Using recycled polyethylene terephthalate (PET) in the production of bottle trays

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Handledare (Arcada):	Mariann Holmberg
Uppdragsgivare:	K.Hartwall Oy Ab

Sammandrag:

Detta arbete är ett beställningsarbete av K.Hartwall Oy Ab och i det undersöks möjligheten att tillverka en flaskbricka ur återvunnet polyetentereftalat (PET). Hittills har brickan producerats ur polyeten med hög densitet (HDPE) genom formsprutning. Svaga flytegenskaper för PET befarades vara ett hinder för att tillverka brickan genom formsprutning. Ur litteraturstudien framgick dock att PET torde ha låg viskositet. Därmed blev ett av huvudmålen att undersöka hur visköst PET är jämfört med HDPE och hur man eventuellt kunde förbättra flytegenskaperna. Flytegenskaperna och de mekaniska egenskaperna hos återvunnet PET jämfördes med motsvarande egenskaper hos jungfruligt PET för att kunna avgöra ifall materialet lämpar sig för ändamålet. Därtill undersöktes det om en bearbetningsmetod som kombinerar funktionerna av formsprutning och formpressning kunde vara ett alternativ för formsprutning. Forskningsmetoderna som användes var: viskositets test, Moldflow simulering, dragprov, smält index mätning, expert intervju och uträkningar. Enligt resultaten så skulle det vara möjligt att formspruta brickan ur PET. Ett högre insprutningstryck skulle dock behövas. En förbättring i flytegenskaperna uppnåddes när återvunnet PET blandades med titandioxid (TiO_2). Återvunnet PET hade bättre flytegenskaper än jungfruligt PET, men inga betydande skillnader i de mekaniska egenskaperna kunde påvisas. I det stora hela så kunde återvunnet PET vara ett lämpligt material för brickan, dock nödvändigtvis inte lämpligare än HDPE. Det visade sig att den ovannämnda alternativa kombinerade bearbetningsmetoden inte lämpade sig för ändamålet.

Nyckelord:	K.Hartwall, flaskbricka, rPET, PET, polyetentereftalat, återvinning
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Abstract:

This thesis was commissioned by K.Hartwall Oy and it investigates the possibility of manufacturing a bottle tray out of recycled polyethylene terephthalate (PET). Until now the tray has been produced out of high density polyethylene (HDPE) through injection moulding. The main concern was that the flow properties of PET would be too poor in order to produce trays with injection moulding. The literature that was reviewed does however suggest that PET has low viscosity. Therefore one of the main aims was to find out how viscous PET is in relation to HDPE and how the flow properties could potentially be improved. It was also investigated whether recycled PET has better flow properties and weaker mechanical properties than virgin PET and if it would be a suitable tray material. Furthermore, injection compression moulding is considered as an alternative to injection moulding. The methods used were: viscosity test, Moldflow simulation, tensile test, melt flow index measurements, interview and calculations. According to the results, it would be possible to injection mould the part out of PET. A higher injection pressure would however be needed. A slight improvement in the flow properties was achieved when mixing recycled PET with titanium dioxide (TiO_2). Recycled PET had better flow properties than virgin PET but no significant difference in mechanical properties was noted. Overall, recycled PET would be a suitable material but perhaps not more suitable than HDPE. Injection compression moulding would not be a suitable production method for this product.

Keywords:	K.Hartwall, bottle tray, rPET, PET, polyethylene terephthalate, recycling
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FOREWORD

I want to thank the following: Mariann Holmberg for support and guidance. Jack Grönholm and Johan Lindström for providing an interesting project. Mathew Vihtonen for advice concerning fluid mechanics. The lab staff for helping with the experiments, especially Erland Nyroth who solved many of the technical difficulties that were encountered. Robin Weber for helping with some of the material preparations. All my friends in school for good company. And last but not least, thanks to Sabina Ekholm for supporting me and listening to all my stories about plastics.

1 INTRODUCTION

It is obvious that during the last decades the importance of plastics has increased. Today it is not easy to find a product that neither contains plastics nor has been produced by equipment containing plastics. A large amount of the plastics used is unfortunately treated as waste after it has served its main purpose or broken down. Even though a plastic part is broken, there is usually still material value left in the part but this is seldom utilized. Luckily, there have been developments in a positive direction. For example, the European Union directive 2004/12/EC requires member states to have a collection system for used packages. Different systems have been applied and especially polyethylene terephthalate (PET) has proven to be practical to recover. The reason for this is that PET is the most common bottle material used for carbonated beverages and water. Bottles are easy to sort and separate from other plastics and some countries have also implemented a refill and deposit system where consumers pay a deposit when buying a bottle which is redeemable when the bottle is returned. This system has a very high return rate and greatly favours the recycling of PET. All of this has led to an increasing abundance of recycled polyethylene terephthalate (rPET) and to advances in technology and equipment needed for successful production and processing of rPET. As companies today are interested in sustainable development that can be done economically, there has also been a steady increase in the interest of using this material in production.

K.Hartwall Oy has many customers in the beverage industry that uses PET bottles and could therefore have good availability to rPET. To make use of this resource, the company would be interested in making beverage trays out of it. The trays are currently being produced out of high-density-polyethylene (HDPE) through injection moulding. At the start of this project it was suspected that producing the tray out of rPET with injection moulding would be problematic because PET has inadequate flow properties. However, the literature reviewed for this work suggests that PET has good flow properties but on the other hand can be problematic with regards to for example moisture sensitivity and crystallization. Nevertheless, one of the main aims for this thesis was to come up with a solution to tackle the poor flow properties. But it was also investigated how PET and rPET flows in reality and in comparison to HDPE, in order to determine if it would

be possible to use injection moulding for this purpose. An alternative production method, injection compression moulding, is also presented and reviewed. This production method combines the applications of injection moulding and compression moulding and reduces the needed injection pressure for a successful moulding.

PET is very sensitive to moisture when processed. When heated to processing temperatures, any moisture present will cause a reduction in the molecular weight due to hydrolysis. While this leads to a decrease in viscosity, it also means that every time PET is re-processed without any modification, mechanical properties should deteriorate. Furthermore, a study suggests that it is difficult to mould amorphous parts out of post-consumer PET bottle scraps because of the reduced molecular weight and the presence of impurities. Impurities can act as nucleating agents which promotes crystallization. It is however possible to modify and extend the molecular chains through different methods and grades with minimal impurities are available. In this thesis unmodified rPET flakes and chain extended rPET granules were tested.

If the tray is to be manufactured out of PET, an amorphous part would be preferred. Amorphous PET offers more toughness and ductility than semi-crystalline PET, which would be desired properties. Because it was suggested that it might be difficult to mould amorphous products from bottle scraps, the unmodified rPET flakes were blended with virgin PET at a 50/50 weight percentage (wt%). At first it was not intended to do any tests with 100 % rPET flakes but as there was some extra material, the material was tested partially. The modified rPET granules were not blended. As the viscosity of unmodified rPET should be lower than that of PET, blending them was viewed as a possible solution for reaching adequate flow properties. Another attempt for a solution was to incorporate titanium dioxide (TiO_2) into a blend of PET and rPET. This was done by mixing TiO_2 with the flakes and then extruding them into pellets. A previous investigation suggests that TiO_2 has positive effects on flow properties when blended with rPET.

A literature survey was done to gather information about the materials, the production methods, polymer rheology and testing methods. The empirical part consists of six methods. An in-mould rheology test was done with all the materials to test the viscosities at different flow rates. HDPE was used as a reference material in order to see if

there is a big difference in viscosity when compared with the PET and rPET materials. An injection moulding simulation was done for the tray with Autodesk Simulation Moldflow Insight 2013, with HDPE and PET as materials. A tensile test was done with all the materials except for HDPE because the goal for this test was to compare the mechanical properties of the PET and rPET materials. The effect of mould temperature on PET was also investigated with the tensile test. A melt flow index test was also done to compare viscosities but because it would be difficult to create a homogenous mix of materials inside the melt flow index cylinder, the PET and rPET blends were not tested with this method. In Table 1 the materials used for each test can be seen. Furthermore, an interview was done to get expert opinions about the suitability of the production methods. Finally cooling time, energy consumption and price indices were calculated and compared.

Table 1. The materials used for each testing method

Method	HDPE	PET 20 °C	PET 30 °C	PET 40 °C	PET/rPET (50/50 wt%)	PET/rPET/TiO_2 (49,75/49,75/ 0,5 wt%)	rPET gran-ules	rPET flakes	rPET/TiO_2 (99/1 wt%)
Viscosity test	X	X			X	X	X	Par-tially	X
Melt flow in-dex	X	X					X	X	X
Tensile test		X	X	X	X	X	X	X	X

The research questions for this thesis are:

1. Does PET have too poor flow properties to be used for producing trays through injection moulding?
2. Do the rPET materials have better flow properties and weaker mechanical properties than PET? How does TiO_2 affect flow properties?

3. Does rPET have more value than HDPE, in terms of material performance and from the economic and ecologic viewpoint?
4. Would injection compression moulding be a more suitable production method?

2 BACKGROUND

K.Hartwall Oy was founded in 1932 in Sipoo and started with producing the wiring and clamps for the porcelain caps for Finland's bottle industry. Today K.Hartwall Oy has customers in 30 countries and local sales in 15. The head office is still located in Sipoo. The company offers solutions and returnable goods carriers in five areas: retail, beverage, dairy, logistics and lean. Products come in the form of beverage trays, roll containers, dollies, foldable cages, adaptor pallets and so on. Key drivers for the company's product development are the following: low weight, low noise, excellent fit for automated processes, ergonomic and attractive design, environment friendliness and use of newest materials and technology.

The beverage trays are a part of the Tray-Dolly-Pallet (TDP) system and come in different sizes depending on how many and what size bottles it is designed to carry. The trays can be stacked on dollies and the dollies can be placed on adaptor pallets. During production, warehousing and transporting all individual parts of the system are connected. When the bottles reach the markets the dollies are separated from the adaptor pallets and rolled into the stores' beverage departments where they will remain until the bottles are sold. At return, when the bottles have been sold, the empty trays are stacked on the dollies and transported back to production. Figure 1 illustrates the system.

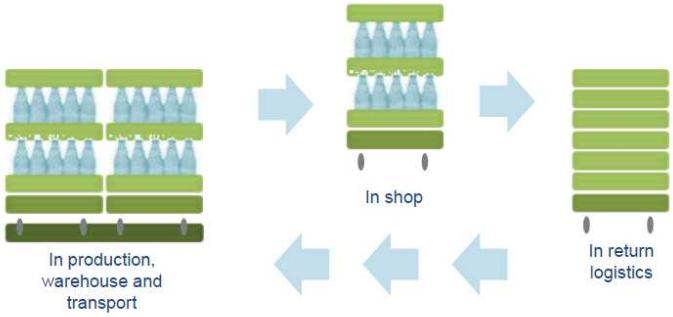

Figure 1. The TDP system (K.Hartwall corporate presentation 2013)

In Figure 2, a beverage tray is shown. This tray is designed to carry twenty four 0,5 litre bottles. The material used is HDPE and it is produced through injection moulding with a double cavity mould. Some of the technical specifications for the tray include:

- It must exhibit sufficient weather resistance for outdoor storage.
- It must remain intact when dropped from a height of one meter.
- It must withstand washing at 70 °C in an alkaline solvent with max 2 % NaCH.

