slightly.

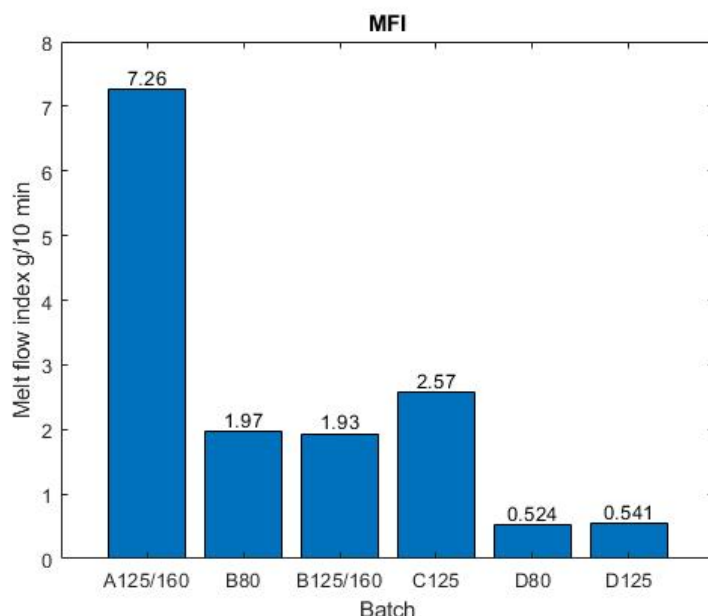


Figure 8: The MFI of the tested batches measured at 190 °C and 5 kg.

5.5.4 OIT of the recycled material

The analysis of the pellets revealed the longest time for A125/160 and the shortest for C125, see figure 9 and figure 10. Protective packaging commonly has a OIT of about 5 min and a time below 3 min is considered low [11]. This means that all batches other than C125 are able to be recycled again without the need for additional antioxidants. The OIT varied distinctly between B80 and C125, with B125/160 in the middle, which is surprising since the plastics are considered the same other than the extra contaminants. This is remarkable due the fact that OIT is used as a measure of the relative amount of antioxidants in the material and is not a parameter that should be affected by contaminants unless they are some kind of metal, which is not probable in this case. A reason behind this could be that the different batches of B and C125 are not

in fact the same type of plastic, containing differing concentrations of antioxidants. One possible explanation for this divergens is that a type of plastic with a different amount of antioxidants is used for pallets stored outside, since C125 was the dirtiest fraction. Another explanation could be a difference in the retention time in the compounder between both batches of B and C125. However, this is unlikely as the mass flow for all three categories was either the same or higher for C125. For the individual OIT curves of the two specimens see appendix G.

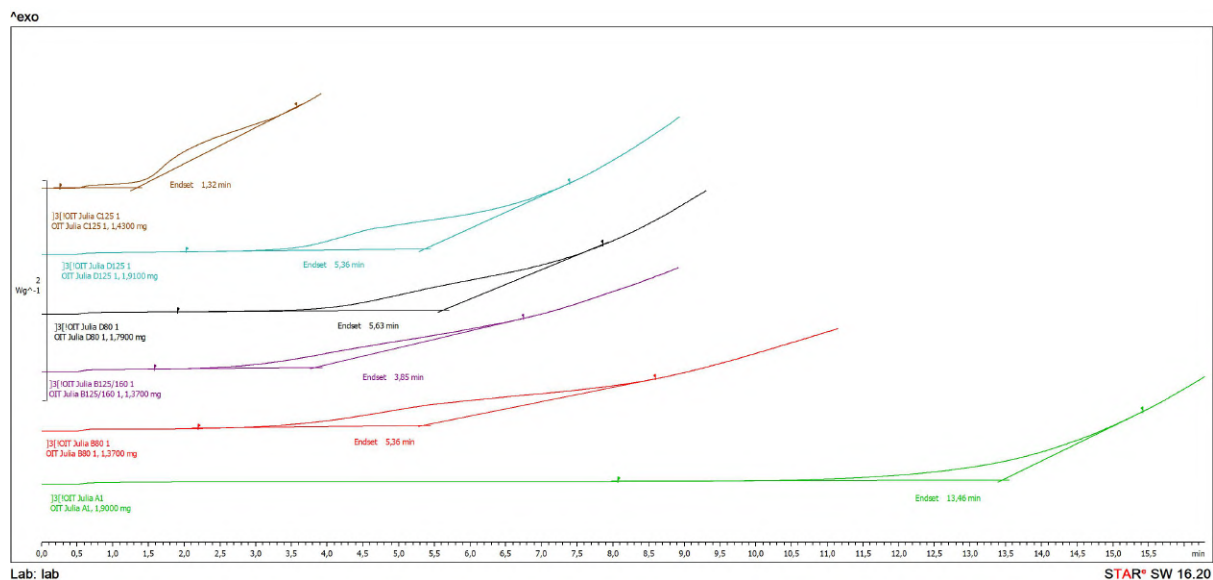


Figure 9: The OIT curves for the first specimen of all samples. The specimens were rapidly heated from 25°C to 200 °C in an inert nitrogen atmosphere, at 200 °C the atmosphere was switched to oxygen. The endset time is when an exothermic reaction first occurred. In order from top to bottom; C125 in brown, D125 in turquoise, D80 in black, B125/160 in purple, B80 in red, and A125/160 in green.

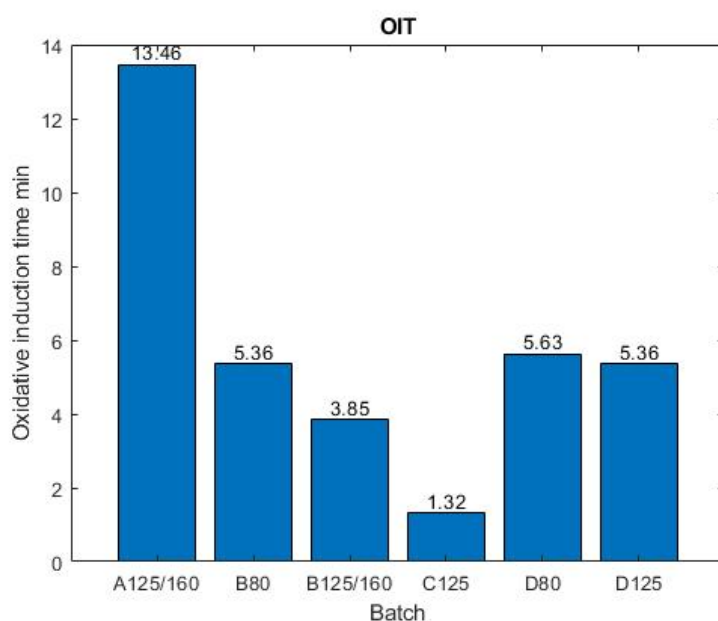


Figure 10: The OIT results for the tested batches.

5.5.5 Tensile strength test of the recycled material

Tensile strength testing on injection molded samples is not the most relevant analysis for a plastic intended for use in films. However, the diverse mechanical properties of the categories are confirmed by the analysis, see figure 11. The analysis shows that all tested batches besides D80 are stretchy and tough, thus possibly making them suitable for film blowing or extrusion of film. In addition, only batches A125/160 and D80 presented a value for strain and stress at yield, showing that batches B80 and C125 are extremely tough, see table 3.

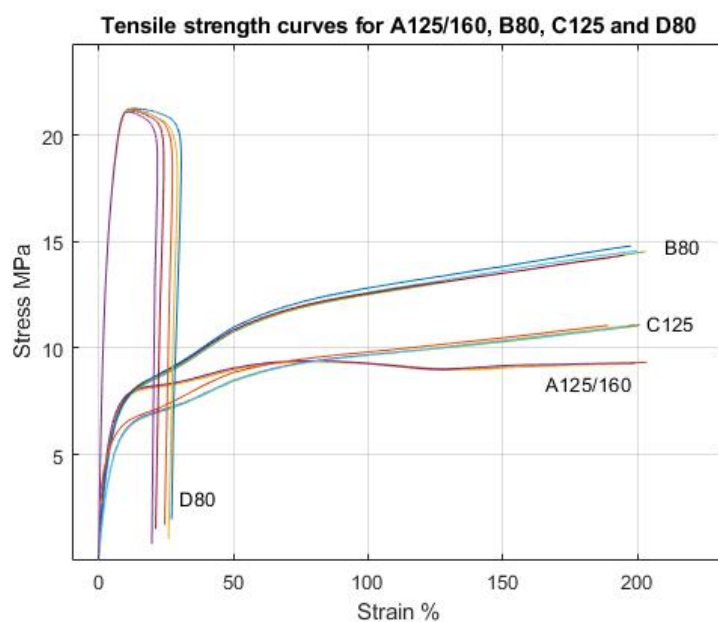


Figure 11: The stress-strain curves for the injection molded samples.

Table 3: Mean tensile strength results.

	A125/160	B80	C125	D80
E-modulus [MPa]	172	158	109	610
Stress at yeild [MPa]	9.44	-	-	21.176
Stress at break [MPa]	-	-	-	12.860
Strain at yeild [%]	74.277	-	-	11.657
Strain at break [%]	-	-	-	25.537

The stress-strain curves for batch A125/160 all follow the same trend. For the individual stress-strain curves of the batches, see appendix H. The low value of stress at yield shows that this material is soft and easily deformed. Batches B80 and C125 are similar and all follow the same trend, although the curves for C125 are lower on the stress-axis, showing that it is more easily deformed, see figure 11. This is further supported by the lower e-modulus, see figure 12. The curves for D80 all generally follow the same trend. Although this was the only sample in which the specimens broke, the strain at break varied from 20.8% to 29.6% between the specimens. This is most likely due to the

crystalline nature of the material compared to the other categories, making the material stiffer than the others. D80 also has a much higher e-modulus than the others, which can also be seen in the steep slope of the initial curve, see figure 11 and figure 12.

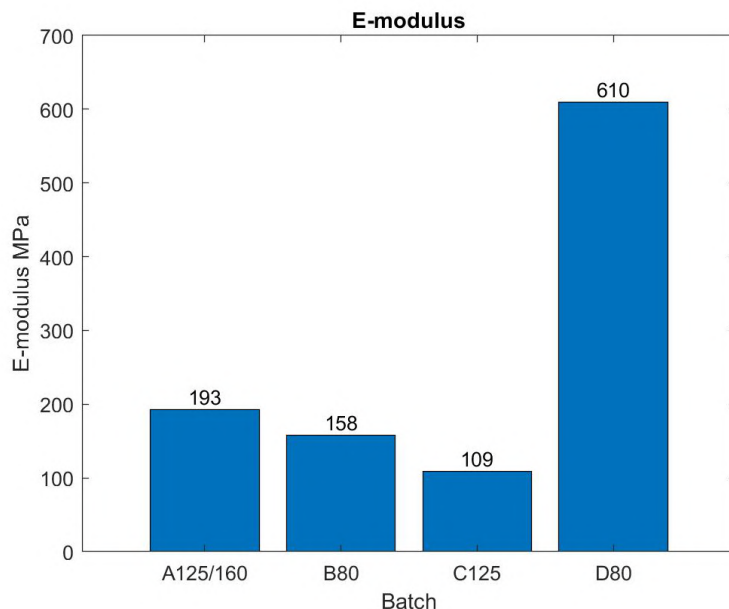


Figure 12: The e-modulus for the tested materials, measured on injection molded test bars.

5.5.6 Manual film inspection

Film was successfully blown from all of the tested batches in a laboratory environment, however this might not be the case on a production scale. The blown films have differing appearances, however they are generally clean and could possibly be used in both transparent and colored products.

A125/160 is slightly sticky and rough to the touch, which is to be expected given that part of the original purpose of the film was to be slightly adhesive. The roughness is most likely due to different melting temperatures in the material, since different materials have been compounded together. The roughness contributes to the muddy visual texture. This combined with a beige hue makes the film more translucent than transparent. The contaminants that went through the filter in the compounding can be seen in medium sized black dots interspersed through the film. The medium sized dots are mostly not incorporated into the material, and due to their size these are most likely the remains of labels. The impurities make the film unsuitable for stretch film, due to the high risk of them becoming breaking points in the material when stretched. However, if the film is washed before recycling this problem might be resolved. As seen in the RISE trial at Reviva Plastics, where the plastic was washed, this alone did not solve the problem, see appendix A. Indicating that both washing and further sorting, as was done in this project, is necessary. On the other hand, A125/160 is suitable for products that are thicker and not intended to be stretched to that extent like covering film, hoods, and garbage bags.

As for B80, there is no sticky feel and although the surface is rough, it is smoother than A125/160. However, there are no medium dots in B80 suggesting that the smaller filter size has worked well. B125/160 is very similar to B80, with the difference that the medium sized dots are there as well as even larger brown dots. Both batches are suitable for covering films, garbage bags, and for hoods as well. The larger dots are most likely pieces of label that have passed through the filter. Despite also having a beige hue, both batches of B are more transparent than A. The brown hues could be due to the labels being burnt during the recycling process. The extra contaminants in C125 compared to B125/160 have decreased the transparency of the film whilst also giving it a distinctly more beige hue, making it more suitable for coloured products. Other than this C125 is comparable to B125/160.

D80 differs the most from all the other films, mainly because the film is stiffer and crackles more when moved. The reason behind the deviant behavior of the blown cylinder is likely due to a big difference in melting temperatures between D80 and the previous material left in the machine, which was LDPE. Since the materials got mixed together when changing between fractions thus generating a heterogeneous material that got blown. The stiffness and crackling sound of the film is an indication that D80 consists of HDPE, which has a different melting temperature than LDPE. D80 also has a whiter colour than the other categories, most likely due to a combination of there being significantly less labels in D and a higher degree of crystallinity. In terms of impurities is the film comparable to B80 which indicates that the melt filtration worked well with this batch also. This in combination with the stiffness of the material make it suitable for hoods and covering films.