Figure 2. Beverage tray (K.Hartwall)

3 LITERATURE REVIEW

In this chapter the company, materials, recycling of PET and the production methods are presented. The rheology of polymers is also reviewed in order to explain what determines the viscosity of a plastic melt. Finally a method for generating viscosity curves with an injection moulding machine is presented.

3.1 Polyethylene terephthalate (PET)

Polyethylene terephthalate (PET) is a thermoplastic polymer that belongs to the polyester family, as it contains the ester group in its main chain. The monomer is mainly synthesized through the esterification reaction of ethylene glycol and terephthalic acid. Synthesization is immediately followed by polymerization through polycondensation

which produces the polymer and as a by-product, water. In Figure 3, the repeating unit of the polymer chain in PET is shown. (Odian 2004:93 f.)

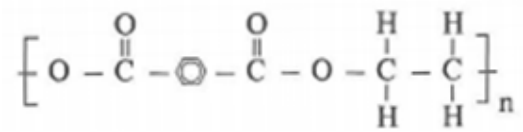

Figure 3. The repeating unit of polyethylene terephthalate (Klason & Kubát 2001:122)

PET can be both amorphous (APET) and semi-crystalline (CPET). By the use of low mould temperatures and quick cooling, amorphous parts can be produced whereas high mould temperatures and slow cooling of the melt leads to semi-crystalline parts. Amorphous polymers solidify in random arrangement while crystalline polymers align in an ordered crystal structure. No polymer can crystallize 100 % but polyethylene for example, can reach 90 %. This means that 90 % of the material is crystalline and 10 % is amorphous. Therefore the term semi-crystalline is used. Figure 4 illustrates the difference between amorphous and semi-crystalline polymers. (Crane et al. 1997:58 f.)

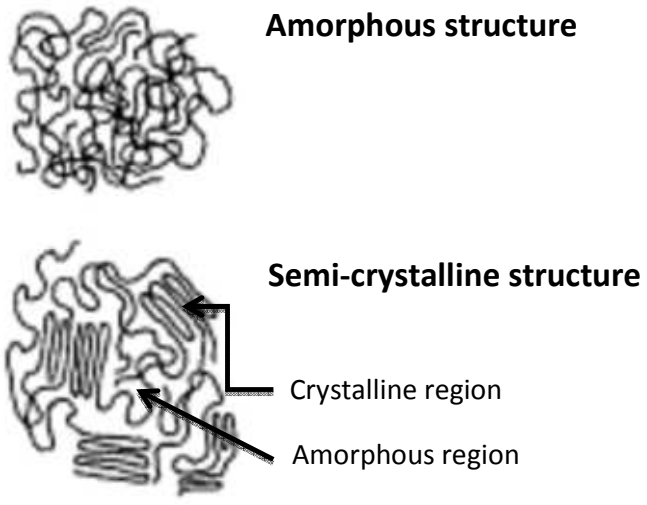

Figure 4. Amorphous and semi-crystalline structure (Crane et al. 1997:59)

Typical properties for amorphous and semi-crystalline polymers are as following:

Amorphous	Semi-crystalline
- Broad softening range - Usually transparent - Low shrinkage - Low chemical resistance - Poor fatigue and wear resistance	- Sharp melting point - Usually opaque - High shrinkage - High chemical resistance - Good fatigue and wear resistance

(Crawford 1998:4 f.)

PET is used in for example beverage bottles, flexible food packaging, fast food trays, space blankets, synthetic fibres, gear wheels and bearings. (Osswald et al. 2006:606)

3.1.1 Processing

PET is a very versatile polymer and can be processed through many methods. The most common methods include extrusion, thermoforming, blow moulding and injection moulding. A combination of injection moulding and blow moulding is the most used production method for PET today and is done to produce bottles for beverages. (Zeus Industrial Products, Inc. 2010:2)

One very important thing to consider when processing PET is moisture. PET is a hygroscopic material and is very sensitive to moisture when processed. When water and sufficient heat is present hydrolysis occurs, which leads to de-polymerization and a decrease in the molecular weight. This means the polymer chain is cut and shortened which results in a decrease in strength, toughness and viscosity. Because of this it is important to dry the material thoroughly and minimize the amount of moisture before processing. (Giles et al. 2005:217)

PET should be dried at a temperature between 137,8 and 160 °C (280-320 °F) using a drier that reaches a dew point of -28,9 °C (-20 °F) or below. The drying time for virgin pellets should be at least four hours and that of recycled flakes at least five to six hours. PET should be dried to a moisture content of 0,01 %. (CWC 1998:2)

According to Giles et al. the moisture limit is 0,02 %, and should not be processed if this value is exceeded. As can be seen in Table 2, dried PET with 0,01 % moisture kept in room temperature and 50 % relative humidity will absorb moisture up to 0,02 % within 15 minutes. (Giles et al. 2005:217)

Table 2. Rate of moisture absorption of PET resin dried to 0,01 % moisture (Giles et al. 2005:217)

Relative humidity %	15 minute exposure	1 hour exposure	24 hour exposure
15	0,015	0,017	0,032
50	0,02	0,03	0,082
100	0,035	0,055	0,3

3.1.2 PET and injection moulding

Other than in bottle production, PET has traditionally not been used as a material for injection moulding. In addition to its moisture sensitivity, it has been difficult to produce semi-crystalline mouldings because PET exhibits a slow crystallization rate and is apt to embrittle upon crystallization. However, nowadays there are solutions to encounter these problems and to enhance the properties of PET. Nucleating agents can be mixed with PET to improve the crystallization rate and quality and drying equipment has been developed to meet the requirements of PET. (Scheirs & Long 2003:495 f.)

The processing temperature window is 260-300 °C and mould temperatures depend on whether the aim is to produce semi-crystalline or amorphous parts. Mould temperatures for semi crystalline parts should be 130-150 °C, which of course means slower cooling. By using nucleating agents the mould temperature can however be slightly lower. For amorphous parts the mould temperature should be according to Osswald et al. 20°C. According to Scheirs & Long (Scheirs & Long 2003:496) unmodified PET can be injection moulded without difficulty only with mould temperatures of 15-40 °C. Shrinkage is notably smaller for APET (0,2 %) than for CPET (1,2-2,0 %). (Osswald et al. 2006:718)

Other than nucleating agents, PET can be modified by the use of a number of different additives in order to overcome problems and to improve certain properties. Plasticizers can also promote crystallization as well as act as processing aids by reducing the inter-molecular forces between the PET chains (Sheirs & Long 2003:521). This has the effect of a lubricant and allows the chains to slip past one another easier. In Table 3 some problems that one might encounter when processing PET are listed, as well as additives that can be used as solutions for the problems. (Sheirs & Long 2003:496)

Table 3. PET deficiencies and suggested solutions (Sheirs & Long 2003:496)

Property deficiency	Remedy
Hygroscopicity	Internal desiccants
Slow to crystallize	Nucleating agents, plasticizers
Uneven crystal size	Nucleating agents
Low glass transition temperature	Glass fibres
Brittle fracture behaviour	Impact modifiers
Notch sensitivity	Impact modifiers
Drop in IV during extrusion	Chain extenders
Oxidation during extrusion	Stabilizers
Hydrolysis	Hydrolysis repair additives
Autocatalytic acid-catalyzed hydrolysis	Carboxyl scavengers
Warpage	Mineral fillers

3.1.3 Properties

As for most plastics, the properties will depend quite highly on the degree of crystallinity and molecular weight. Higher molecular weights (or longer polymer chains) enhance mechanical properties such as strength and stiffness (see Figure 5). PET is available with different molecular weights and as earlier mentioned can be used to produce both amorphous and semi-crystalline parts. Generally, however, PET is considered to be a hard, strong and stiff material with good weathering and UV resistance, good electrical properties, low coefficient of friction. Campo states that PET has high melt flow-properties (Campo 2008:28) and, likewise, Zeus Industrial Products Inc. mentions that PET has a low viscosity which allows it to fill complex and thin sections easily (Zeus Industrial Products, Inc. 2010:5). Furthermore, PET is not susceptible to stress cracking. It has good chemical resistance and is not harmed by weak acids, weak alkali solutions, oils, fats, aliphatic and aromatic hydrocarbons and carbon tetrachloride. On the other hand it can be harmed by strong acids, strong alkali solutions, phenol and long term use

in water above 70 °C. When exposed to hot water hydrolysis can occur. But according to Tammela (Tammela 1989:140) it is possible to sterilize PET in boiling water or hot steam multiple times because sterilization can be done fast enough. (Osswald et al. 2006:606 f.).

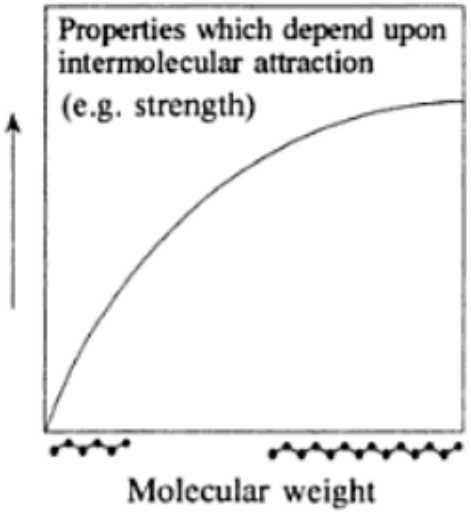

Figure 5. Effect of molecular weight on mechanical properties (Malloy 1994:6)

Semi-crystalline PET (CPET) usually has a degree of crystallinity of 30-40 % and has the following specific properties:

- High stiffness and strength below 80 °C
- Low creep under static load
- Good slip and wear properties
- Low impact resistance

Amorphous PET (APET) has the following specific properties:

- High toughness
- Excellent slip and wear properties
- Low shrinkage
- High dimensional stability
- High transparency
- At temperatures above 80 °C, Young's Modulus declines considerably

(Osswald et al. 2006:606 f.)

Table 4 shows some properties for amorphous and semi-crystalline PET.