5.5.7 Density and thickness of the blown film

The density of the blown films of A125/160 and C125 do not fit into any interval of LDPE, LLDPE or HDPE, see table 4 and table 1 in section 2.1 and these values are lower than desired [4]. A reason for that could be that the material consists of a different polymer, but this is not likely since multiple other tests show that it is PE. The more probable cause behind the low density is the presence of contaminants that interfere and inhibit the polymers ability to pack themselves closely as well as the composition of the PE. This interpretation is supported by the visual inspection of category A before recycling where a large amount of labels were observed as well as the dark colour of the compounded batch C125. Both of these categories could not be filtered any finer than 125 μm . With this in mind, it is most likely that A125/160 and C125 are LDPE or LLDPE. To solve the issue it would be beneficial to wash the batches before recycling. The theory that the impurities lowers the density is further supported by the fact that both batches of B fit into the density interval of LDPE and LLDPE, as B and C are considered the same type of material besides the concentration of contaminants. The density of D80, however, aligns better with HDPE, this is also supported by the results from other tests.

The thickness of the films are strongly dependent on the manufacturing process and the desired product. Blown films are thinner than extruded film. Covering films and hoods are a thicker type of film at around 50 μm , garbage bags come in a wide variety of thicknesses and designs. Shrink and stretch film is a thinner type of film, its thickness depends on the application, an example is that they can be 17 μm .

Table 4: The densities and thicknesses of the films.

Specimen	Thickness [μm]	Density [g/cm^3]
A125/160	32	0.885
B80	29	0.921
B125/160	30	0.922
C125	30	0.886
D80	27	0.938

5.5.8 Falling dart of the blown film

The minimum values for shrink and stretch film are 200 g and for garbage bags 150, which qualifies all the batches except A125/160 and D80 for these applications, as B80 is within the margin of error for this type of analysis [4]. The required value for covering films and hoods are however, lower thus making all the batches suitable for those purposes. This means that achieving true circularity for A125/160, to become a new shrink and stretch film, is not possible in this aspect, unless mixed with virgin material. This is further supported by the fact that the value was too low even though the film was thicker than shrink and stretch film products. The film made of batch C125 had a considerably higher resistance to puncturing with a value of 715 g compared to the others, which is advantageous for all films, see figure 13. It is remarkable that the value for C125 is considerably higher than both batches of B, since it is considered the same as B except for the extra contaminants, especially as they were equal in thickness, 29-30 μm . The lowest value was generated by D80, which aligns well with the stiffness observed in the manual inspection of the film, as well as the fact that hoods may have been the original

purpose for the film [9]. The value may have been higher and more comparable if the film was not the thinnest of the batches at $27\text{ }\mu\text{m}$. However, further trials would be necessary to establish this. Another solution, to widen the areas of application, is to add virgin material to increase the value.

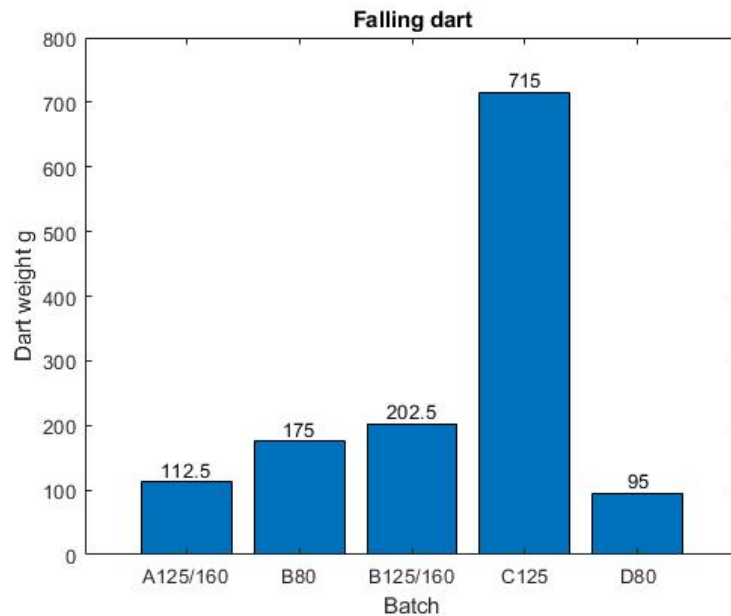


Figure 13: The falling dart results for the tested batches. The dart weight shows the maximum weight that does not penetrate the film.

5.5.9 Tear strength of the blown film

Tear strength is a property highly dependent on the manufacturing process, specifically the size of the bladder. This means that the results for all batches may be very different on a production scale. All the CD values are higher than the MD values for each batch of film, which is to be expected since the polymer chains are aligned in the machine direction during the manufacturing process, see figure 14. It is desirable that the difference between CD and MD is small, since it means a more durable material, as is the case with A125/160. However, all the batches qualify as suitable for covering films and hoods, since the property is not the most important for these products. On the other hand the minimum MD value for garbage bags is 1500 which qualifies A125/160, B80 and C125 as suitable. For 17 μm thick shrink and stretch film, the minimum MD value is 1100 and CD 6000, making no batch suitable for this purpose.

The results for C125 were remarkably high for both MD and CD. B80 and B125/160 had comparable results. The main difference being that whilst B80 had a much higher MD value, for CD, B125/160 had a slight advantage. A125 was higher than both batches of B in both directions, which was expected due to it being tougher originally. D80 had the largest difference between the MD and CD values, where its MD was significantly lower than the other categories. This could be due to the polymer chains being aligned during the film blowing process to a greater degree than for the other categories.

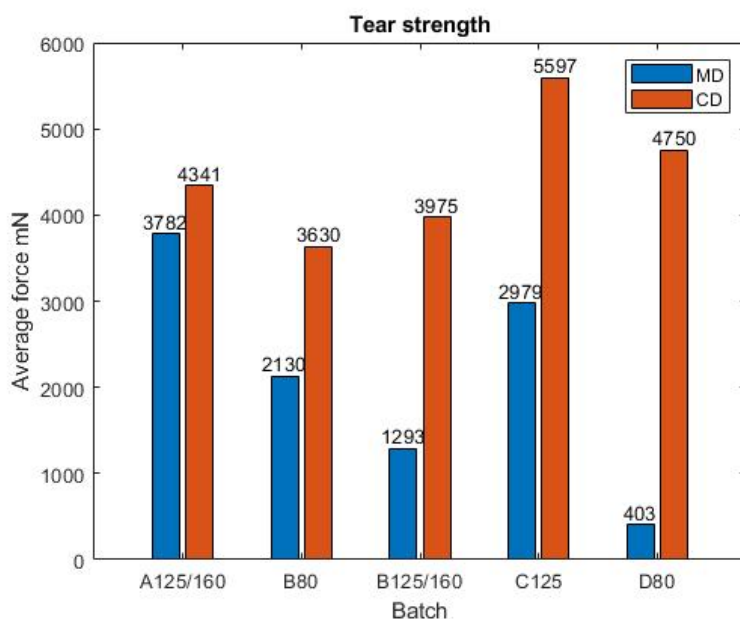


Figure 14: The tear strength results for the tested batches. The average force required to tear the specimen apart is presented. The left hand bars are MD, which is the machine direction, the direction the film was blown. CD, meaning cross direction, perpendicular to the direction the film was blown, is on the right hand side.

5.6 Suitability for new products

All the batches are able to be made into new film products for use in the construction industry. However, to assess the suitability of the different recycled batches for different products, information about the standards of the products are required. This is not available data and therefore the suitability analysis will be in terms of the data that is present, the standards of garbage bags produced by Trioworld, see appendix A. All films that meet these requirements are also able to be made into covering film as well as into hoods, due to the fact that these are considerably thicker at around 50 μm and are not meant to be stretched. One reservation for hoods is that they need to be transparent enough so that barcodes can be scanned through them at the specified thickness.

A125/160 is suitable for film extruded products, if washed, as covering films and hoods [4]. The wash is necessary to increase the density by removing impurities. To widen the areas of application further, virgin material should be mixed in, to make the MFI value suitable for film blowing. In order to achieve true circularity, both washing and mixing with virgin material is required to produce shrink and stretch film .

Both batches of B meet the requirements for covering films, hoods and garbage bags, despite the impurities found in B125/160 [4]. The darker colour of C125 means that it is mostly unsuitable for all applications with demands on aesthetics, unless it is washed. Doing so will also increase the density which is another requirement. In addition, C125 would need extra antioxidants before any additional recycling.

Batches D80 and D125 have very similar properties, and thus their films would most likely behave similarly. They are able to be made into covering film and hoods, if mixed with virgin material in order to increase their MFI. The main limitation, in terms of making garbage bags, is that the tear strength in MD is too low but this, as well, can be altered with virgin material.

6 Conclusions

The different batches recycled in this project can all be used to produce new film products for use in the construction industry. Specifically, they can be made into covering film, hoods and garbage bags. However, only category B can be used in its current state, the others need to be washed or mixed with virgin material in order to stabilize some property. In addition, if both washed before recycling and mixed with virgin material the possibility to produce different products increases drastically. True circularity may thus be achieved, saving large amounts of CO₂ equivalents from being released into the atmosphere.

7 Suggestions for improvements in further studies

The biggest improvements in this project can be made in making the different batches more comparable. In this project the different batches were filtered with different filter sizes, the finest possible filter was used for each category. To improve the study the same size filter should be used for all categories as well as the finest possible for each batch, to make the results more comparable and to provide information about how the filter size affects the material. The current method introduces more variables into the project that may have increased the uncertainty of the result.

Prior to recycling, samples were taken of each category to perform tests upon. The assumption was that these were representative of the entire category. It may be beneficial to take more samples to identify possible differences within the categories. In addition, other tests could be performed prior to recycling, for example OIT. This could present more interesting comparisons of pre and post recycling and increase the understanding of the effects of the recycling process.

Another improvement that could be made is to use the same ISO-standard for MFI as in the previous trial in the CirEm2 project, in order to produce more comparable results. To supplement this, standard deviations for all tests should be included. To evaluate the uses of the recycled film further, a transparency test should be performed in order to assess how well a bar code could be scanned through the film.

To further this study, additional trials should be performed where the material is both sorted, washed and mixed with virgin materials to investigate if the suggested measures have the desired effect.

8 Suggestions for furthering recyclability

In the construction industry, PE labels should be used instead of paper. This will reduce the need for washing of the films before recycling as well as the need for melt filtration. Washing is still required however, to remove the adhesive used for the labels and eventual dirt on the film. This will introduce more coloured film to the recycled material, however the gains may be larger than the losses.

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Appendices

- A RISE report: Återvinningsförsök hos Reviva Plastics
14 Oktober, 2021

RI. SE

MATERIAL OCH PRODUKTION
POLYMER, FIBER OCH KOMPOSIT



Återvinningsförsök hos Reviva Plastics
14Oktober, 2021

Annika Boss och Karin Lindqvist

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1 Bakgrund

Försök har genomförts att samla in sorterad emballageplast i bygghandeln och på byggplatser. Målet var att, om möjligt, samla in transparent och färgad plast separat. Totalt samlades ca 12 000 kg plast in under perioden December 2020 - Juni 2021. Plasten balades och transporterades till återvinningsanläggningen Reviva Plastics i Korsberga.

2 Syfte

Syftet var att tvätta, komponentera och pelletera plasten hos Reviva Plastics och att därefter testa renhet och egenskaper på den återvunna plasten från de olika insamlingarna samt utvärdera möjligheterna att använda plasten till nya emballageprodukter hos Trioworld samt i trä/plastkompositprodukter hos PolyPlank.

3 Insamlad plast

Tabell 1. Insamlad plast

Test #	Insamling plast	av	Stad	Transportör	Återvinning	Mängd insamlad [kg]
1	Beijer		Mölnlycke	Renova	Revivaplastics	150
2	Optimera		Marieholm, Göteborg	Ragnsells	Revivaplastics	2 040
3	NCC		Kineum, Göteborg	Ragnsells	Revivaplastics	2 710
4	NCC		Liseberg, Göteborg	Renova	Revivaplastics	2 600
5	JM		Stockholm	Ragnsells	Revivaplastics	460
6	JM		Stockholm	Ragnsells	Revivaplastics	1 340
7	BEWI		Varberg	-	Revivaplastics	2 000
8	PEAB		Platinan, Göteborg	Ragnsells	Revivaplastics	611
9	PEAB		Göteborg	Ragnsells	Revivaplastics	220

Tabell 1 sammanfattar alla insamlade volymer som transporterats till Revivaplastics i Korsberga.

Plast som samlats in av Bewi (Figur 1 och 2), och mellanlagrats i Varberg, var delvis insamlad på byggarbetsplats, men bestod mest av transparent film och innehöll en del förpackningsemballage från vitvaror. Denna fraktion behandlades som "transparent".



Fig 1. Plast insamlad av Bewi, till höger i bilden: emballagefilm från vitvaror



Fig 2. Plast insamlad av Bewi: vissa inslag av färgad film. Mycket kompakterad film, troligen genom balpressning.

Insamlad plast som transporterats från Göteborg (Fig 3 och 4) bestod av 13 balar (5,4 ton) som omhändertagit av Ragnsells samt 4 balar (2,56 ton) som hanterats av Renova. Den var främst insamlad på byggarbetsplatser och innehöll mycket färgad film.



Fig 3. Insamlad plast transporterad från Göteborg innehållande mycket färgad film. Insamling främst på byggarbetsplatser.



Fig 4. Insamlad plast, transporterad från Göteborg.

Plasten som samlats in av JM i Stockholm (fig 5) , bestod mest av transparent film och hanterades därför tillsammans med den transparenta plasten som samlats in av Bewi. Figur 6 visar ett exempel på oönskad plast, med armering som sorterade ut före inmatning till återvinningsanläggningen.



Fig 5. Plast insamlad av JM i Stockholm bestod mest av transparent film.



Fig 6. Oönskad, armerad film, troligen från byggarbetsplats, sorterades ut före inmatning i återvinningsanläggningen.

4 Återvinningsprocessen

Balarna öppnades i en container före inmatning på bandet till riven som sönderdelar plastfilmen (figur 7 och 8). Maskinisten som hanterade plasten före inmatning i anläggningen skakade loss metallband som suttit runt balarna, men avlägsnade också oönskad plast som bundits in i balarna. Exempel på oönskad plast var armerad film, tuber som innehållit lim och silikon, skummad plast samt nät (fig 9 och 10).



Fig 7. Balöppning i container. Gripklo till vänster greppar del av plasten i en bal och skakar loss metall/polyesterband som hållit ihop balen. Maskinisten inspekterar innehåll så att ev. oönskad plast kan avlägsnas.



Fig 8. Film matas in till riv/shredder som storleksreducerar före tvätt.



Fig 9. Oönskad plast som följt med film som samlats in. Tuber som innehållit klister och silikon ger problem i återvinningsprocessen.



Fig 10. Plastnät från byggarbetsplats som inte kan hanteras i återvinningsprocessen för film.

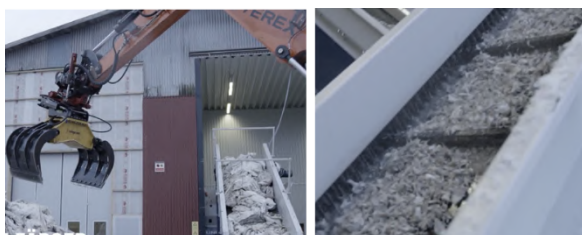


Fig 11. Inmatning till shredder/riv och vidare transport av fragmenterad film till tvättanläggningen.



Fig 12. Blandat transparent och färgad film före inmatning till extrudern.



Fig 13. Pricipskiss med de processteg som ingår i återvinningsanläggningen på Reviva Plastics.

Figur 11 visar inmatning till shredder/riv och vidare transport av fragmenterad film till tvättanläggningen. Tvättanläggningen separerar i första steget bort smuts med högre densitet i en s.k. sink-floattank. Därefter följer friktionstvättar (fig 14) som innebär att plastfragmenten möter en vattenström och sköljs medan transporteras uppåt via en skruv som ger friktion mot ytor i utrustningen. På så sätt separeras alla plastfragment från varandra och får kontakt med vattnet. Mellan två av friktionstvättarna går plasten genom ett mellanliggande "bad". Efter sista sköljning avlägsnas vatten i centrifug och plasten torkas med varmluft innan den går in i extrudern för smältning, blandning (kompounding) och filtrering.

Figur 12 visar den tvättade färgade plastfilmen innan den matas in i extrudern. Plasten såg ut att vara ren, utan föroreningar och etiketter. Extrudern kördes vid 230°C och plasten smältsfilterades genom att pressas genom ett metallfilter på med masköppningar på 120µm. Före filtret sitter en kniv som kontinuerligt avlägsnar föroreningar som ansamlas på filtret. Föroreningarna pressas ut på sidorna av extrudern. Vid något tillfälle under körning av den insamlade plasten, steg trycket i extrudern, vilket tydde på att föroreningar fångats upp av filtret. Det berodde sannolikt på att vissa förpackningar med produktrester av silikon och klister följt med in i processen. Figur 15 visar den vattenkylda pelleteringens vid extruderns mynning. Granulatet torkas och transporteras efter pelletering via en luftström för påfyllnad i oktabiner. Anläggningen hade körts tom på den jordbruksfilm som normalt återvinns men extrudern som processar ca 1 ton plast/timma, innehöll ändå rester av jordbruksfilm och därför startades uttag av prov på granulat efter ca 1 timmas körning med inmatning av filmen från CirEm.



Fig 14. Tvättanläggning med friktionstvätt (markerad med pil) som via en skruv förflyttar plasten upp till nästa bad

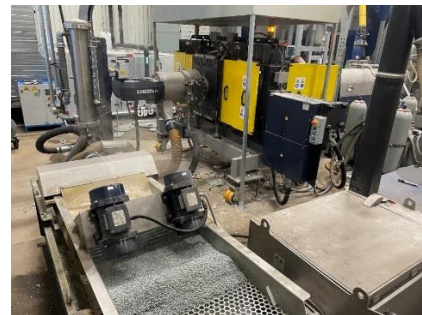


Fig 15. Munstycke och pelleteringsutrustning med vattenkylning i slutet på extrudern.

Återvinningen av CirEms film startade med den större volymen på 8 ton transporterad från Göteborg som innehöll en hel del färgad film. Prov togs ut från denna volym vid några tillfällen för att kunna utvärdera hur homogena egenskaper som erhålls på materialet. Längre fram på dagen beslutades att övergå till återvinning av de balar som uppskattats innehålla mest transparent film (insamlat av Bewi och JM). För att få ut granulat som i så stor utsträckning som möjligt innehöll endast transparent film, togs inget prov ut förrän ca 1 timma efter att det transparenta börjat köras in i extrudern.

Totalt fylldes 8 oktabiner (1 ton granulat/oktabin) varav 2 uppskattades bestå av enbart transparent material. Av dessa skickades 4 oktabiner med granulat från färgad film till Polyplank och resten till Trioworld. Oktabinerna med recyclet från transparent film var märkta.

5 Utvärdering av recycelat

5.1 Filmblåsning på Reviva Plastics



Fig 16. Recyclat av färgad film blev mörkgrå och transparent film ljusgrå.



Fig 17. Filmblåsning av recyclat

Prover av granulat togs ut vid flera tillfällen under dagen. Recyclat från färgad film blev mörkgrå och halvtransparent vid filmblåsning (Fig. 16-19). Dock fungerade blåsningen tillfredställande och defekter i form av prickar uppskattades till 3 enligt Revivas "likare" som används för intern produktkontroll. Figur 20 och 21 visar resultaten vid filmblåsning av de material som bedömts bestå av mest transparent film (med en del färgat tryck). Filmerna var transparenta om än med något grå ton och vissa prickar.



Fig 18. Filmbåsning av granulat med inslag av färgad film, gråaktigt resultat



Fig 19. En del prickar i recyclat som innehöll en del färgat material men filmen uppskattad till 3 enligt Revivas interna likare.

Uttag av granulat gjordes vid två tillfällen då den transparenta filmen kördes. Båda dessa prov gav betydligt mer transparent film vid blåsning, även om det sista provet hade något fler svarta prickar. Sammanfattningsvis var filmbåsningstesterna på emballageplasten godkända enligt Reviva Plastics bedömning, i alla fall för att den återvunna emballageplasten ska kunna användas för tillverkning av plastpåsar. Prickarna i filmen var få vilket betyder att pappersetiketter och andra föroreningar kunnat separeras bort i tvättstegen eller smältfiltret.



Fig 20. Filmbåsning av prov uttaget av recyclat som var mest transparenta med få prickar i filmen.



Fig 21. Sista prov av transparent uttaget uppvisar en del prickar men för övrigt ofärgad.

5.2 Utvärdering Trioworld

Trioworld utvärderade recyclaten genom att köra dem i en labbextruder ansluten till filmblåsningsutrustning. Filmprov blåstes upp i bredd ca 170 mm samt tjocklek ca 40 µm. Resultat av testerna på filmen visa i tabell 1.

Tabell 1. Resultat av filmprovning utförd av Trioworld.

Oktabin-märkning	Dartdrop g:	Rivstyrka MD mN:	Rivstyrka TD mN:	MFI:	Densitet**:
2 13:25	160	984	3530	0,38	0,923-0,925
3 15:40	175	1261	5092	0,43	0,923-0,925
4 16:40	150	1703	7048	0,43	0,923-0,925
19:08	165	1786	4663	0,49	0,923-0,925
Krav på sopsäck*	Min 150	Min 1500	Min 3 500	0,5-1,5	0,920-0,930

Dartdrop är en provning som innebär att man släpper en vikt på filmen från 60 cm höjd. Resultatet visar vid vilken vikt filmen går sönder och är ett mått på hur lätt filmen punkteras. För sopsäckar är kravet för dartdrop minst 150 g men det är olika krav för olika applikationer. Rivstyrka MD och TD innebär provning i maskinriktning och tvärsriktning. Maskinriktning är samma riktning som filmen blåses. Provningsen innebär att man gör en anvisning i filmen innan man river. Rivstyrkan i maskinriktning ska helst vara runt 3000mN, så de testade filmerna har ett, i jämförelse, lägre värde i maskinriktningen med stor spridning.

Smältindex är viktigt för materialets egenskaper under formningsprocessen och ett lågt smältindex krävs för filmblåsning men allmänt önskas MFI > 0,7 även om de återvunna materialen fungerar för att blåsa film.

Trioworld summerar resultaten med följande slutsatser: Analyserna visar inte på perfekta egenskaper för användning i aktuella produkter:

- **Sträckfilm:** Ej godkänd processbarhet eller mekaniska egenskaper för att fungera i denna applikation.
- **Täckfolie + Toppark:** Ok mekaniska egenskaper, men infärgningen begränsar.
- **Säckar:** Begränsningar i mekaniska egenskaper samt MFI medför att fraktionerna inte är optimala. Lägre inblandningshalt, tjockare säckar alt. enklare applikationer kan vara ett alternativ, vilket dock ej är optimalt.

Provoktabiner: Kan användas upp via lägre inblandning i enklare svarta sopsäckar.

5.3 Utvärdering RISE

Figur 22 visar tvättade flingor av det färgade och transparenta materialet. Det är främst det helt infärgade materialet som vitt, blått och svart som gör att filmen inte blir transparent. Figur 23 visar det transparenta materialet med tryck.



Fig 22. Färgad och transparent tvättad film före inmatning till extrudern



Fig 23. Transparent tvättad film med tryck före inmatning i extrudern.

Tabell 2. Egenskaper för tre recycelatprov

Prov	färgad film	transparent 1	transparent 2
E-modulus (MPa)	198	249	219
Stress @ Yield (MPa)	14,3	15,8	14,6
Stress @ Break (MPa)	13,4	14,7	—
Strain @ Yield (%)	160	141,2	211,2
Strain @ Break (%)	169,6	150,3	—
MFR 5kg/190°C (g/10min)	1,49	1,03	1,63

Uttag av recycelat utvärderade på RISE genom dragprovning av formsprutade stavar och MFI. Värdet på E-modulen visar att det är ett mjukt material, lämpligt för filmer och folier. De relativt låga värdena på MFI visar också att filmblåsning eller extrudering är lämpliga formningsprocesser. Det låga värdet på flytgränsen (stress at yield) och spänningen vid brott visar att materialet lätt deformeras. Hög töjning (strain at yield) är nödvändigt för att kunna forma materialet vid filmblåsning. För provet "transparent 2" var det endast en av fem stavar som gick att dra av, vilket innebär att det blir en lång tunn sträng av de övriga provstavar.

5.4 Utvärdering Polyplank

Polyplank har testat att använda recycelatet från den färgade filmen för att blanda med träspån som sedan komponderas med HDPE för att formspruta pluggar. Pluggarna används till rullar inom pappersindustrin, se Figur 24. Pluggarna är en stor volymprodukt för Polyplank och i denna produkt fungerar det bra att använda recycelat från den färgade byggemballageplasten. Det finns inga krav på färg och utseende på pluggarna.

Polyplank tillverkar också bullerplank av plastträkomposit, se Figur 25. Det är deras största produkt och planken tillverkas i flera färger. För att kunna färga in planken så behöver den återvunna plasten vara transparent så därför var recycletet från färgad emballageplast inte lämplig även om egenskaperna på plasten i övrigt sannolikt skulle fungerat bra.

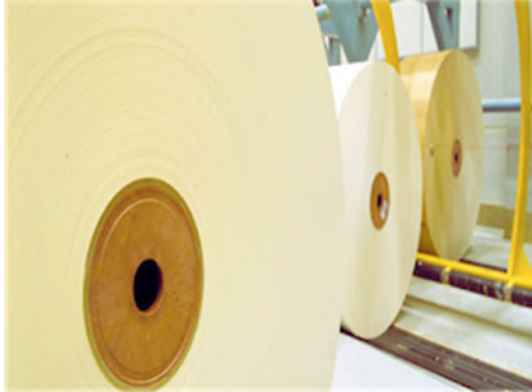


Fig 24. Plugg för pappersrullar, tillverkade av Polyplank



Fig 25. Exempel på plank tillverkade av extruderade "plank" från Polyplank.

6 Slutsatser

- Den insamlade plasten behövde sorteras för att undvika att få med armerad film, spackeltuber etc. En förbättrad sortering är nödvändig för att återvinningsprocessen, främst smältfiltreringen ska fungera. Önskad plast (tex rester av spackel, silikon etc) kan orsaka att smältfiltret sätts igen och ger produktionsstopp.
- Reviva Plastics anläggning med dess tvätt och extruder fungerar utmärkt för att ge hög kvalite på recycletet.
- Möjligheterna att ytterligare förbättra separationen av helt transparent plastfilm från färgad plastfilm bör undersökas för att höja värdet på recycletet.
- Den mest transparenta recycletplasten kan sannolikt används till plasthuvuar enligt Troworld. Den färgade plasten kan användas till virkestäckfilm och till säckar och avfallspåsar med låga krav.
- Den färgade recycletplasten kan använda i träplugg som Polyplank tillverkar.

B RISE report: Climate assessment of recycled plastic packaging material

Climate assessment of recycled plastic packaging material

RISE Research Institutes of Sweden AB

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Purpose and method

This assessment analyses the climate impact and potential climate impact savings of recycling waste polyethylene (PE) packaging material, compared to using virgin plastic or incinerating the waste plastic. The purpose of this analysis is to establish what carbon savings that could be achieved by recycling plastic packaging material, based on the first use cycle of the material.