Table 4. CPET and APET physical properties

Property		Unit	CPET	APET
Density		g/cm^3	**1,37** (Tammela 1989:142)	**1,33** (Tammela 1989:142)
Glass transition temperature		°C	**73-79** (Tammela 1989:142)	**68-77** (Tammela 1989:142)
Melting temperature		°C	**255-258** (Tammela 1989:142)	
Vicat softening temperature		°C	**188** (Tammela 1989:142)	**80** (Tammela 1989:142)
Specific heat		kJ/kgK	**1,05** (Osswald et al. 2006:733)	
Thermal conductivity		W/mK	**0,24** (Osswald et al. 2006:733)	
Heat of fusion		kJ/kg	**137** (Osswald & Menges 2003:123)	
Temperature resistance	**Short term**	°C	**200** (Tammela 1989:142)	**180** (Tammela 1989:142)
	Long term	°C	**100** (Tammela 1989:142)	**100** (Tammela 1989:142)
Tensile strength		MPa	**74** (Tammela 1989:142)	**55** (Tammela 1989:142)
Strain at break		%	**50-300** (Tammela 1989:142) **<10** (Torres et al. 2000:2079)	**150-300** (Tammela 1989:142) **>100** (Torres et al. 2000:2079)
Tensile modulus		MPa	**2850** (Tammela 1989:142)	**2500** (Tammela 1989:142)
Notched impact strength (Charpy)		kJ/m^2	**4** (Tammela 1989:142)	**5** (Tammela 1989:142)
Low temperature toughness		°C	**Between -40 and -60** (Zeus Industrial Products, Inc. 2010:4)	

3.2 Recycled polyethylene terephthalate (rPET)

Recycled polyethylene terephthalate (rPET) is material derived from products made originally out of PET. The quality of rPET will depend on things like:

- Thermal history
- The conditions in which previous processing has been carried out
- Amount of contamination
- Molecular weight

Recyclates are available as flakes and pellets, in different qualities. Clean and high quality recyclates can compete with virgin PET in many areas. For example, rPET can be used in the production of packaging for both non-food and food items. These include

bottles, boxes, trays, shallow pots, and cups. When producing food packaging, the quality of the recyclate has to be very high. (Plasticseurope 2013)

According to Petcore, the largest amount of rPET can be found in fibres. In Figure 6 rPET applications are divided into four categories and their share in the total amount of rPET used is shown. (Petcore 2012:1)

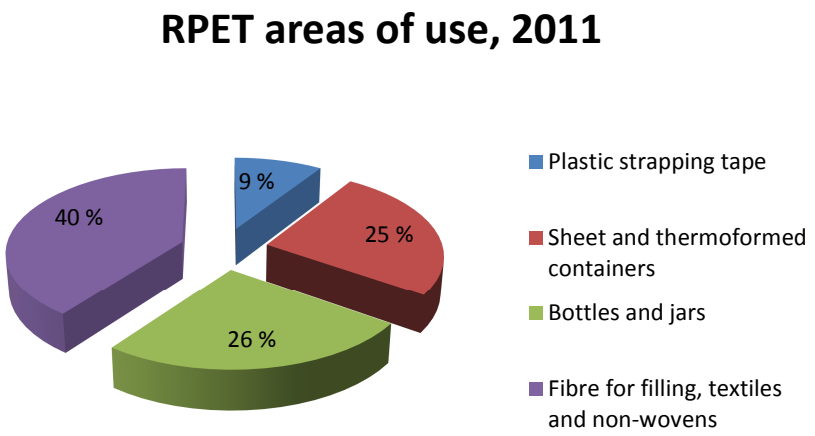

Figure 6. RPET areas of use, 2011 (Petcore 2012:1)

Flakes can in theory directly be placed into an injection machine but there is a risk that bridging will occur. This means that a blockage at the feed throat, which connects the feed hopper with the barrel (see chapter 3.5), is caused by clumps that are formed out of flakes because of the following reasons: the size and the low bulk density of flakes and their tendency to curl and mechanically interlock when dried. Therefore it is common that flakes are pelletized before injection moulded. (Brandau 2011:190)

PET recycling offers the following environmental benefits:

- Oil is conserved. When a ton of rPET replaces PET, 3,8 barrels of petroleum is saved. (Benefits of recycling 2013)
- Saving space on landfills. (Benefits of recycling 2013)
- Energy consumption, in comparison to PET, is reduced by 84 % and a reduction in greenhouse gas emission of 71 %. (Napcor 2013)

According to Franklin Associates, the energy consumption for producing PET resin is 31,9 Btu/1000 pounds (1 Btu = 1,055 Joule) and that of rPET flakes is 5,1 Btu/1000 Pounds. (Franklin Associates 2010:39)

3.2.1 Collection

The European Union Packaging and Packaging waste directive 2004/12/EC, stipulates that member countries must have a collection system for recovering used packages and that the collection rate should be above 22,5 %. According to Petcore, European post-sorting PET collection reached 1,59 million tonnes in 2011. This is an increase of 9,4 % since 2010. The overall collection rate of all PET bottles in the market reached 51 % within Europe, in 2011. The mechanical reclamation capacity within the 27 EU member states plus Iceland, Norway, Switzerland and Turkey was estimated to be 1,9 million tonnes which means the recyclers are able to absorb a large increase in the PET collection rate.

The first step in recovering PET material is collection. This can be done in many ways but if we take the European Union as an example, three different procedures are used for collecting plastics: drop off locations, kerbside collection and refill and deposit. Drop off locations mean that the recyclables are collected by citizens who then take them to specific locations. The plastic recovered through this procedure contains a level of contamination up to 10-30 %. The kerbside collection system is done through waste separation in households. Citizens put recyclable materials in specific waste bags, which are then collected the same way as regular refuse. This is convenient for citizens and offers low contamination levels. The refill and deposit method works by selling bottles with a refundable deposit, which is redeemable when the bottles are returned. Both refillable and single use bottles can be involved in this system. Return vending machines that are placed at locations where bottles are sold are often used for this purpose. Therefore the bottles can be returned whenever people go buying groceries or beverages and no separate trip to a drop off location is needed. Furthermore return rates up to 90 % and a very low degree of contamination is achieved. (Petcore 2013)

Collected bottles are then compacted into bales in order to reduce volume and make transportation more efficient. After this the bales are sold to reclaimers which can proceed through three different methods, depending on the quality and the level of contamination of the collected material. If the contamination level is low, new raw material can be produced through mechanical recycling. With a medium contamination level chemical recycling can be utilized to break down the polymers into the starting monomers, terephthalic acid and ethylene glycol. These are then purified and used to polymerize new PET resins. This is not as widely used as mechanical recycling at the moment, because cost efficiency is achieved only if very big recycling lines are used. The third alternative is to use the material as an energy source by burning it. This method is used if the material has high contamination levels. PET has an intrinsic energy content that is comparable to soft coal, 23 MJ/kg, which makes it a good fuel. Furthermore, PET is safe to recover by combustion as it only produces carbon dioxide and water with controlled burning. (Plasticseurope 2013)

3.2.2 Mechanical recycling

Reclaimers can utilize different processes to produce flakes or granules, but typically the procedure would look more or less as following: When the bales reach the recycling plant, the first step is sorting de-baling which is done by a bale breaker. Metals and tins that still are present will be removed by a high energy magnetic drum separator. After this the material will be checked for any coarse nonferrous metals. This is done with sensors that emit a high frequency electromagnetic signal. If any metal pass the sensors the signal amplitude will change which is noticed by a receiver coil inside the sensor and the metals will be separated by blasts of air. The sensor can be adjusted so that small metal particles attached to bottles are ignored in order to avoid unnecessary loss of whole bottles. These small particles are removed later on. Next, foreign plastics that are different in composition to PET are removed. As these plastics might be quite similar optically, they are identified using infrared spectroscopy. Finally the bottles are sorted according to colour by using a high speed charged couple device camera system. (Garmson & Gardiner 2010 82 f.)

After sorting, the bottles are ground through a dry granulation process or a wet shredding process. Next the flakes go through a hot wash in order to remove labels and glues. Polyolefin caps are removed by feeding the flakes into a flotation tank where PET material will sink to the bottom and the polyolefin materials will remain floating due to their lower densities. After this the small metal particles that were ignored before are now removed. The flakes are inspected with a segmented high-frequency detector that can detect very small metal pieces. Any metal detected will be removed by a blast of air. If the material is to be further treated in order to produce food grade material, two main methods are used:

1. URRC (American United Research Recovery Corporation) process: the flakes are heated and their outer surfaces are peeled off by friction using a chemical dissolver. This way any substances that have migrated into the plastic will be removed. After this the flakes are colour-sorted by using a true colour camera that recognizes 256 million colours. Discoloured flakes, flakes with remaining glue and polyolefin parts are rejected. Light blue flakes will remain with clear flakes in order to brighten the colour. As a result of heating the flakes, plastics like polyvinyl chloride (PVC) or polyamide (PA) change colour and can easily be removed. Finally, contaminants that cannot be separated by colour are detected by a polymer type separator that uses infrared spectroscopy.
2. SSP (Solid State Polycondensation) process: further decontamination is done by re-pelletizing the flakes but unlike the URRC process, this takes place after the colour and polymer type separation. This process uses special reactors and extruders. The flakes are melted and volatile contaminates residing in the flakes and by-products of the process are removed by a gas purification system. This is followed by extrusion and pelletizing. After this, the intrinsic viscosity (see chapter 3.2.3) of the pellets is increased by heat in the absence of oxygen and water.

(Garmson & Gardiner 2010 84 ff.)

3.2.3 Intrinsic viscosity

One important factor concerning price and quality of rPET is molecular weight. When dealing with rPET, molecular weight is most commonly expressed in terms of intrinsic

viscosity. Te value for intrinsic viscosity is obtained by first measuring the viscosity of a polymer solution. The time taken for the polymer solution to pass between two marks is compared to the time it takes for a pure solvent and the ratio between these is the viscosity. Successive dilutions give a range of concentrations and times which are then used to calculate the intrinsic viscosity. The relationship between molecular weight and intrinsic viscosity can be seen in the Mark-Houwink equation:

$$Intrinsic\ viscosity = KM^X$$

Where: $K\ and\ X = Constants\ for\ the\ particular\ solvent\ being\ used,$
$referred\ to\ as\ the\ Mark - Houwink\ parameters$
$M = Molecular\ weight$

(Forrest 2002:14)

For PET, there are certain demands for the intrinsic viscosity depending on in which product area the material is used. Table 5 contains the ranges of the intrinsic viscosities used within certain areas.

Table 5. Intrinsic viscosity range of PET (Wikipedia 2013a)

		Intrinsic viscosity (dl/g)
Fibre grade	Textile	0,40 – 0,70
	Technical, tire cord	0,72 – 0,98
Film grade	BoPET (biaxially oriented PET film)	0,60 – 0,70
	Sheet for thermoforming	0,70 – 1,00
Bottle grade	Still water bottles	0,70 – 0,78
	Carbonated soft drink bottles	0,78 – 0,85
Monofilament, engineering plastic		1,00 – 2,00

To increase the quality of the recyclate, different ways of increasing the molecular weight and intrinsic viscosity are utilized. As earlier mentioned this can be done when the material is in solid state (SSP) but it can also be done in the melt state through reactive extrusion. This is a faster process and can be applied during the ordinary melt processing. One problem with reactive extrusion is that it can be difficult to control the extent of chain lengthening. (Tajan et al. n.d.:1)

Tajan et al. studied the effect of hexamethylene diisocyanate (HMDI) when used as a chain extender, in reactive extrusion, to increase the molecular weight of rPET. Experiments were done with bottle grade PET and colourless post-consumer bottle rPET. Their respective intrinsic viscosities were 0,75 dl/g and 0,59 dl/g. The reaction was performed in a BETOL 2525SP single screw extruder. Different weight percentages of HMDI mixed with PET and rPET was tested and 0,9 wt% proved to be suitable for these experiments. Both the virgin and recycled PET were dried for 2 hours at 170 °C in an ordinary oven before the HMDI was added. Melt flow index was done according to ASTM D1238, method A. The load weight was 2,16 kg, the temperature was not mentioned. Intrinsic viscosity measurements were done according to ASTM D4603 by using a capillary viscometer. Rheological characterization was performed with a capillary rheometer. (Tajan et al. n.d.:1 ff.)