The recycling process was modelled using data from an industry source producing similar recycled granulated PE. Figure 1 shows the processes and inputs used. Other inventory data was taken from the verified database Ecoinvent 3.8. The processes were modelled using the SimaPro software and the impact assessment method IPCC 2013 GWP 100a v.1.03. With this method climate impact in the unit kg CO₂-equivalents (CO₂e) was estimated.

Datasets modelled for Swedish conditions were used when possible. However, the reference virgin LDPE production process was modelled according to average European production. For more fair comparison to the virgin LDPE, a scenario with average European electricity was included for the recycling process. The climate impact for the European electricity mix is almost 9 times as high as the Swedish electricity mix.

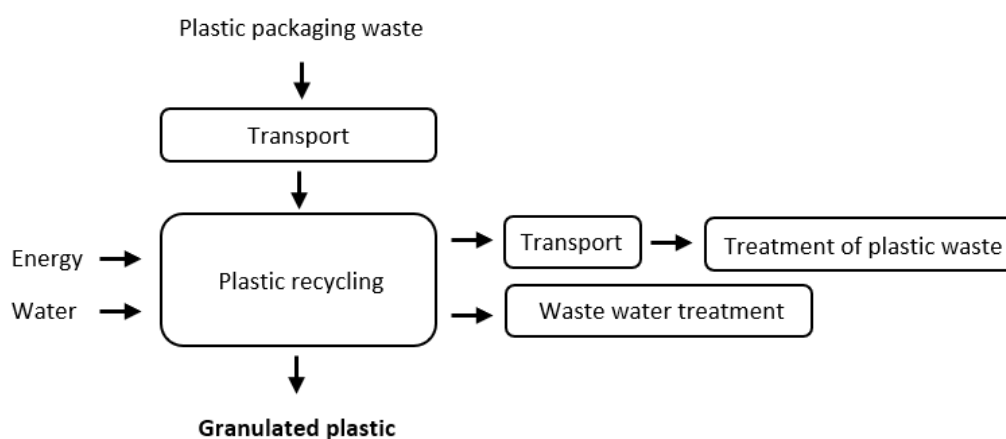


Figure 1. Included processes and inputs for the recycled plastic. The transport to the recycling site was assumed to be 400 km in total and the transport to the waste treatment (incineration) assumed to be 30 km in total, based on data from the industry source. 5% of the plastic packaging waste going in to the system is assumed to go to incineration.

The results are related to the functional unit 1 kg plastic granulate.

Allocation was made according to the Cut-off principle, meaning that the burden of waste handling is put on the producer of the waste. The producers do not receive any credit for the production of useful material/energy that comes as a result of the waste handling. For example, heat generated from the incineration of plastic comes burden-free to the user of the heat, and the entire burden is put on the producer of the waste that is being incinerated. For more details on this method, read more here: <https://ecoinvent.org/the-ecoinvent-database/system-models/>

It is important to note that the assessment only covers the first use cycle, and not the entire life cycle of the material. The results do not take into consideration the recycling/waste handling of the material after use, where for example the virgin plastic might be easier to recycle than the plastic that has already been recycled.

Result

When using Swedish electricity the main impact from the recycling process comes from the waste handling. This is mainly due to the incineration of plastic waste. When using a European electricity mix, energy is the main source of climate impact. See figure 2.

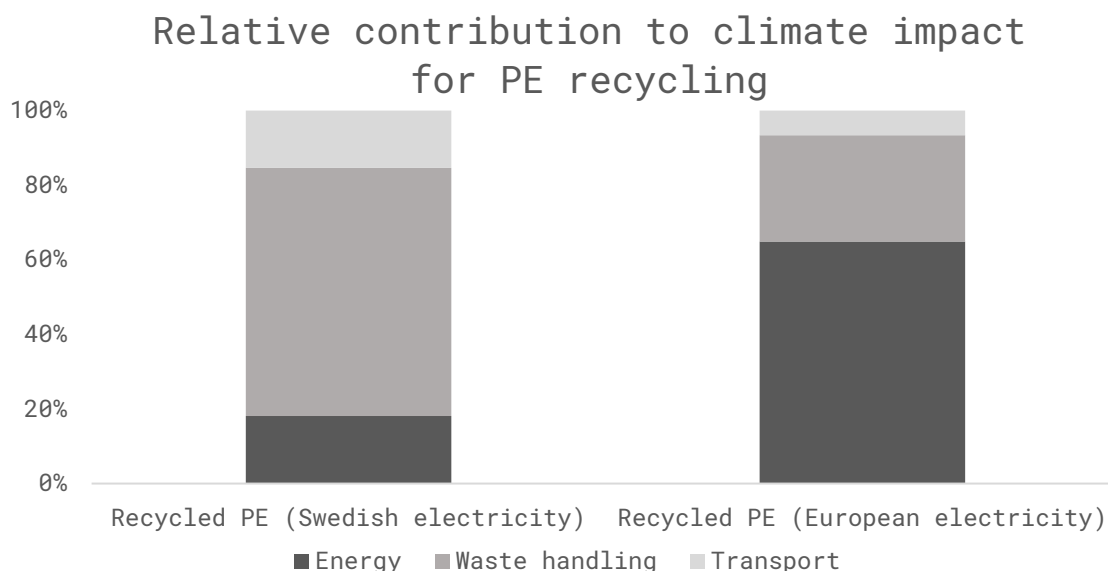


Figure 2. Relative contribution to climate impact for plastic (PE) recycling, for scenario with average Swedish electricity and average European electricity.

The climate impact for production of recycled granulated PE is 12-28% of the climate impact for the production of virgin low density PE (LDPE), depending on electricity mix used. See figure 3.

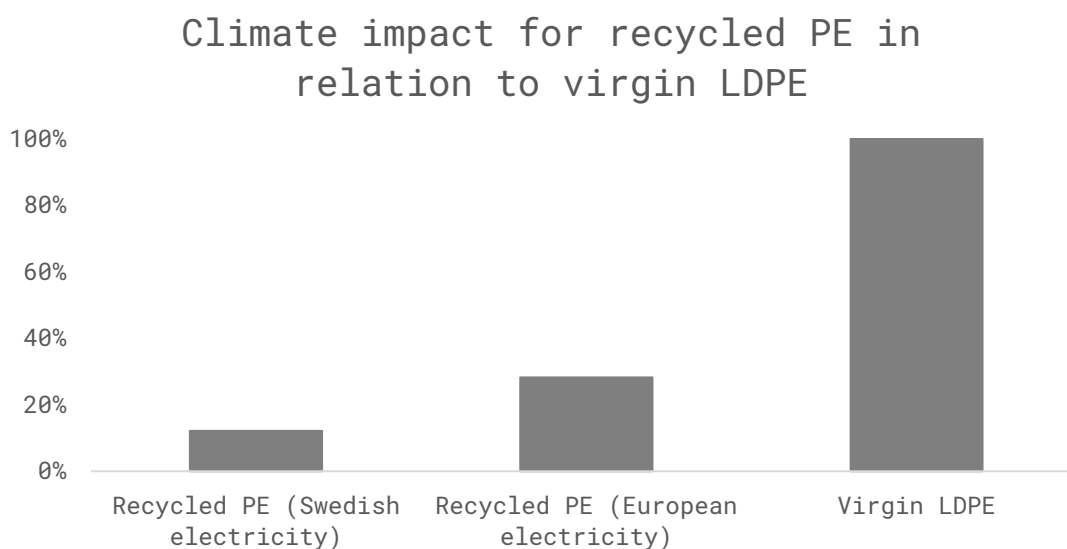


Figure 3. Climate impact for recycled PE, for scenario with average Swedish electricity and average European electricity, in relation to virgin LDPE (produced in Europe).

When recycling PE and avoiding incineration, the immediate CO₂e emission savings are between 2,6 – 2,9 kg CO₂e per kg PE granulate, see figure 4. The climate impact of recycling PE in relation to incineration are between 8 and 18% depending on electricity mix used, see figure 5.

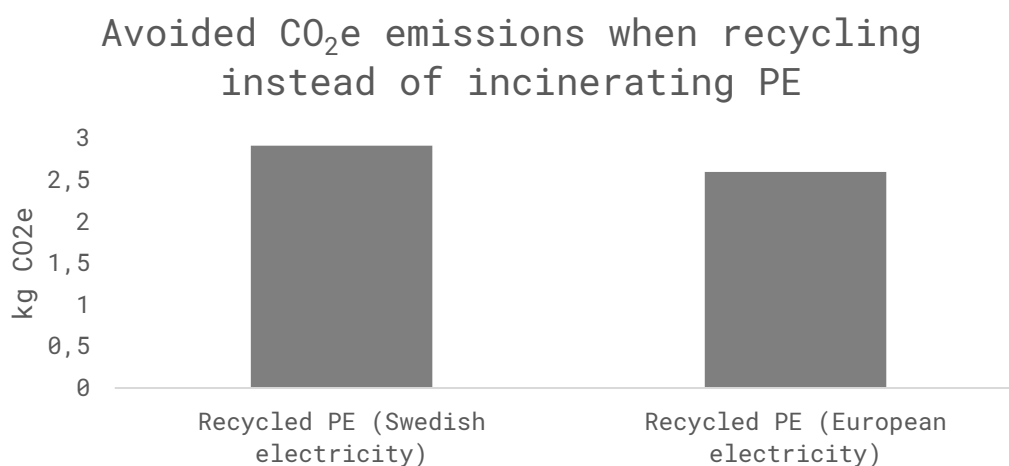


Figure 4. Avoided kg CO₂e emissions when recycling PE instead of incinerating it, for scenario with average Swedish electricity and average European electricity.

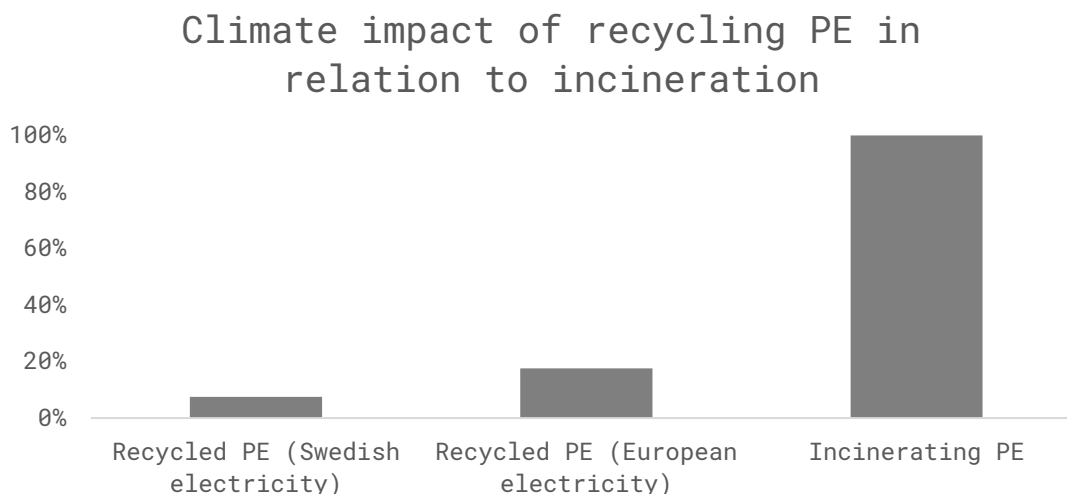


Figure 5. Climate impact for recycled PE in relation to incineration, for scenario with average Swedish electricity and average European electricity.

References

Inventory data regarding transport and input/output flows for the recycling process were received from an industry source.

The following processes from the Ecoinvent 3.8 database were used:

Electricity, medium voltage {SE}| market for | Cut-off, U

Electricity, medium voltage {RER}| market group for | Cut-off, U

Diesel {Europe without Switzerland}| market for | Cut-off, U

Wastewater, average {Europe without Switzerland}| market for wastewater, average | Cut-off, U

Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U

Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, U

Waste polyethylene {SE}| market for waste polyethylene | Cut-off, U

Polyethylene, low density, granulate {RER}| production | Cut-off, U

C Individual FT-IR spectra from the investigation

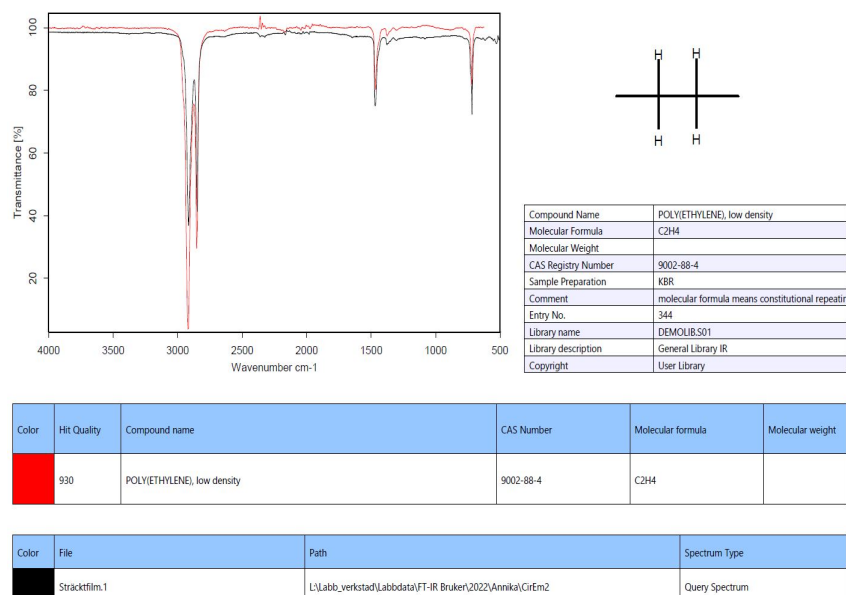


Figure 15: FT-IR spectrum of Sample A.