When the modified PET (PETm) was extruded with a speed of 10 rpm, the MFI decreased from 35,08 g/dl to 11,50 dl/g. When using speeds higher than 10 rpm the MFI did not decrease as much, indicating that the residence time was too short and the reactions were uncompleted. For modified rPET (rPETm), however, the minimum MFI was obtained when using a speed of 20 rpm. Furthermore it was found that amount of reacted HMDI in rPETm was higher than that of PETm, 0,514 g and 0,310 g respectively. It was suspected that the reason for this was that rPET was subjected to a higher degree of thermal and hydrolytic degradation and thus producing more hydroxyl and carboxyl end groups which increased the amount of reactions between HMDI and rPET. In Table 6, the melt flow indices and the intrinsic viscosities can be seen. (Tajan et al. n.d.:1 ff.)

Table 6. MFI and intrinsic viscosity before and after reactive extrusion (Tajan et al. n.d.:2)

Material	Screw rotating speed (rpm)	Melt flow index (g/10 min)	Intrinsic viscosity (dl/g)
PET		35,08	0,75
mPET	10	11,50	1,25
PETR		81,12	0,59
mPETR	20	31,40	0,90

3.2.4 Earlier research concerning the technical properties of rPET

It is difficult to find specific information about the properties of rPET because the quality can be so varying, but a fair amount of studies about this subject have been done. In this chapter one study will be reviewed.

Torres et al. compared the thermal, rheological and mechanical properties between two rPET flake types and virgin PET. One of the rPET types (rPETb) was produced from homogenous deposits of blue bottles, containing less than 20 ppm of PVC. The other type (rPETc) was produced from heterogeneous deposits of mixed colours, containing 6000 ppm of PVC. The virgin PET pellets were dried for 5 hours at 160 °C, the rPET flakes 2 hours at 120 °C and 4 hours at 140 °C in a dehumidifying drier. Test specimens were prepared through injection moulding with a barrel temperature of 250-280 °C and a mould temperature of 8 °C. The test specimens were conditioned at 20 °C for a minimum of three days. Thermograms were produced with a differential scanning calorimeter and the viscosity measurements were done with a viscosimeter. The molecular weight was calculated with the Mark Houwink equation presented in the previous chapter. Crystallinity was calculated with the enthalpy of crystallization and enthalpy of melting. Table 7 shows the results for intrinsic viscosity and molecular weight and Table 8 contains results for the glass transition temperature (T_g), crystallinity and mechanical properties. (Torres et al. 1999:2075 ff.)

Table 7. Intrinsic viscosity and average molecular weight before and after injection moulding (Torres et al. 1999:2078)

	Intrinsic viscosity (dl/g)	Average molecular weight
PET pellets	0,76	44000
PET injection moulded	0,74	42200
rPETb flakes	0,77	44900
rPETb injection moulded	0,69	37900
rPETc flakes	0,80	47600
rPETc injection moulded	0,61	31300

Table 8. Glass transition temperature, crystallinity and mechanical properties (Torres et al. 1999 2077:2077 ff.)

	PET	rPETb	rPETc
T_g (°C)	80	81	80
Crystallinity before injection moulding (%)	46	31	31
Crystallinity after injection moulding (%)	10	13	16
Young's Modulus (MPa) ISO 527, 1 mm/min	2140 (±206)	2170 (±184)	1996 (±210)
Strain (%) ISO 527, 50 mm/min	270 (±57)	5,4 (±0,6)	3,0 (±0,4)
Charpy impact strength (notched, 20 °C, kJ m^{-2}) ISO 179	3,0 (±0,2)	2,4 (±0,5)	1,8 (±0,3)
Appearance of test bars	Transparent	Opaque	Opaque

The intrinsic viscosity reduces significantly for the rPETb and rPETc when processed, especially rPETc. Torres et al. states that one contribution for this could be that the amount of retained moisture coming from the flakes is greater than that of the PET pellets and. Simultaneously the contaminants, such as PVC and adhesives, that are present in the flakes generate acid compounds during processing which catalyze the hydrolytic scission. (Torres et al. 1999:2078)

The results show that the crystallinity was higher for rPETb and rPETc, than for PET. The authors explain that the crystallization of rPET is facilitated by two main things: the presence of contaminants that act as nucleating agents and the decrease in molecular weight after processing. The rPET test bars also exhibited crystalline behaviour both from the aspect of mechanical properties and appearance. The Young's Modulus was quite similar for all materials but strain was strongly reduced and impact strength was lower for the recycled materials. This brittleness along with the opaque appearance is evidence of semi-crystalline behaviour. The results show that the amount of contaminants is an important parameter for rPET.

3.3 High density polyethylene (HDPE)

Polyethylene is available in many different types with different properties. As a homopolymer, PE can be categorized according to density. Density depends on the degree of crystallinity which, in turn, will depend on molecular weight and what type of structure and branching the polymer has. PE can be divided into four different groups when classified by density:

1. Density: 0,910 - 0,925. Low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE).
2. Density: 0,926 - 0,940. Medium-density polyethylene (MDPE).
3. Density: 0,941 - higher. High-density polyethylene (HDPE)
4. Density: 0,930 – 0,940. Ultra-high-molecular-weight polyethylene (UHMWPE).

The molecular weights are as following in respect to each other: LDPE/LLDPE< MDPE< HDPE< UHMWPE. For UHMWPE, the molecular weight is so high that the packing of the long chains into the crystalline structure cannot happen as densely as for HDPE. Therefore HDPE has a higher density. The degree of crystallinity for HDPE is typically 60-80 % (Osswald et al. 2006:515). The repeating unit of polyethylene can be seen in Figure 7. (Tammela 1989:31)

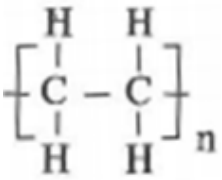

Figure 7. The repeating unit of polyethylene (Klason & Kubát 2001:108)

HDPE is the most used polyethylene type and can be processed through, for example, injection moulding, extrusion, blow moulding, thermoforming and rotational moulding. It offers both strength and processability which are desired properties, especially for injection moulding. HDPE is harder and more rigid than the lower density polyethylene types. Generally it is considered as a material with low density, relatively low strength and stiffness (although a large strength to weight ratio), high toughness, high elongation at break, good friction and wear behaviour and very good electrical and dielectrical properties. On the negative side it is prone to stress cracking, has high mould shrinkage

and is UV-sensitive. Some of the properties can be seen in Table 9. (Vasile & Pascu 2005:16 f.)

When processing HDPE through injection moulding the melt temperature window is wide, 180-250 °C. Mould temperatures should be between 10 °C and 60 °C and mould shrinkage can be expected to be 1,5-3,0 %. (Osswald et al. 2006:718)

Table 9. HDPE physical properties

Property		Unit	Value
Density		g/cm^3	**≥ 0,941** (Tammela 1989:31)
Glass transition temperature		°C	**-110** (Vasile & Pascu 2005:31 ff.)
Melting temperature		°C	**120-130** (Vasile & Pascu 2005:31 ff.)
Vicat softening temperature		°C	**112-132** (Vasile & Pascu 2005:48)
Specific heat		kJ/kgK	**2,1-2,7** (Osswald et al. 2006:733)
Thermal conductivity		W/mK	**0,38-0,51** (Osswald et al. 2006:733)
Heat of fusion		kJ/kg	**245** (Ineos 2009)
Continuous service temperature	**Max.**	°C	**100-120** (Vasile & Pascu 2005:31 ff.)
	Min.	°C	**-70** (Vasile & Pascu 2005:31 ff.)
Tensile strength		MPa	**20-35** (Vasile & Pascu 2005:31 ff.)
Strain at break		%	**150** **100-1000** (Osswald et al. 2006:731)
Tensile modulus		MPa	**413-1241** (Vasile & Pascu 2005:31 ff.)
Notched impact strength (Charpy)		kJ/m^2	**2-12** (Vasile & Pascu 2005:60)

The energy consumption for producing HDPE resin is according to Franklin Associates, 35,8 Btu/1000 pounds. (Franklin Associates 2010:39)

3.4 Titanium Dioxide (TiO_2)

Many of the most durable pigments consist of metallic oxides, such as titanium dioxide. These offer properties such as heat stability, light stability, chemical inertness, lack of bleeding and migration, desired electrical characteristics and low absorption. The most common crystal forms of titanium dioxide are anatase and rutile. Both of these crystal forms are tetragonal and in an octahedral pattern. As can be seen in Figure 8 each octahedron in anatase shares four of the twelve edges with neighbouring octahedral whereas in rutile, two of twelve edges are shared. (Lutz & Grossman 2001:43 f.)

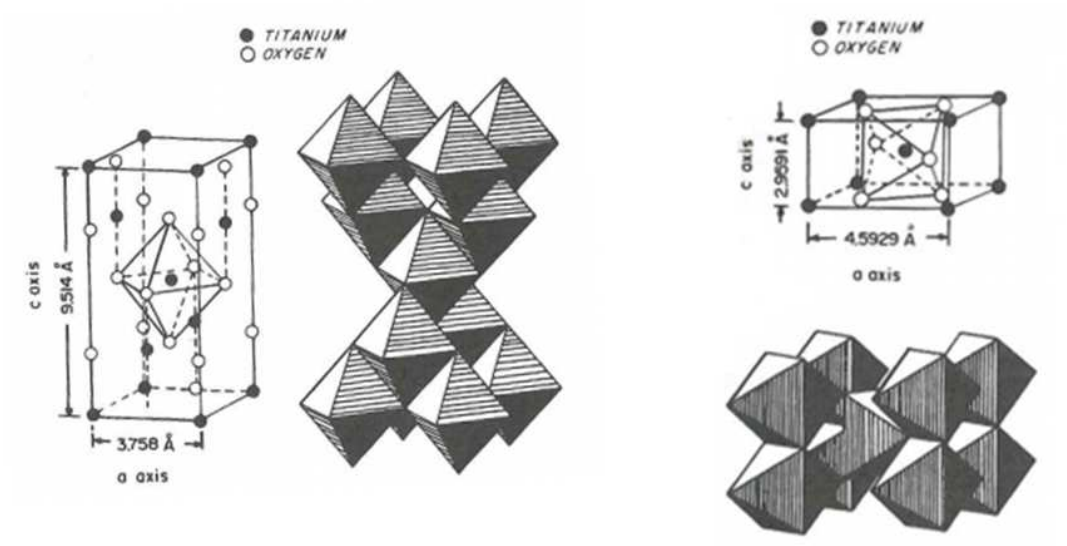

Figure 8. Crystal structure of anatase (left) and rutile (right) titanium dioxide (Lutz & Grossman 2001:44 f.)