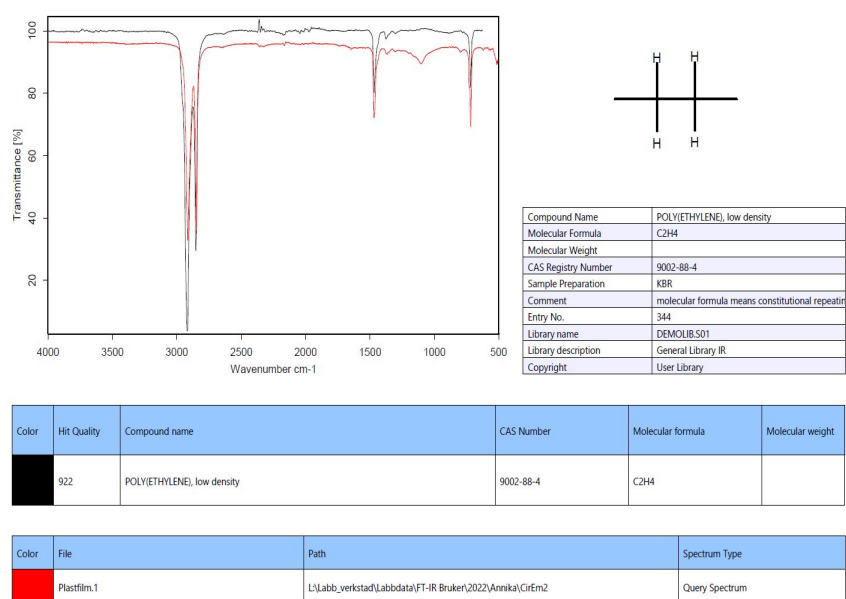


Figure 16: FT-IR spectrum of Sample B.

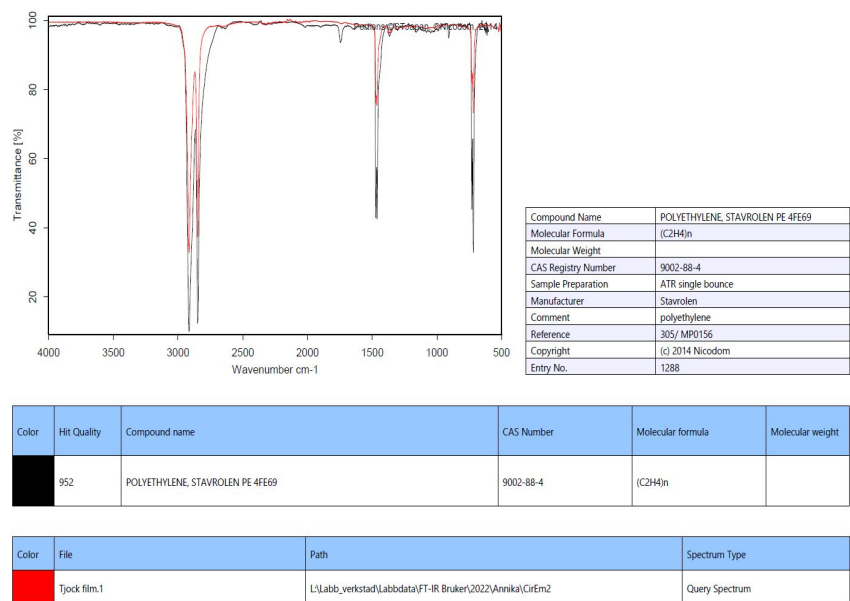


Figure 17: FT-IR spectrum of Sample D.

D Individual DSC thermograms from the investigation

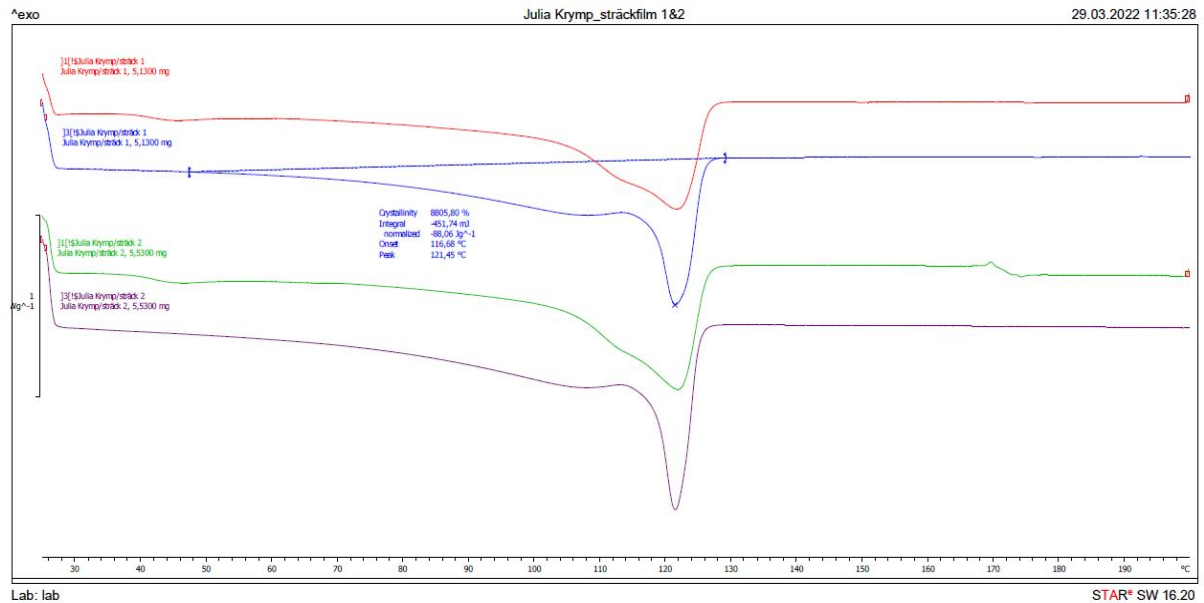


Figure 18: DSC thermogram of Sample A. Specimen 1 is at the top and specimen 2 at the bottom.

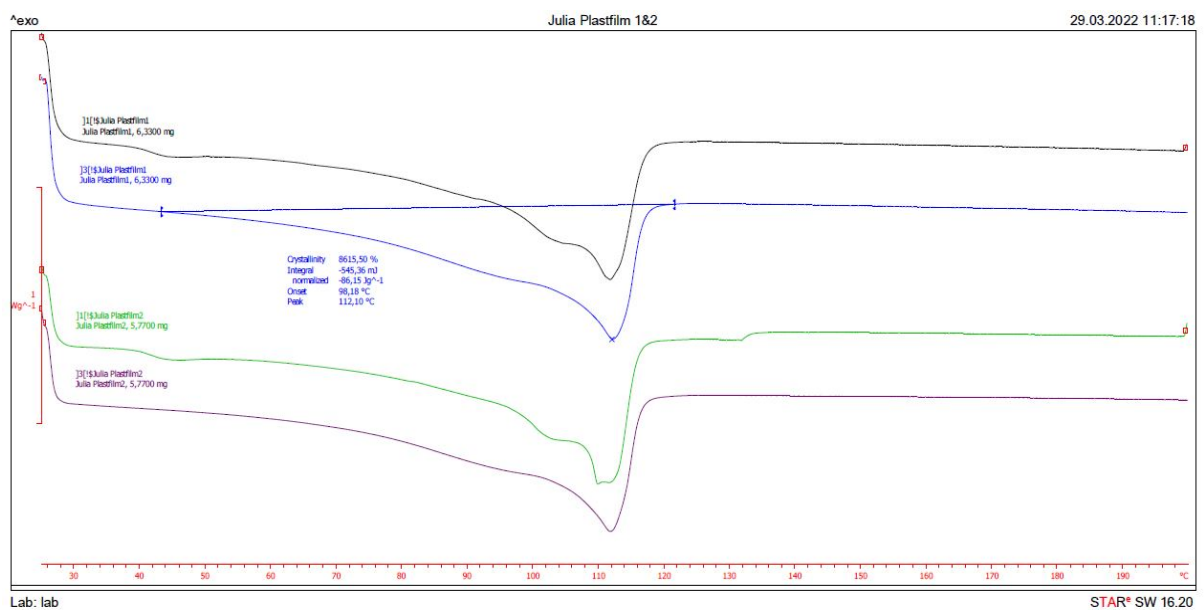


Figure 19: DSC thermogram of Sample B. Specimen 1 is at the top and specimen 2 at the bottom.

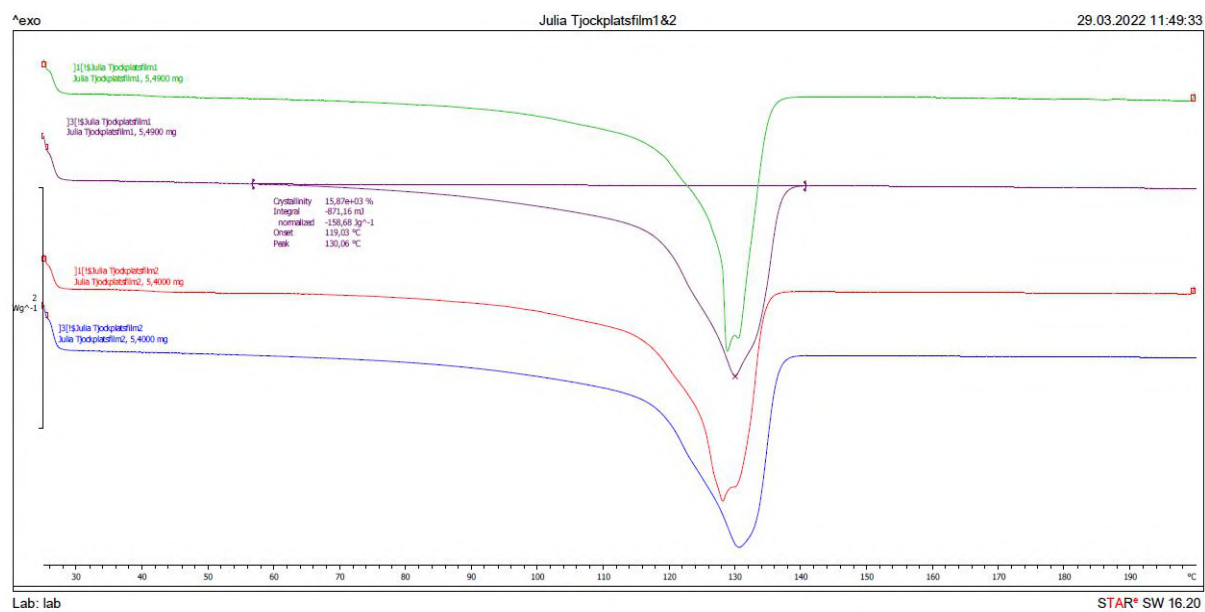


Figure 20: DSC thermogram of Sample D. Specimen 1 is at the top and specimen 2 at the bottom.

E Individual FT-IR spectra after recycling

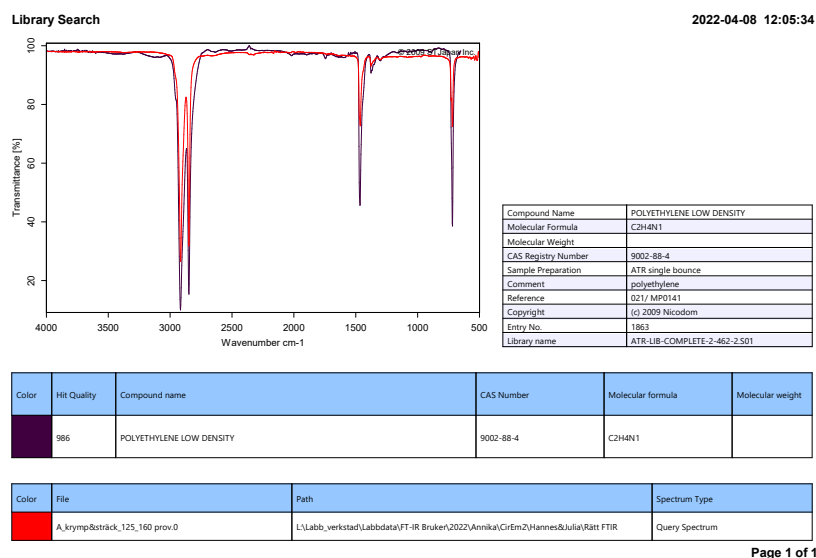


Figure 21: FT-IR spectrum of A125 post recycling.

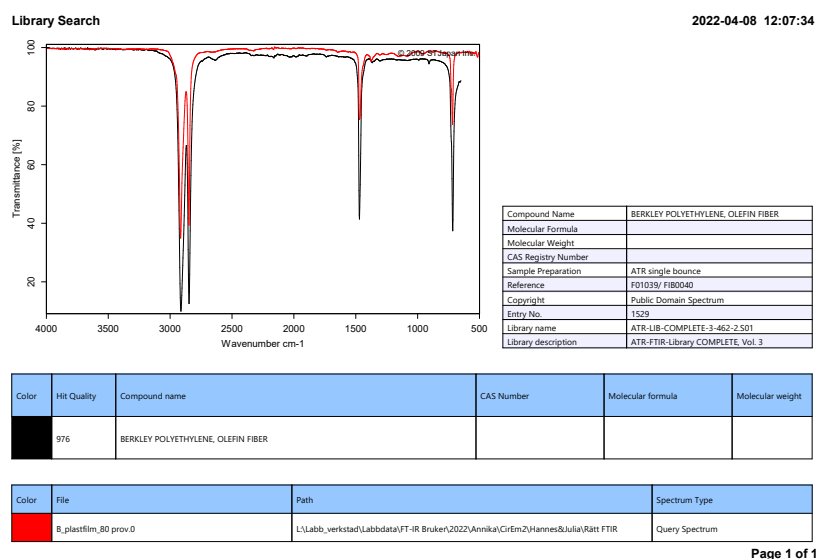


Figure 22: FT-IR spectrum of B80 post recycling.

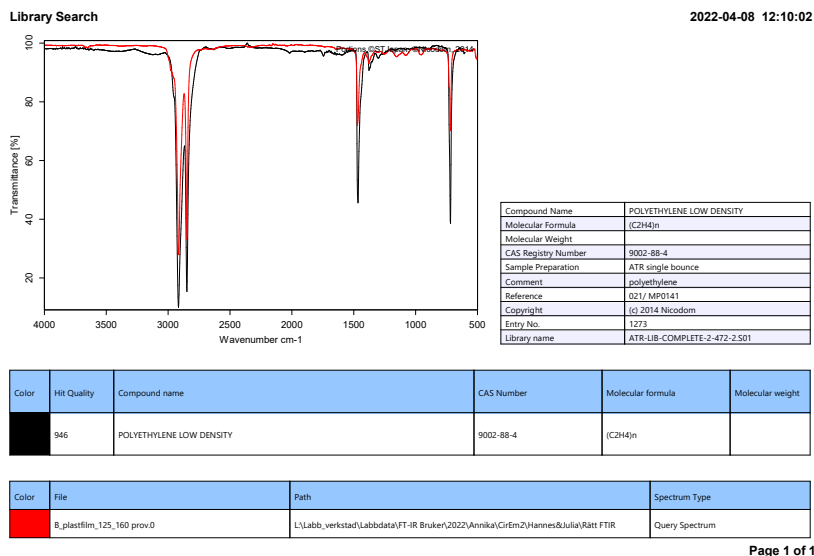


Figure 23: FT-IR spectrum of B125/160 post recycling.

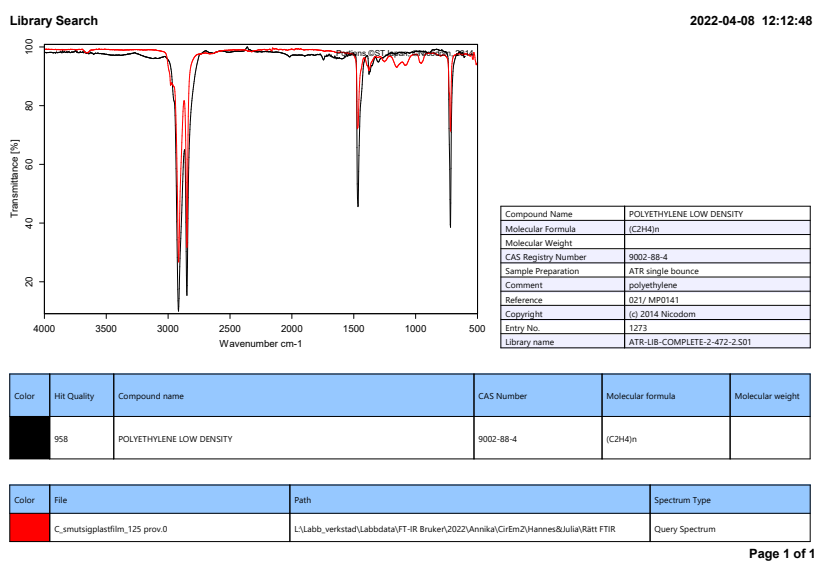
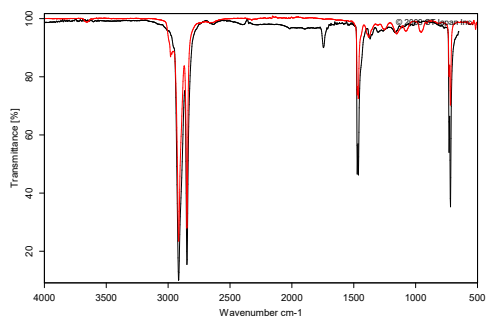


Figure 24: FT-IR spectrum of C125 post recycling.

Library Search

2022-04-08 12:16:54



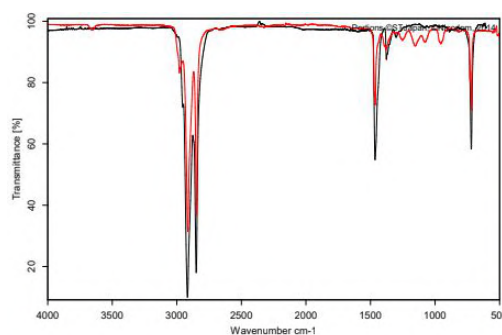
Compound Name	POLYETHYLENE, DAPLEX BF 4572
Molecular Formula	C2H4N1
Molecular Weight	
CAS Registry Number	9002-88-4
Sample Preparation	ATR single bounce
Comment	polyethylene
Reference	303/MPD145
Copyright	(c) 2009 Nicodrom
Entry No.	1868
Library name	ATR-LIB-COMPLETE-2-462-2-501

Color	Hit Quality	Compound name	CAS Number	Molecular formula	Molecular weight
	909	POLYETHYLENE, DAPLEX BF 4572	9002-88-4	C2H4N1	

Color	File	Path	Spectrum Type
	D:\jockplastfilm_80 prov.0	L:\Labb_verkstad\Labbdatab\FT-IR Bruker\2022\Annika\CrEm2\Hannes&Julia\Ratt FTIR	Query Spectrum

Page 1 of 1

Figure 25: FT-IR spectrum of D80 post recycling.



Compound Name	POLYETHYLENE, ENGAGE 8180
Molecular Formula	(C2H4)n
Molecular Weight	
CAS Registry Number	9002-88-4
Sample Preparation	ATR single bounce
Manufacturer	Dow
Comment	polyethylene
Reference	044/MPD148
Copyright	(c) 2014 Nicodrom
Entry No.	1280

Color	Hit Quality	Compound name	CAS Number	Molecular formula	Molecular weight
	968	POLYETHYLENE, ENGAGE 8180	9002-88-4	(C2H4)n	

Color	File	Path	Spectrum Type
	D:\jockplastfilm_125 prov.0	L:\Labb_verkstad\Labbdatab\FT-IR Bruker\2022\Annika\CrEm2\Hannes&Julia\Ratt FTIR	Query Spectrum

Figure 26: FT-IR spectrum of D125/160 post recycling.

F Individual DSC thermograms after recycling

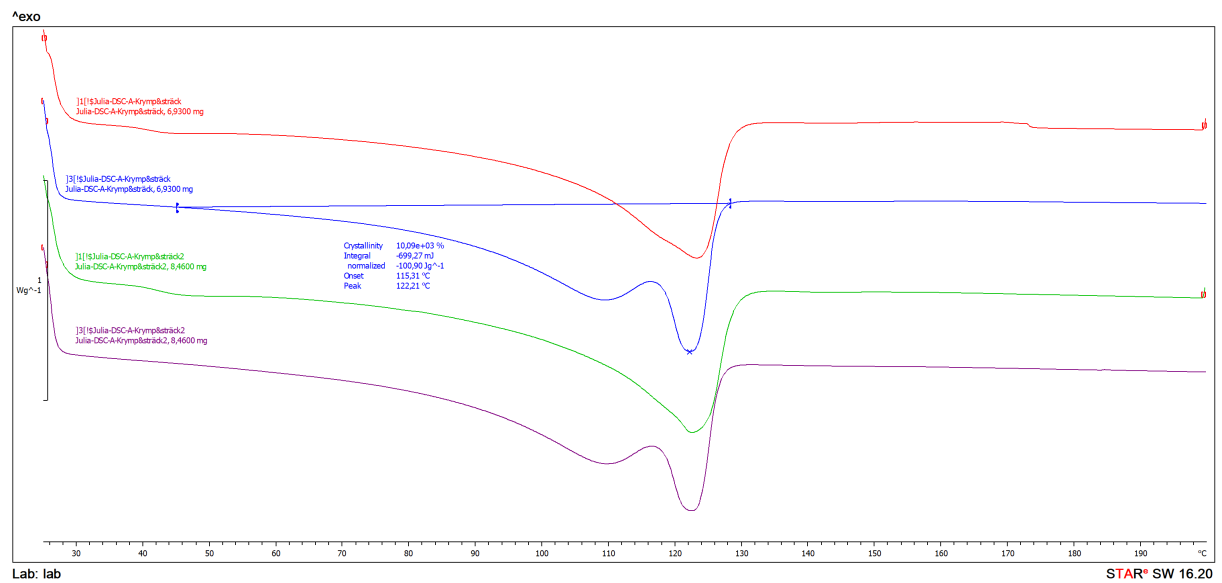


Figure 27: DSC thermogram of A125 post recycling. Specimen 1 is at the top and specimen 2 at the bottom.

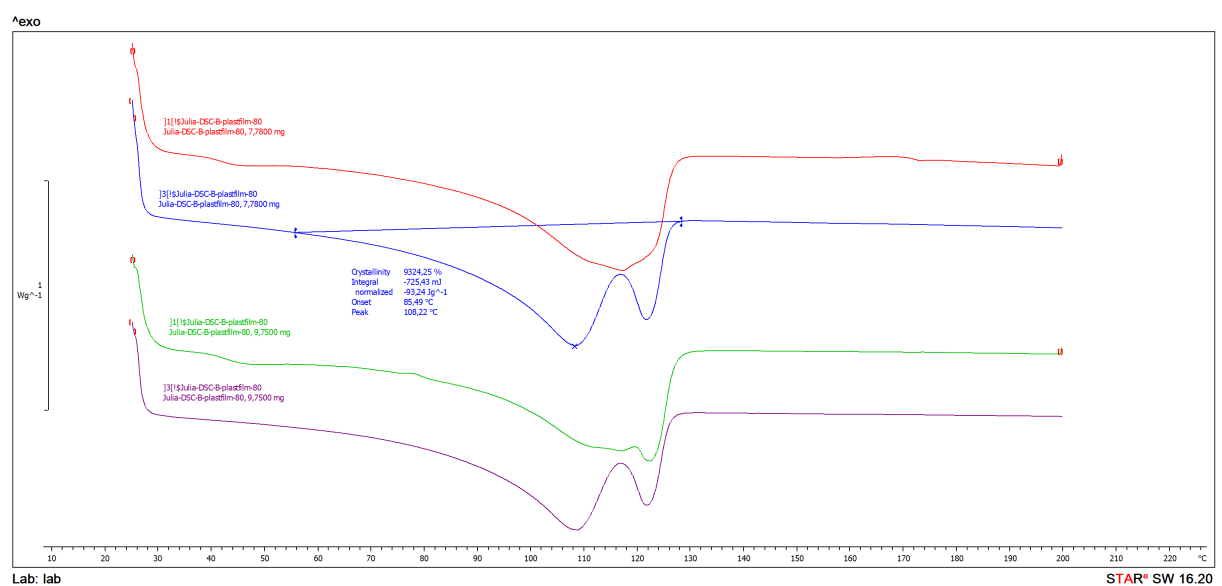


Figure 28: DSC thermogram of B80 post recycling. Specimen 1 is at the top and specimen 2 at the bottom.

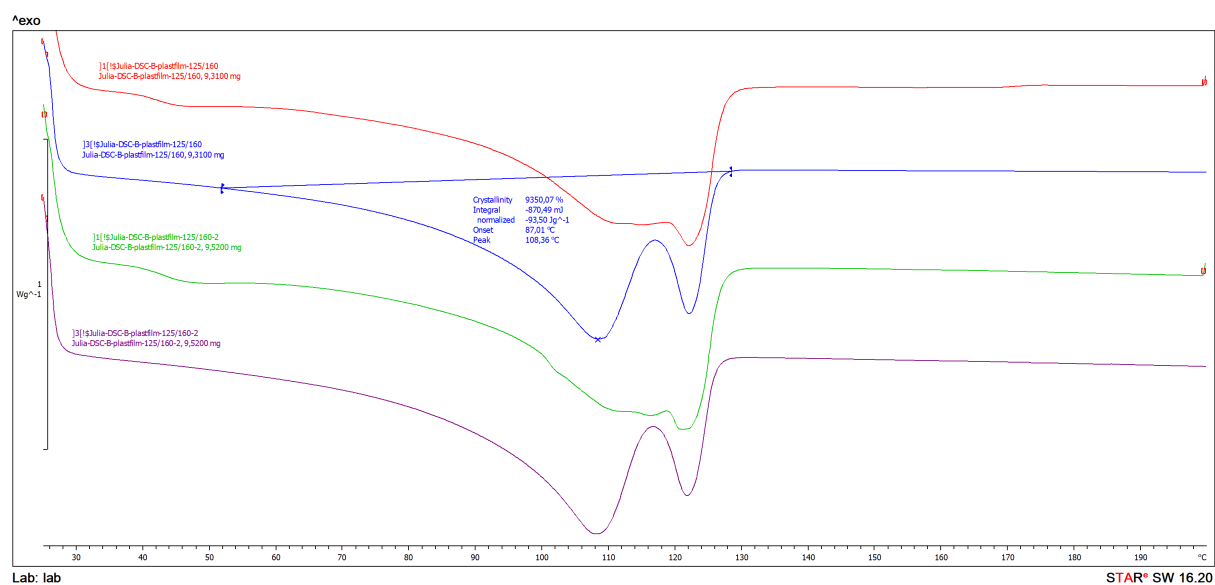


Figure 29: DSC thermogram of B125/160 post recycling. Specimen 1 is at the top and specimen 2 at the bottom.