When incorporated, titanium dioxide offers whiteness (the whitest pigments known), brightness and opacity. The rutile form has the highest refractive index of white pigments and resists chalking better than the anatase form. Anatase have a slightly bluer shade and thus will appear whiter, it has a lower refractive index and is easier to disperse. Rutile pigments can exhibit higher brightness and opacity and have better weathering properties. Because of this, rutile pigments have largely replaced anatase pigments in polymer systems. Some properties of anatase and rutile can be found in Table 10, where they are compared with zinc oxide. Zinc oxide is also used as white pigment, but its use is very small in comparison to titanium dioxide. (Lutz & Grossman 2001:44)

Table 10.Typical properties of titanium dioxide and zinc oxide (Lutz & Grossman 2001:141)

Property	Titanium dioxide		Zinc oxide
	Anatase	Rutile	
Average particle size (μm)	0.3	0.2–0.3	0.2
Density (g/cm^3)	3.9	4.1	5.6
Refractive index	2.55	2.76	2.01
Tinting strength	1200	1600	210
Oil absorption (lb/100 lb)	18–30	16–48	10–25
Hardness (Mohs)	5–6	6–7	4+

3.4.1 Earlier similar studies with Titanium dioxide

An investigation was done in Industrial Research Institute Swinburne by Mark Kegel about how some commonly used additives affect the processability and physical properties of rPET. The additives were: TiO_2 (Tioxide A-HR organically coated anatase), Carbon Black, Linear-low-density-polyethylene and polyethylene wax. These additives were blended with rPET so that four blends contained one of the additives separately and one blend was made containing all of the additives. Table 11 shows the weight percentage of each additive used in the blends. These blends were then analyzed for shifts in thermal transition points, degree of crystallinity, physical properties and processability. The blends were first dried, then pre compounded with an extruder, then dried again and finally injection moulded. Impact testing was done according to ASTM D 256 and tensile testing was done according to AS 1145. Thermal testing was performed through differential scanning calorimetry (DSC) at heating and cooling rates of 15°C per minute. Processability was determined by looking at parameters such as throughput in kg/h and amperage in %. The standard deviations were taken from the tensile and impact test and were assessed in order to determine how much variation in physical properties, from shot to shot, the blends exhibited. The smaller the standard deviation, the higher score for reproducibility was given to the blend. (Kegel et al. 2002:1-5)

Table 11. Levels of addition of the additives (Kegel et al. 2002:6)

Additive	Rate (weight %)
TiO_2	0.5
LLDPE	0.9
Wax	0.2
CB	0.06
All	All additives at respective rates of addition

Table 12 shows the results for rPET without additives and Table 13 shows the results for rPET containing TiO_2. In Table 14 the relative reproducibility of the blends can be seen. The results showed that the mechanical properties remained practically unaltered for all the blends. However, notable changes in processability, glass transition temperature and degree of crystallinity could be seen. The TiO_2 blend proved to be better than the other blends and significantly better than unmodified rPET, in terms of processing and reproducibility. This blend also produced the highest degree of crystallinity. (Kegel et al. 2002:4-6)

Table 12. Properties of unmodified re-extruded rPET (Kegel et al. 2002:6)

Processability	Poor
Impact Strength (J/m)	29.8
Tensile Strength at Yield (MPa)	57.4
Elongation at Yield (%)	5.3
Modulus (MPa)	1804
Crystallinity (%)	32.3
T_g (^oC)	81.6

Table 13. Properties of rPET/TiO_2 blend (Kegel et al. 2002:6)

Processability	Very Good
Impact Strength (J/m)	29
Tensile Strength at Yield (MPa)	56.7
Elongation at Yield (%)	5.2
Modulus (MPa)	1805
Crystallinity (%)	34.7
T_g (^oC)	79.9

Table 14. The relative reproducibility of results (Kegel et al. 2002:6)

RPET re extruded	2
TiO_2	5
CB	2
LLDPE	4
WAX	3
All additives	1

3.5 Injection moulding and injection compression moulding

Injection moulding is one of the most important and most used production methods in the plastics industry. This method allows the production of parts with very complex shapes in an economical manner. Parts made with this method can be found just about in every building and vehicle. There are many different types of injection moulding processes, but in this chapter only the traditional type will be presented. Some examples of injection moulded parts: cell phone shells, various buckets and lids, television housings and fascia panels. (Crawford 1998:278 f.)

There are two main parts in a traditional injection moulding machine: the injection unit and the clamping unit. The task of the injection unit is to melt the polymer and to inject it into the mould. Typically this unit consists of a granulate hopper, cylinder, screw, nozzle, heating bands and hydraulic drives. (Plastics Wiki 2010b)

The main parts for the clamping unit are usually stationary platen, movable platen, mould, tie rods and hydraulic drives. This unit serves the purpose of opening and closing the mould, providing the clamping force in order to keep the mould closed and ejecting the finished part. In Figure 9 the parts of an injection moulding machine are shown. (Plastics Wiki 2010a)

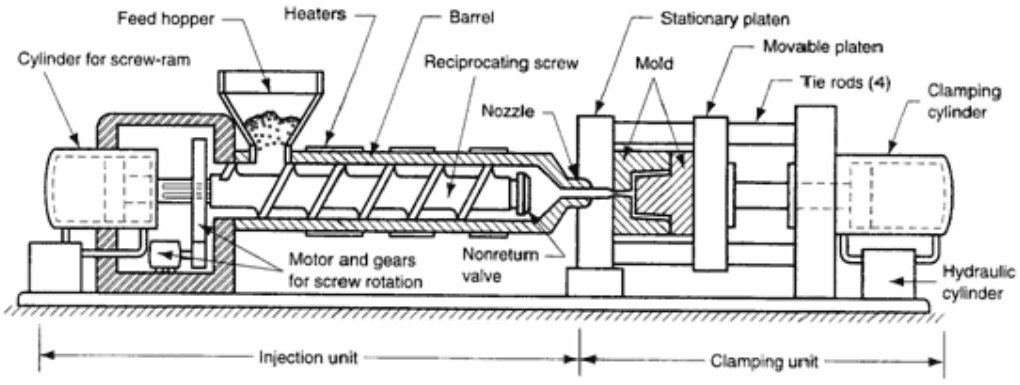

Figure 9. The various parts of a typical injection moulding machine (Plastics Wiki 2010b)

The quality of the moulding will be determined by the processing conditions where pressure, flow rate, time and temperature are the variables. These will greatly affect the outcome when considering strength, dimensional stability and surface properties. By changing the parameters it is possible to vary for example internal stresses, orientation, crystallinity and to prevent thermal- and mechanical degradation. Some plastics can be processed within wide ranges of these parameters and it is relatively easy to make the production robust for these. But some plastics have very narrow processing windows and therefore it is important to find the appropriate parameters in order to have a production with repeatable quality. (Klason & Kubát 2001:222 f.)

3.5.1 Process cycle

Injection moulding is, simply put, about melting the polymer, injecting it into a cold mould where the melt will start to solidify, applying hold pressure as it solidifies in order to compensate for shrinkage, cooling the part within the mould until it is cool enough to finally be ejected without deforming. (Klason & Kubát 2001: 232)

For normal injection moulding, a cycle would proceed as following: The mould closes and the screw acts as a plunger and injects the melt into the mould. The air inside will be pushed out through small vents as the melt flows into the mould. When the injection is completed and sufficient melt has been pushed in, a holding pressure will be applied. This will squeeze more melt into the cavity and thus compensate for shrinkage that occurs when the polymer cools. This will continue until the gate(s) freezes after which the screw will start to rotate, hence conveying in new melt for the next shot. As the material is being conveyed to the front of the screw where it cannot escape, pressure will build up and the screw will be pushed backward until the correct shot size is prepared. The material melts partly because of the friction that will arise from the conveying and partly of the heat added by the heating bands. The mould remains closed until the moulded parts temperature has decreased to the extent that it is solid enough to retain its shape. After this the mould opens and the part is ejected. Finally the mould closes again and the cycle is repeated. (Crawford 1998:282 f.)

The cycle time will mostly be defined by the cooling time as it adds up to more than two thirds of the whole cycle time, as illustrated in Figure 10.

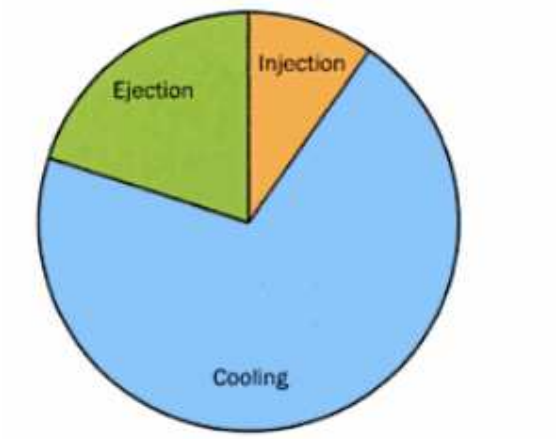

Figure 10. Typical injection moulding cycle (Shoemaker 2006:153)

Cooling time can be calculated with the following formulas:

For the centreline to reach ejection temperature in a plate:

$$t_c = \frac{h^2}{\alpha\pi^2} \ln\left(\frac{4}{\pi}\left(\frac{T_M - T_W}{T_E - T_W}\right)\right)$$

Equation 1. Cooling time for a plate (Malloy 1994:86)

For the centreline to reach ejection temperature in a cylinder:

$$t_c = 0{,}173\frac{r^2}{\alpha} \ln\left(1{,}6023\left(\frac{T_M - T_W}{T_E - T_W}\right)\right)$$

Equation 2. Cooling time for a cylinder (Malloy 1994:86)

Where: $t_c = cooling\ time$

$h = wall\ thickness$, thickest section

$r = radius$

α =thermal diffusivity

$T_M = melt\ temperature$

$T_W = wall\ temperature$

$T_E = ejection\ temperature$

(Malloy 1994:86)

Thermal diffusivity is calculated the following way:

$$\alpha = \frac{k}{\rho C_p}$$

Where: $k = thermal\ conductivity$

$\rho = density$

$C_p = specific\ heat$

(Malloy 1994:86)

3.5.2 Injection Compression Moulding

Injection compression moulding is a combination of injection moulding and compression moulding. In this process the volume of the cavity is slightly larger at the start of injection, which allows the melt reach the extremities of the mould with a relatively low pressure. During or after filling, the wall thickness of the mould cavity reduces into its final shape thus compressing the melt and completing the filling. The advantages of this method is that relatively stress free parts with homogenous properties and dimensional stability can be produced using lower pressure and clamp tonnage in comparison to conventional injection moulding. Material and cycle time can also be saved. (Osswald et al. 2006:335 f.)

According to Pötsch & Michaeli injection compression moulding is suitable for very thin-walled parts as the pressure need can be reduced as well as the risk of solidification during filling. The main disadvantage for this process is that expensive telescoping moulds that are subjected to high wear must be used. Conventional injection moulding machines can be used for the process, but an additional control module is necessary for the mould compression stage. Figure 11 illustrates the process. (Pötsch & Michaeli 1995:171 f.)

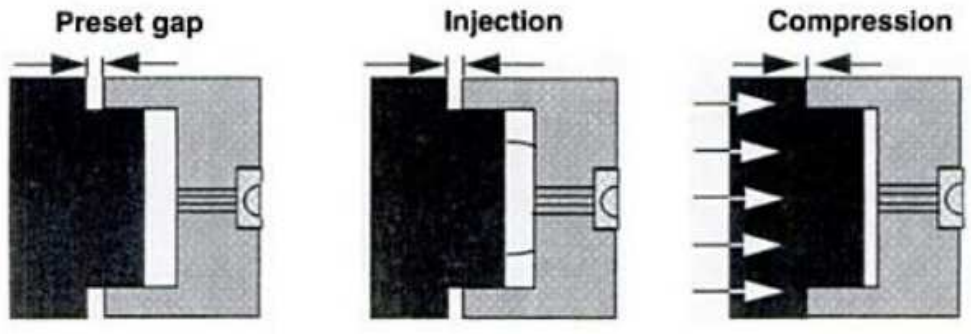

Figure 11. Stages of injection compression moulding(Avery 1998:133)

Although this process is mainly used for products like optical lenses and compact discs (Pötsch & Michaeli 1995:19 f.), Remaplan Anlagenbau GmbH has used this method to produce transport pallets out of a blend with 75 % rPET, 20 % post-consumer polyolefins and 5 % additives. (Doba 2000)

3.6 Polymer rheology

One way of characterizing fluids is to look how their viscosities respond to shearing. Viscosity can be seen as the fluids inner resistance to flow. From this aspect a fluid can be Newtonian or non-Newtonian. The viscosity of Newtonian remains constant with changing flow rate, or shear rate. The viscosity of Non-Newtonian fluids on the other hand, will vary depending on the shear rate. Shearing occurs because the melt adheres to the adjacent surfaces. This can be understood by imagining the flow between a moving plate and a stationary plate (see Figure 12). As a result of the relative movement of the plates, the liquid layers within the fluid will have different velocities which lead to shearing. Figure 13 shows how a volume element in the fluid will deform due to shear stress. The shear rate is calculated by dividing the difference in velocity between the upper and lower face of the volume element by its thickness. (Pötsch & Michaeli 1995:19 f.)

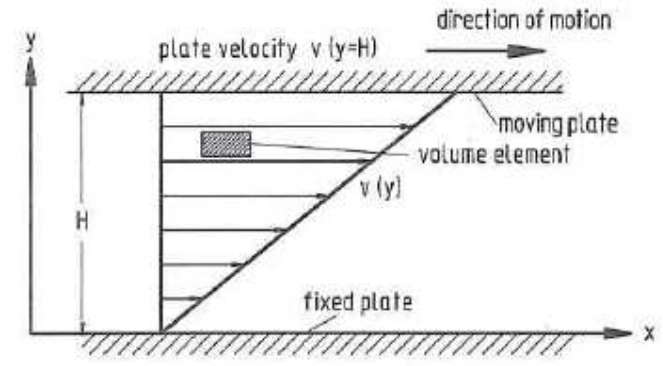

Figure 12. Two plate model of laminar shear flow (Pötsch & Michaeli 1995:20)

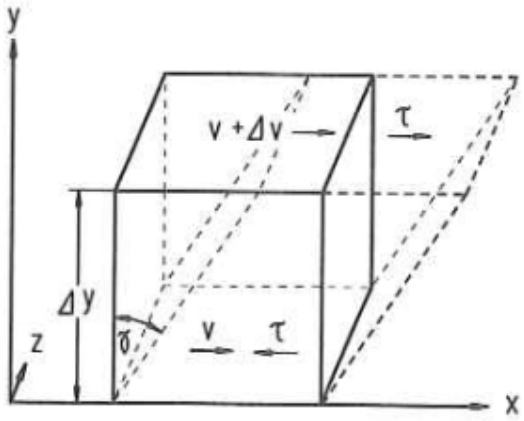

Figure 13. Volume element in shear stress (Pötsch & Michaeli 1995:20)

At very low shear rates plastics will behave more or less like a Newtonian fluid but at as the shear rate increases they will begin to exhibit non-Newtonian behaviour and viscosity will start to decrease as shear rate increases. This behaviour is called pseudo plastic, or shear thinning. The reason for this behaviour is that polymers consist of long molecules that entangle each other and thus resist movement. At low shear rates the chains remain entangled and so the resistance remains the same. It is not until the flow reaches higher shear rates that the polymer chains will eventually disentangle, aligning themselves to the direction of the flow leading to a reduction in viscosity. Due to this characteristic, higher injection rates in injection moulding lead to lower viscosities. Therefore, shorter fill times can potentially reduce the pressure drop and thereby decrease the pressure needed to fill a mould. It can also be mentioned that for some non-Newtonian flu-

ids viscosity will increase as shear rate rises, a behaviour called dilatant. Figure 14 shows the effect of shear rate on viscosity on a log-log graph and Figure 15 illustrates the effect without the use of a log scale. (Beaumont 2007:10 f.)

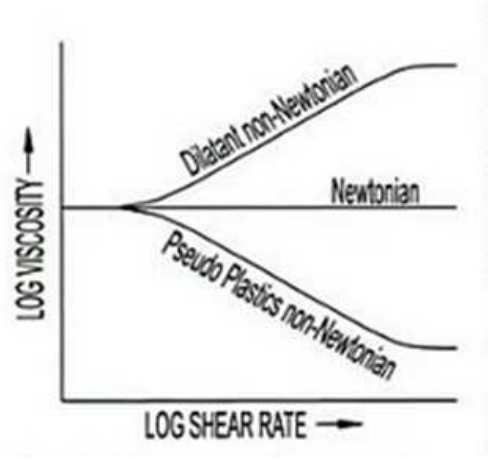

Figure 14. Viscosity vs. shear rate, log-log scale (Beaumont 2007:10)

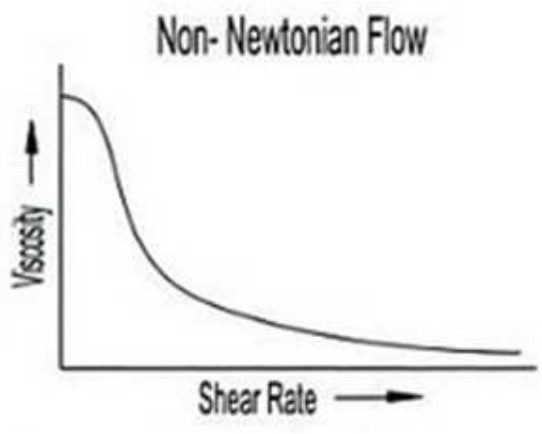

Figure 15. Viscosity vs. shear rate, non log-log scale (Beaumont 2007:11)

In addition to shear rate, viscosity will also depend on temperature and molecular weight. Pressure also somewhat affects viscosity as it will restrict the free movement of the molecules, but is normally neglected. An increase in temperature will lead to a reduction in viscosity, but too high temperatures will lead to degradation of the material. Molecular weight has effects on both mechanical and rheological properties. High molecular weights mean, as earlier mentioned, to stronger mechanical properties but this also leads to higher viscosities as longer chains will entangle easier (see Figure 16). Because the individual polymer chains within a polymer will seldom have the same length

there will be a molecular weight distribution. If the distribution is wide it means that there are some chains that are significantly shorter than the largest ones. These short chains can act as lubricants and improve the flow properties. If the distribution is narrow the flow properties will be worse because not short enough chains will be present. Narrow weight distribution also means that a higher force is needed to disentangle the chains, therefore higher shear rates are needed in order to reach the shear thinning area. (Pötsch & Michaeli 1995:27 f.)

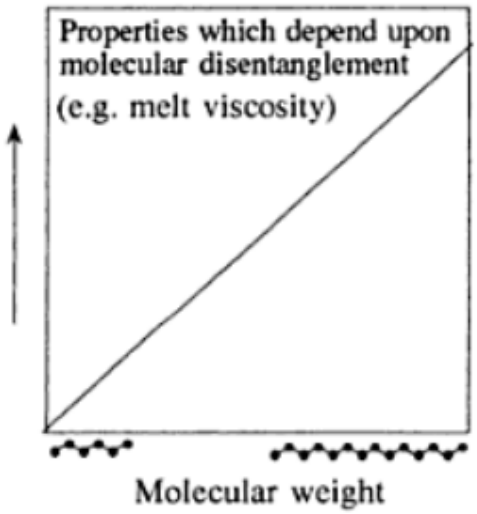

Figure 16. The effect of molecular weight on viscosity (Malloy 1994:6)

3.6.1 Mathematical models

For a Newtonian fluid the shear stress is proportional to shear rate and the viscosity serves as the proportionality constant:

$$\tau = \eta\dot{\gamma}$$

Equation 3. Shear stress, Newtonian fluids (Pötsch & Michaeli 1995:20)

Where: $\tau = shear\ stress$

$\eta = viscosity$

$\dot{\gamma} = shear\ rate$

(Pötsch & Michaeli 1995:20)

For non-Newtonian fluids different mathematical models have been developed to approximate and compare the rheological properties of different materials. The simplest formula for this is the power law;

$$\tau = \Phi\dot{\gamma}^{n}$$

Equation 4. Shear stress, non-Newtonian fluids (Pötsch & Michaeli 1995:29)

Where: $\eta = viscosity$

$\tau = shear\ stress$

$\Phi =$ fluidity

$\dot{\gamma} = shear\ rate$

$n = degree\ of\ shear\ thinning$

(Pötsch & Michaeli 1995:29)

Viscosity is represented by;

$$\eta = \Phi\dot{\gamma}^{n-1} = K_{OT}\dot{\gamma}^{m}$$

Equation 5. Viscosity, non-Newtonian fluids (Pötsch & Michaeli 1995:29)

Where: $\eta = viscosity$

$\Phi =$ fluidity

$\dot{\gamma} = shear\ rate$

$n = degree\ of\ shear\ thinning$

$K_{OT} = proportionality\ factor$

$m = n - 1$

(Pötsch & Michaeli 1995:29)

Note that the power law is limited because the parameters K_{OT} and m are valid only at certain shear rates. There are other models that will give a more precise approximation such as the Carreau law and the law of Vinogradow and Malkin. But the power law is still the most used model because of its simplicity. (Pötsch & Michaeli 1995:29)

The maximum shear rate will be at the wall of the flow channel and can be calculated with the following formulas:

For a round channel:

$$\dot{\gamma} = \frac{4\dot{Q}}{\pi R^3}$$

Equation 6. Shear rate for a round channel (Crawford 1998:376 f.)

For a rectangular channel:

$$\dot{\gamma} = \frac{6\dot{Q}}{TH^2}$$

Equation 7. Shear rate for a rectangular channel (Crawford 1998:376 f.)

Where: $\dot{\gamma} = shear\ rate$

$\dot{Q} = volume\ flow\ rate$

$R = Radius$

$T = width$

$H = wall\ thickness$

(Crawford 1998:376 f.)