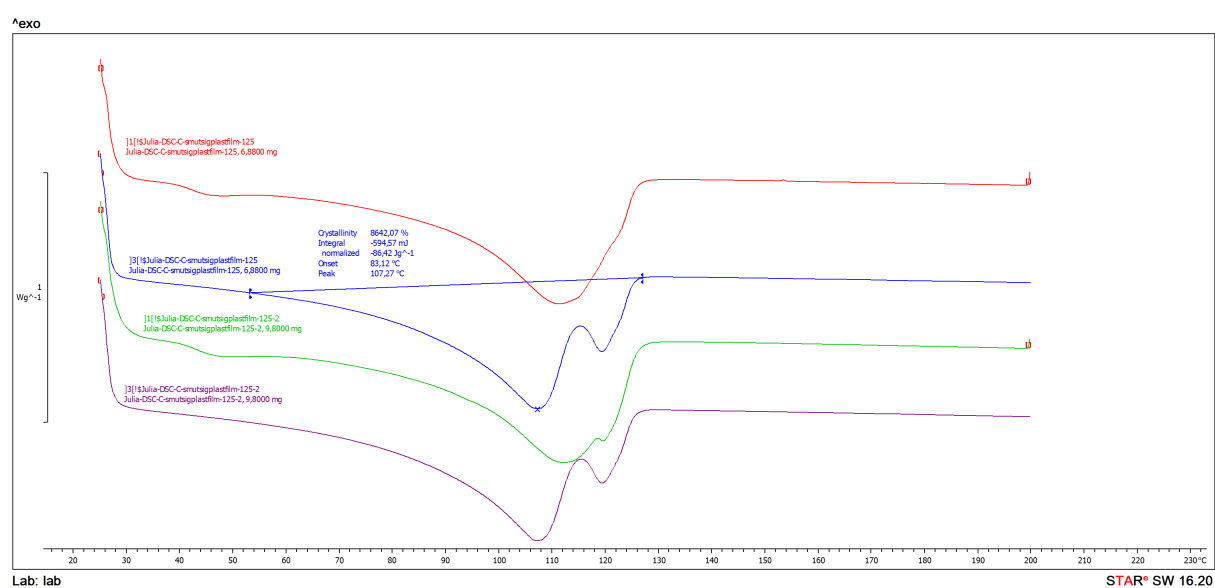


Figure 30: DSC thermogram of C125 post recycling. Specimen 1 is at the top and specimen 2 at the bottom.

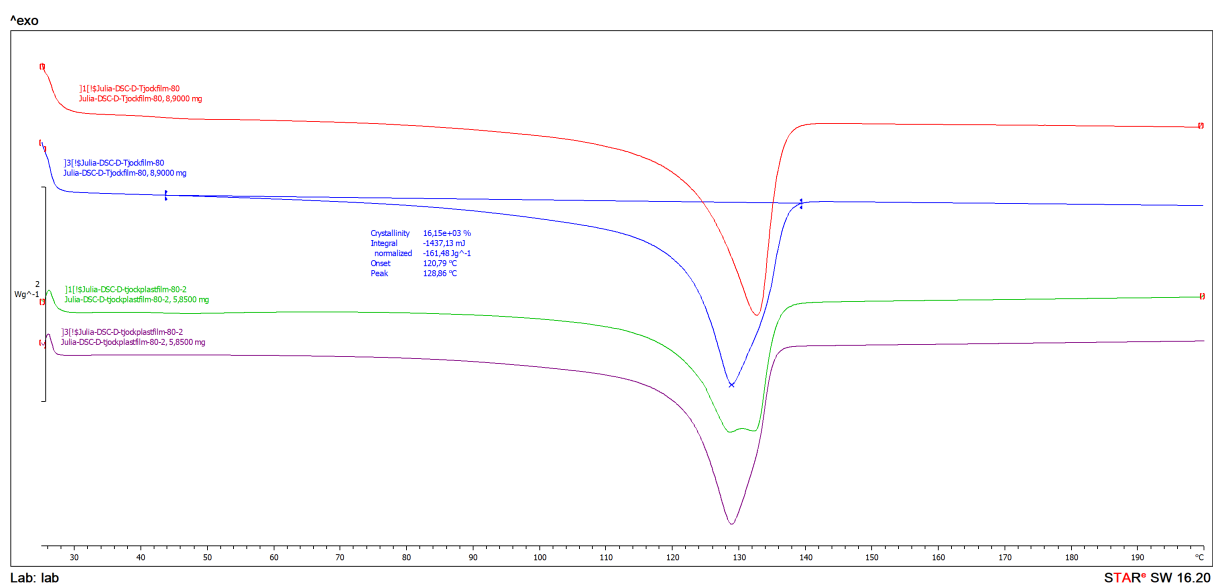


Figure 31: DSC thermogram of D80 post recycling. Specimen 1 is at the top and specimen 2 at the bottom.

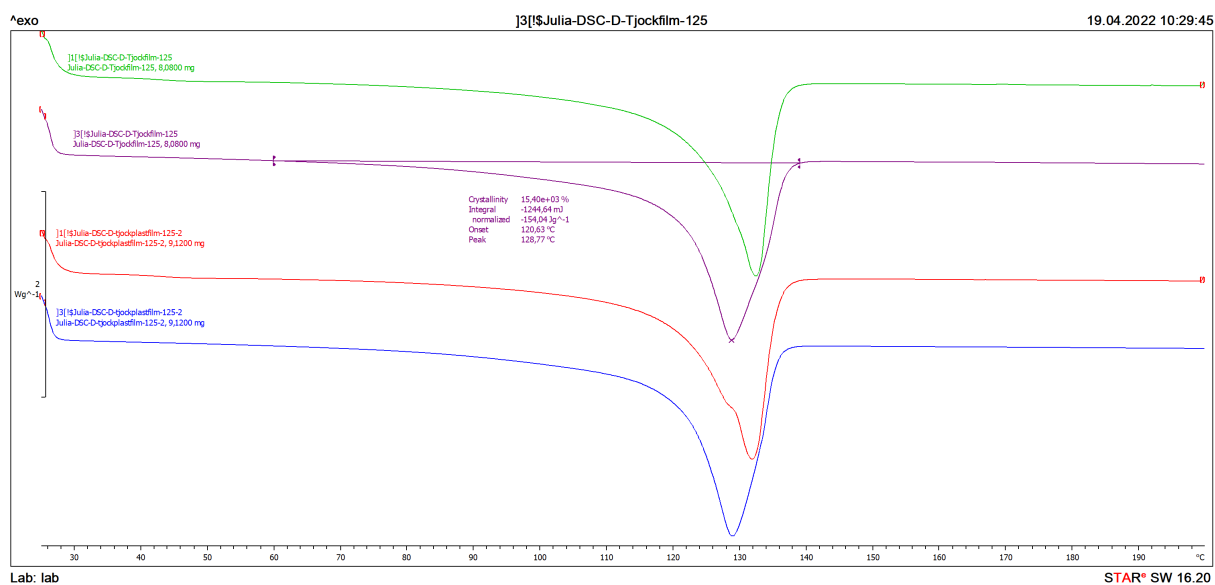


Figure 32: DSC thermogram of D125 post recycling. Specimen 1 is at the top and specimen 2 at the bottom.

G Individual OIT curves for all batches

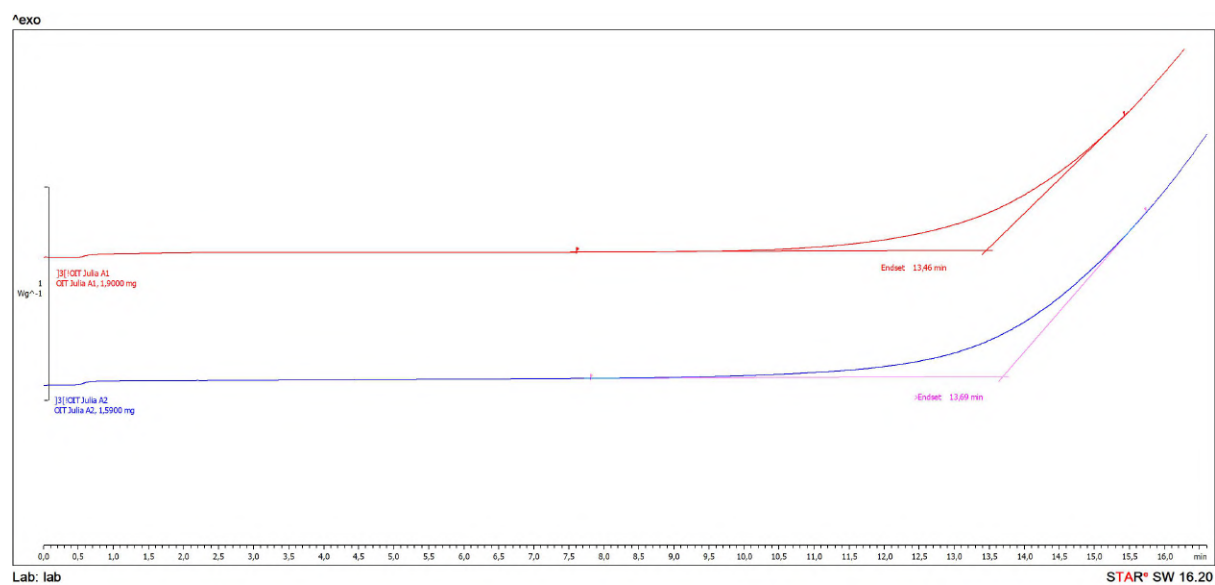


Figure 33: OIT curves for A125/160. Specimen 1 is at the top and specimen 2 at the bottom.

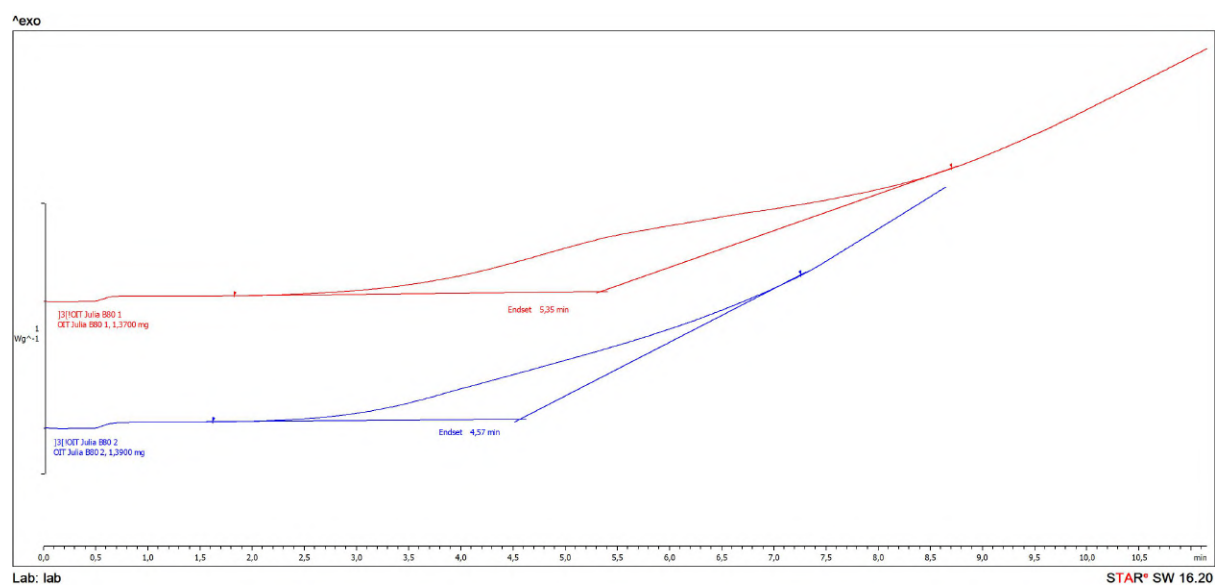


Figure 34: OIT curves for B80. Specimen 1 is at the top and specimen 2 at the bottom.

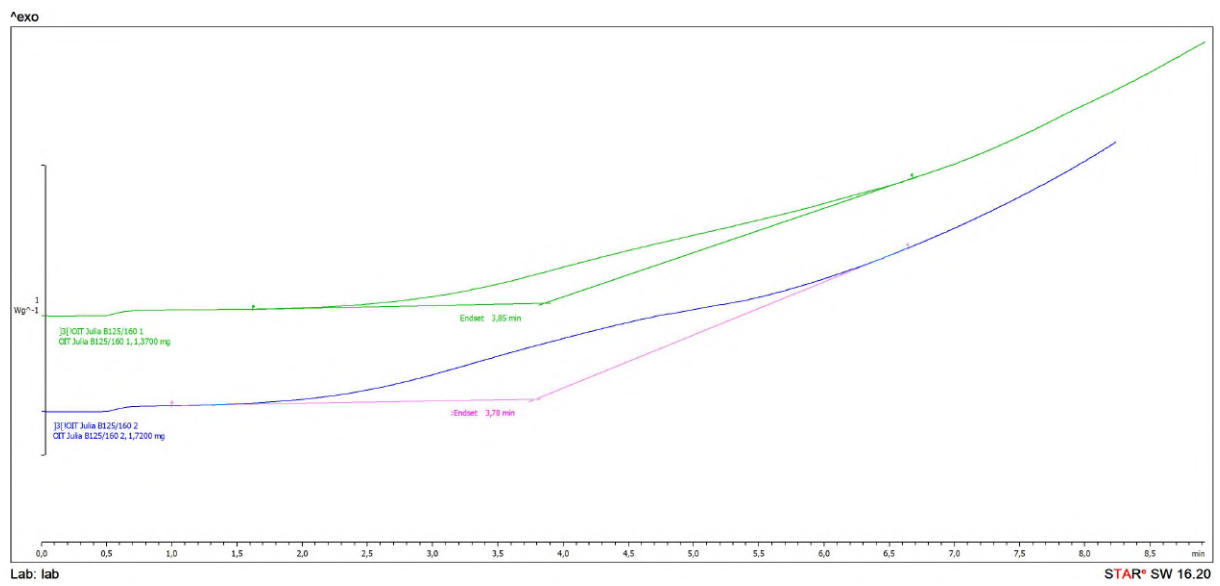


Figure 35: OIT curves for B125/160. Specimen 1 is at the top and specimen 2 at the bottom.

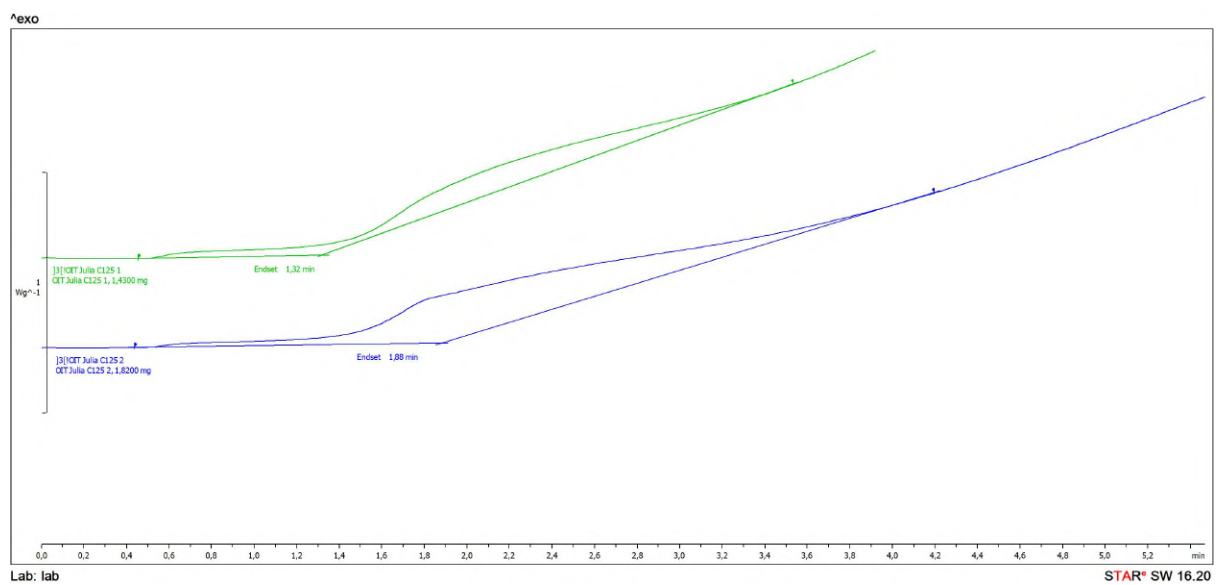


Figure 36: OIT curves for C125. Specimen 1 is at the top and specimen 2 at the bottom.

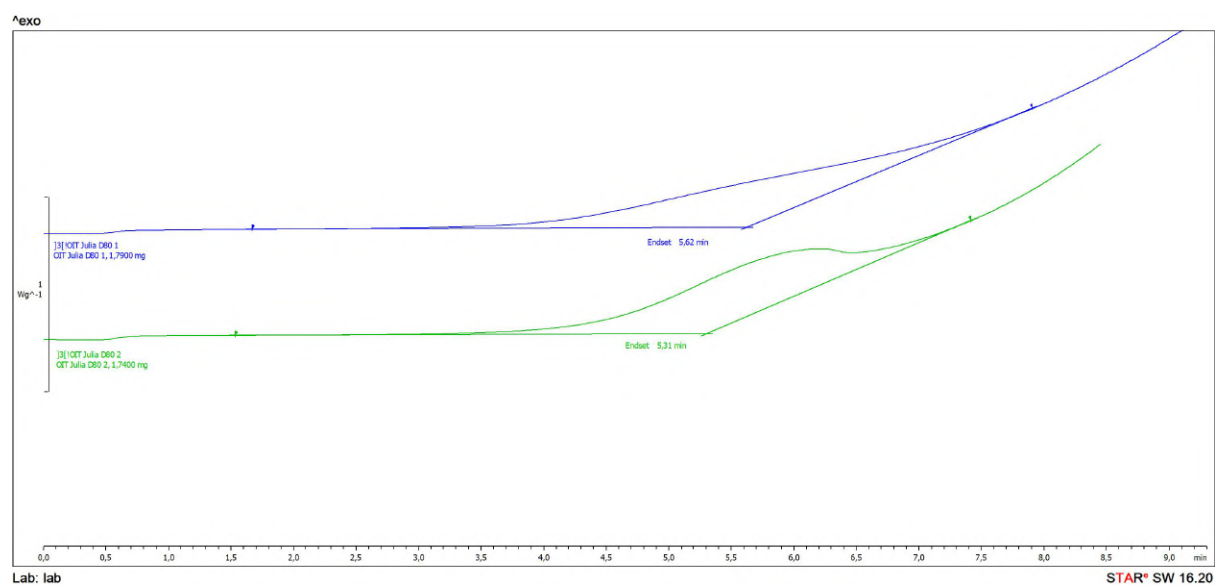


Figure 37: OIT curves for D80. Specimen 1 is at the top and specimen 2 at the bottom.

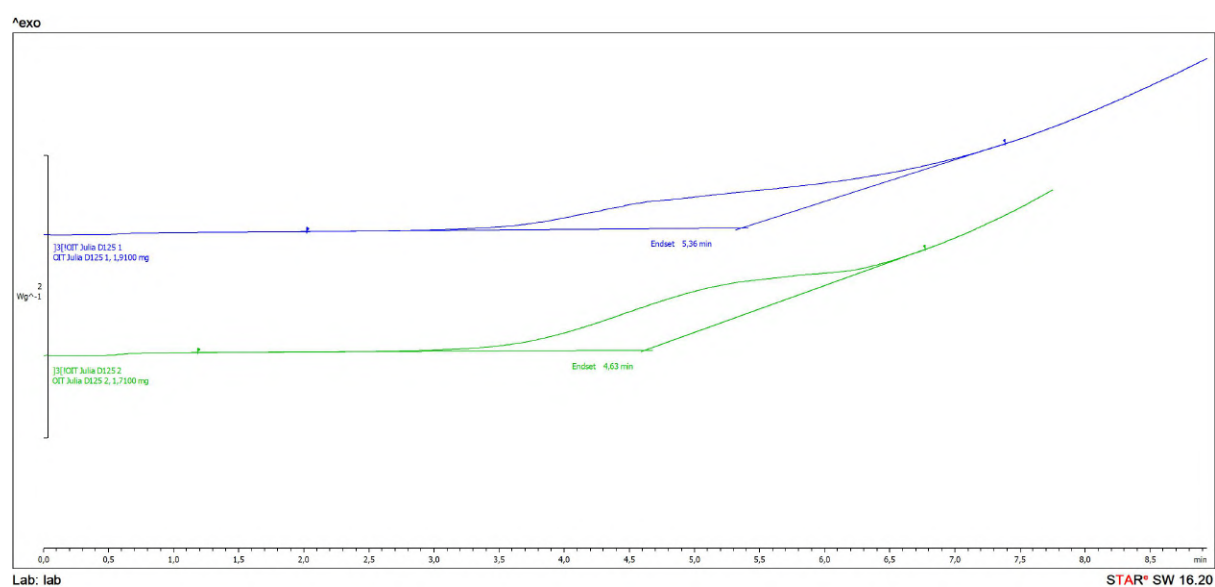


Figure 38: OIT curves for D125. Specimen 1 is at the top and specimen 2 at the bottom.

H Individual tensile strength curves for the tested batches

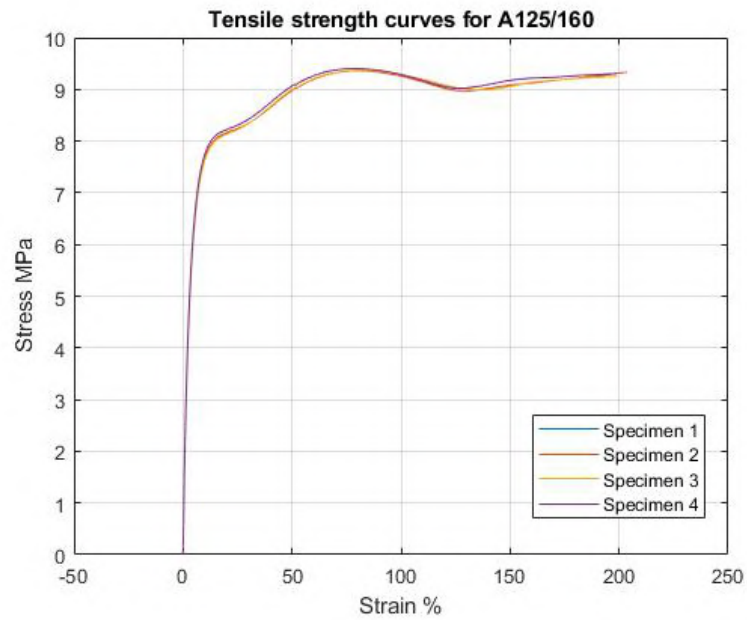


Figure 39: Tensile strength curves for A125/160.

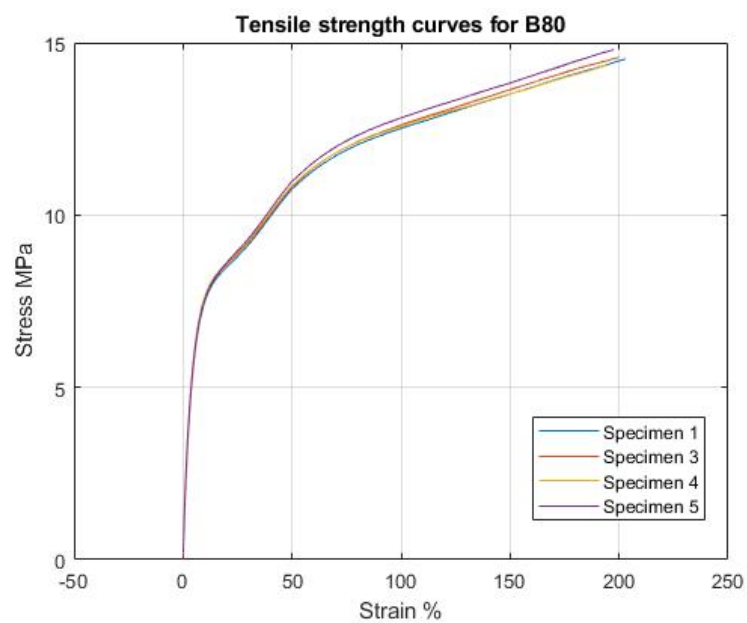


Figure 40: Tensile strength curves for B80.

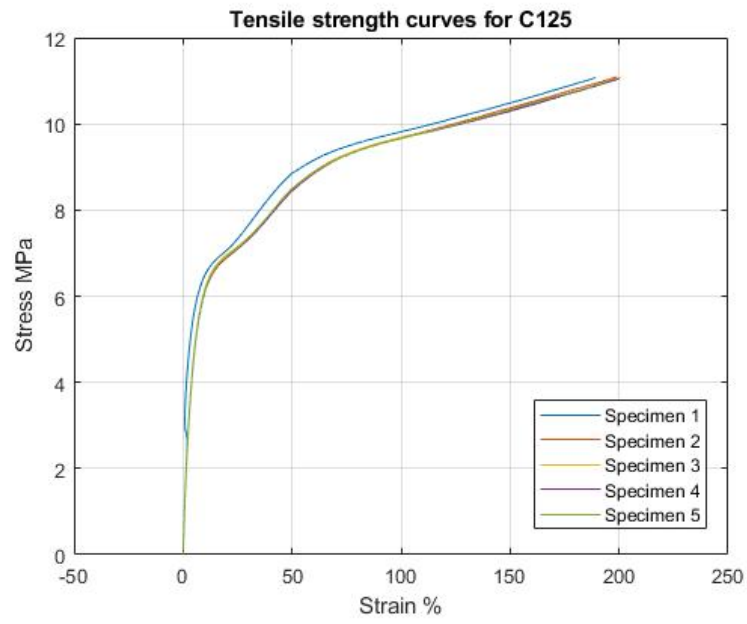


Figure 41: Tensile strength curves for C125.

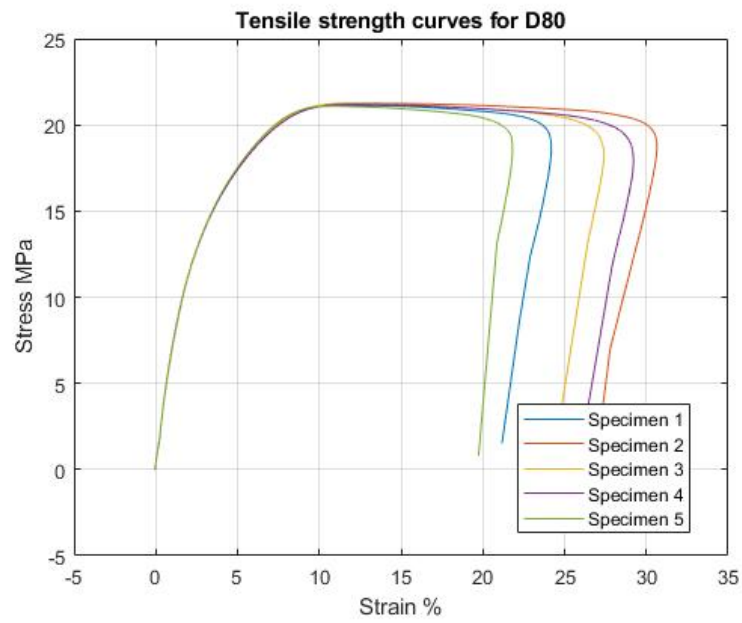


Figure 42: Tensile strength curves for D80.



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