Pressure loss for a constant for a pipe with constant cross section and flow rate, can be solved from the following equation:

$$\eta = \frac{\pi P R^4}{8L\dot{Q}} = \frac{PR}{2L\dot{\gamma}} -> P = \frac{2L\dot{\gamma}\eta}{R} = \frac{2L\tau}{R}$$

Equation 8. Pressure loss (Crawford 1998:371)

Where: $\eta = viscosity$

$P = pressure\ loss$

$R = Radius$

$L = length$

$\dot{Q} = volume\ flow\ rate$

$\dot{\gamma} = shear\ rate$

$\tau = shear\ stress$

(Crawford 1998:371)

3.7 In-mould rheology test

When injection moulding, it is possible that the flow rates throughout the mould cavity can vary from shot to shot due to natural variations. As the viscosity of polymers vary in terms of shear rate and hence flow rate, these variations can notably effect how the polymer will flow inside the mould and therefore the quality of the moulded parts can also vary from shot to shot. However, at high enough shear rates the viscosity will remain fairly constant regardless of small variations in the flow rates. In order to maintain a robust production it is therefore important to know which injection rates that produce high enough shear rates. Figure 17 demonstrates the results of an in-mould rheology test. For this mould and for this machine an injection speed, for example, of 70 % would insure a production with repeatable quality.

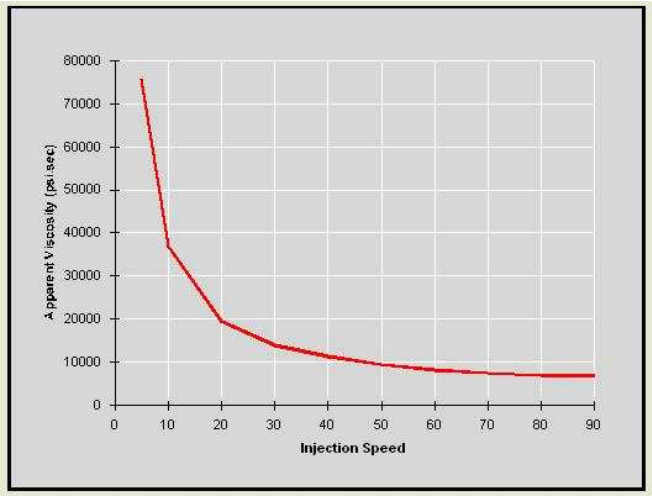

Figure 17. Viscosity curve created through the in-mould rheology test (Fimmtech 2007)

According to Fimmtech the test should be done accordingly:

1. Set the melt temperatures to those recommended by the manufacturer. If there is a range, set the temperatures to the center of the range.

2. Set all the holding phase parameters to zero. This means that there will not be any holding phase and only injection.

3. Set the injection pressure to the maximum available.

4. Set the cooling time to a safe value such that the part will be cool and has reached the ejection temperature before mould opening.

5. Set the injection speed to ‘slow’ and make a part. The part should be short. If not adjust the transfer position to make the part such that it is filled only about 50%.

6. Increase the speed in steps and make sure that the parts are still short. Mould a part with close to the maximum injection speed and make sure that it is still short. If it is full, then adjust the transfer position, such that it is about 95 % full part. If it is less than 95 % full, then also adjust such that the part is 95% full. This means that at close to the maximum injection speed you have a 95% full part with no holding time or pressure.

7. Make another shot and record the fill time and the peak hydraulic pressure required to fill the part. Note: The peak hydraulic pressure will be the pressure required to move the screw at the set injection speed. This is taken from the available pressure from the machine. For example, the machine is set to 2200 psi but may require only 1850 psi to move the screw at the maximum speed of 5 in/sec.

8. Next, lower the speed by a small amount, for example from 5 in/sec to 4.5 in/sec or from 90% to 80%. Note the fill time and the peak injection pressure.

9. Repeat the above step all the way till you get to the lowest injection speed possible. Divide the available injection speed range into about 10 - 12 speeds so that you get as many data points.

10. Find the Intensification Ratio of the screw from the machine manufacturer. If this number is not available, pick it to be 10. It does not really matter since this is a constant used in the equation and will factor the viscosity proportionately.

11. To get the viscosity, use the following formula: Viscosity = Peak Injection Pressure X Fill Time X Screw Intensification Ratio. Plot the graph of viscosity vs injection speed.

(Fimmtech 2007)

4 METHOD

The empirical part of this thesis was done through the following methods:

1. Viscosity measurements using the in-mould rheology test method.
2. Injection moulding simulations using the Autodesk Simulation Moldflow software.
3. Tensile test.
4. Melt flow index measurement.
5. Expert interview.
6. Cooling time, energy need for melting and shear rate calculations.

The material used for the tests were the following:

1. HDPE HMA 025, High Density Polyethylene. Producer: Exxon Mobil.

2. PET Lighter C 88. Virgin PET. Producer: Equipolymers. Intrinsic viscosity 0,76 ± 0,02 dl/g.
3. CleanPET Non-Food Light blue Flakes. Recycled PET flakes. Producer: Veolia Umweltservice. No technical specifications were available at the time as this was a new grade. It was assumed that these flakes possessed similar properties as the CleanPET coloured WF as they have been produced similarly. CleanPET coloured WF intrinsic viscosity 0,74 ± 0,03 dl/g.
4. Recycled PET granules. Produced by Preformia, who is no longer in business. Intrinsic viscosity 0,75 dl/g.
5. Tioxide A-HR. Anatase titanium dioxide. Producer: Huntsman.

The flakes were extruded, with a KFM Eco Ex Extruder, and pelletized to make the feeding into the injection moulding machine easier. Another reason was that this way a more homogenous mixing of the rPET flakes and TiO_2 could be done. Drying was done with a Labotek FMD MM 25 40 v flexible modular drying unit with a dew point of -35 °C.

The flakes were dried before pelletized. RPET and TiO_2 were mixed manually before dried and pelletized. 1 % of TiO_2 was mixed with 99 % flakes in order to get a 0,5 % content of TiO_2 in the final PET/rPET/TiO_2 mix. The blends of the produced pellets and the PET pellets were mixed manually and dried again before injection moulded. Like-wise, all the PET and rPET materials were dried before injection moulded. Table 15 summarizes the preparations done for each material and blend. No preparations were needed for HDPE, which was taken straight from the bag.

Table 15.Preparation steps for the in-mould rheology test

Material (weight %)	Mixing	Drying	Extruded & pelletized	Mixing	Drying
PET					4 h 140 °C
PET/rPET (50/50 wt%)		6 h 140 °C	Yes	rPET & PET	6 h 140 °C
PET/rPET/TiO_2 (49,75/49,75/0,5 wt%)	rPET flakes & TiO_2	6 h 140 °C	Yes	rPET/TiO_2 & PET	6 h 140 °C
rPET granules					6 h 140 °C
rPET flakes		6 h 140 °C	Yes		6 h 140 °C

4.1 Viscosity test

In-mould rheology tests (see chapter 3.7) were done for all the materials with a test specimen mould. A 3D drawing of the mould can be seen in Figure 18. The materials were tested at three different injection temperatures in order to compare the viscosities. For each speed and temperature, two shots were done and from these an average apparent viscosity was calculated. Although the test instructions given by Fimmtech state that the mould should be filled 95 %, it was only filled 90 % in order to slightly reduce the overall pressure need. The machine used was an ENGEL ES 200/50HL CC90 injection moulding machine. The maximum injection speed on the machine is 130 mm/s and the maximum hydraulic pressure is 200 bar. The highest injection speed used in the tests was, however, 42 mm/s and the maximum hydraulic pressure was set at 140 bar. The reason for this was that some technical problems were encountered when using hydraulic pressures above 140 bar. If the set maximum hydraulic pressure is reached, the process will become pressure limited. This means that set injection speeds cannot be reached completely. In order to gain optimal results, the tests should not be pressure limited. Higher injection speeds usually leads to a higher pressure need and 42 mm/s

proved to be the best top speed for this purpose. Unfortunately, the pressure limit was still reached at certain temperatures for some of the materials. 12 mm/s was selected as the lowest injection speed because it proved to be difficult to fill the mould before freezing occurred, with slower speeds. The range 42 mm/s – 12 mm/s was divided into 11 different speeds, with a difference of 3 mm/s between each speed. The injection speed can be defined so that it changes throughout the injection, but in this test the speeds were set to be constant. For each speed, two tests were done and the fill time and peak pressure was recorded. The apparent viscosities were obtained by multiplying peak pressure with fill time and then multiplying the product with 11, which was the intensification factor for the machine.

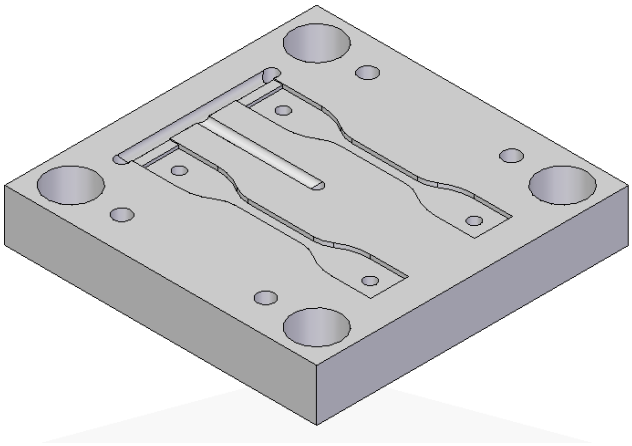

Figure 18. 3D drawing of the test specimen mould (Vihtonen 2011)

The temperature could be controlled at the nozzle and at three different zones of the barrel. According to Meinander the temperature of the nozzle represents the melt temperature and should be at the lowest temperature of these four zones (Meinander 2004:2). The zone next to the nozzle should be at least 10 °C warmer than the nozzle (Meinander 2004:2). In this test the all the barrel zones were set at 10 °C higher than the nozzle temperature, for example 265(nozzle)/275/275/275 °C. The PET and rPET materials were tested within the melt temperature range 265-285 °C whereas HDPE was tested in the range 200-240 °C because of the materials wide processing range.

Even though the temperatures and injection speeds are specified, the actual values of these will vary. Temperatures will vary depending on the amount of heat created from

shearing and injection speed will vary, for example, due to acceleration and deceleration of the screw. Nevertheless, the conditions remained similar for all the materials.

4.2 Moldflow

Autodesk Simulation Moldflow Insight 2013 is an injection moulding computer aided engineering (CAE) software that can be used to validate and optimize the design and process parameters for injection moulding. With this software, simulations were done for a tray (see Figure 19) with both HDPE and PET in order to compare the materials. The objective was to find out the how the mould filling would differ between the materials. The values that were compared were: fill time, pressure need, temperature at flow front, shear rate, shear stress and clamp force. Because only these values were relevant, a fill and pack analysis was sufficient. Other analyses, such as cooling and warpage, were excluded. The values obtained for the HDPE simulation were compared with a previous simulation done for the same tray, in order to validate that the simulations produced realistic results.

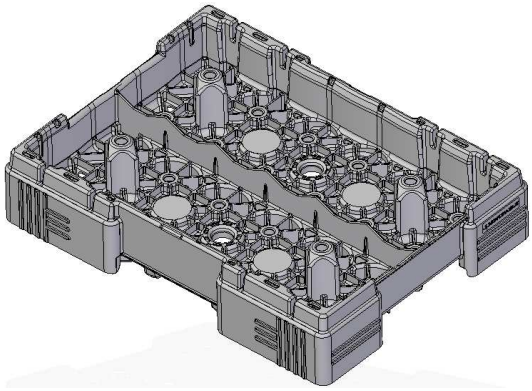

Figure 19. 3D-drawing of a tray (K.Hartwall Oy 2009)

4.2.1 Mesh

Before doing simulations, a mesh needs to be created for the 3D model. A mesh is a web of small elements, where each element has a node at every corner. The shape of the part is represented by the mesh and the moulding properties are analyzed and calculated at every node. With the software, it is possible to create three different kinds of meshes: midplane analysis, dual domain analysis and 3D-analysis. The midplane and dual domain analyses are appropriate when the part is thin walled. Both of these are built with

triangular elements that form one-dimensional representations. A midplane mesh has one one-dimensional representation that goes through the centre, where as a dual domain mesh has representations on each surface of the part. Therefore the dual domain analysis will give a more accurate result. The thickness is determined by the distance between opposing faces and can be visualized as a hollow shell. If the part contains many thick regions, the 3D analysis is more appropriate. This analysis contains four-node tetrahedral elements which will give a true 3D representation and produce the most accurate results. However, as the tray mostly consists of thin walls the dual domain analysis was used. This mesh is less complicated than the 3D, and it was already very challenging to generate the dual domain mesh because of the complexity of the part. (Autodesk Simulation Moldflow Insight 2013)

There are a number of things that are important when generating a mesh for a successful analysis. The most important things for a dual domain analysis are the aspect ratio and the match percentage. The aspect ratio is the ratio of the largest side of the element to the height perpendicular to that side and should be below 8:1. The match percentage represents the amount of elements that has matching elements on the other side of the part. This value should be above 85 %. (Autodesk Simulation Moldflow Insight 2013)

4.2.2 Simulation conditions and materials

The tray has been produced with a double cavity mould with hot runners. The runner and gate dimensions used in the simulations are not exactly the same as in reality or in the previous simulation, but similar. Figure 20 and Figure 21 shows the runner system created in Moldflow.

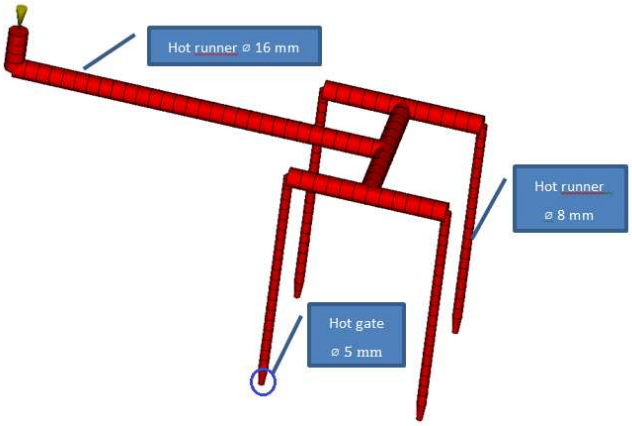

Figure 20. The runner system used in the simulations

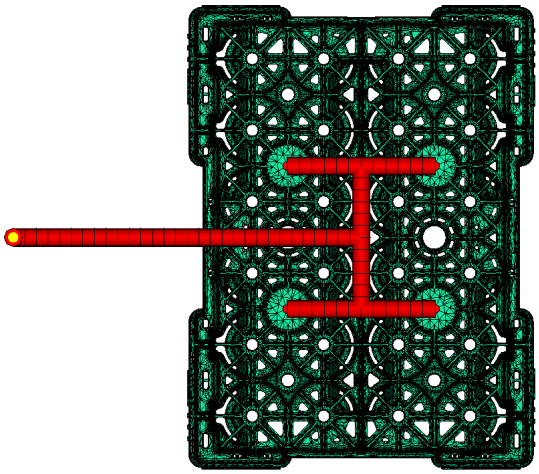

Figure 21. The tray and the runner system

The materials used in the simulations were: HDPE 12450: Dow Chemical USA and Skypet BL:SK Chemicals Ltd.. Figure 22 and Figure 23 displays the materials viscosity curves respectively.

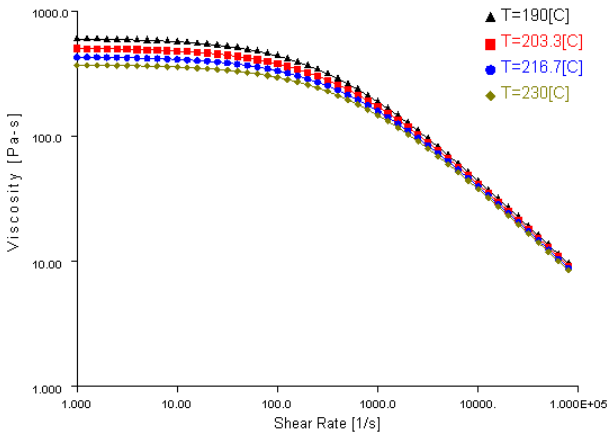

Figure 22. Viscosity curve, HDPE 12450: Dow Chemical USA (Moldflow material database)

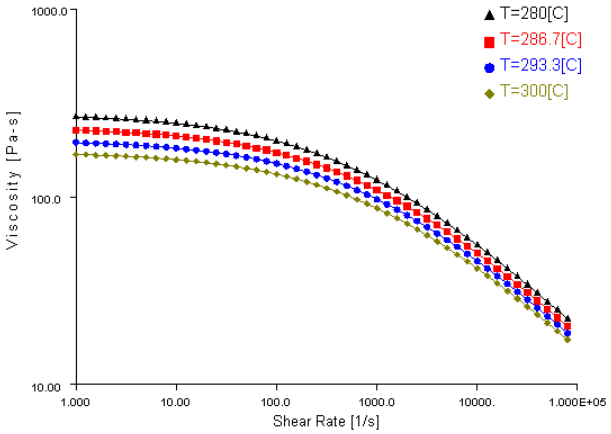

Figure 23.Viscosity curve, Skypet BL:SK Chemicals Ltd. (Moldflow material database)

For each material, simulations were done with two different injection times. The process settings and shear properties can be seen in Table 16.

Table 16. Process settings and shear properties for the materials (Moldflow material database)

	HDPE 12450: Dow Chemical USA	Skypet BL:SK Chemicals Ltd.
Mould temperature (°C)	20	20
Melt temperature(°C)	230	290
Injection time (s)	3 and 4	3 and 4
Velocity/pressure switch-over	Automatic	Automatic
Cooling time	Automatic	Automatic
Pack/Holding time (s)	8	10
Pack/holding pressure (% of injection pressure)	70	70
Maximum shear stress (MPa)	0,2	0,5
Maximum shear rate (1/s)	40000	50000

4.3 Tensile test

The mechanical properties of all PET and rPET materials were tested through a tensile test. The machine used was a Testometric M 350-5CT. Test specimens were prepared with the same injection moulding machine that was used in the in-mould rheology test. The materials were dried in the same manner as for the viscosity test. The mould temperature used was 20 °C, but PET test specimens produced with mould temperature 30 and 40 °C were also tested to see if any difference in crystallinity or other properties would be seen. The moulding parameters can be seen in Table 17. The tests were conducted at a load speed of 50 mm/min and according to ASTM D638, except that the Young's Modulus measurements were not done at 5 mm/min load speed nor was an extensometer used. The test specimens were conditioned at room temperature for a minimum of one week, before the tests.

Table 17. Moulding parameters

Parameter	Value
Melt temperature (°C)	275
Mould temperature (°C)	20 (PET also tested with 30 and 40)
Injection speed (mm/s)	42
Hold pressure (bar/MPa)	15-35 bar

4.4 Melt flow index (MFI)

According to Malloy, the melt flow index can provide a rough indication of the molecular weight when comparing polymers that are within the same family (Malloy 1994:173).

The tests were conducted according to the ISO 1133 and procedure A. When searching for standard test temperature and load weight for PET, different values were found. The most common found was 280 °C and 2,16 kg, therefore this was used. HDPE was tested with the same load weight at two different temperatures: 190 °C, which is the standard, and 230 °C to see how different the MFI is at the higher end of the processing range. A minimum of three tests for each material and test condition was done. When the results were varying, six tests were conducted. Again, the PET and rPET materials were dried in the same manner as for the viscosity test.

4.5 Interviews

An interview with Markku Hirn, CEO of EM-Kone Oy was done in order to get an expert opinion about whether injection compression moulding would be a feasible alternative. EM-Kone Oy represents Arburg in Finland, which produces injection compression moulding machines. The interview was done over phone and by e-mail.

4.6 Calculations

Calculations were done for shear rates as well as relative cooling time, energy consumption and prices.

Shear rate: The shear rates within the cavity were calculated for the runners, gates and the broad and narrow sections of the test specimens. Dimensions can be seen in Figure 24. The flow rate was obtained by multiplying the injection speed with the area of the screw, which had a diameter of 30 mm. Calculations were done for all injection speeds.

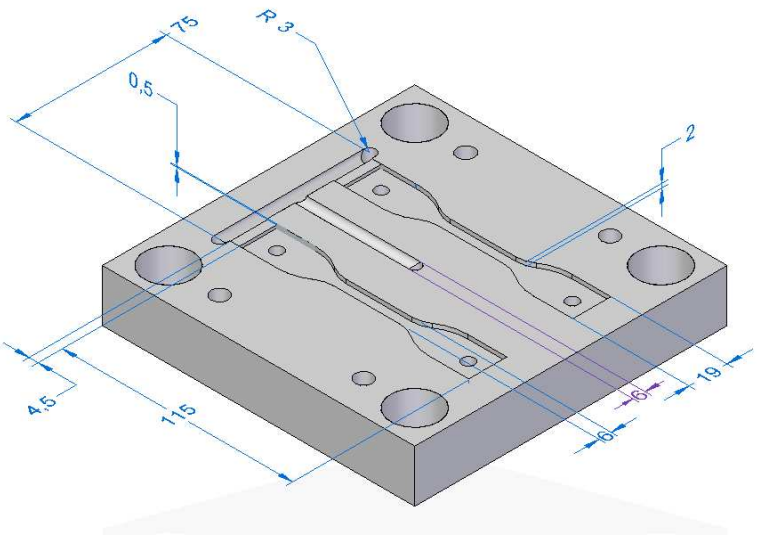

Figure 24. Dimensions of the test specimen mould. 3D modelling by Vithonen (Vithonen 2011)

Equation 7 was used for the rectangular cross sections:

$$\dot{\gamma} = \frac{32\dot{Q}}{\pi D^3}$$

An approximate shear rate for the half round shaped runners was calculated by simplifying the shear rate equation for a round cross section (Equation 6) and then substituting the radius with the maximum distance from the centroid:

$$\dot{\gamma}_{round} = \frac{32\dot{Q}}{\pi D^3} = \frac{4\dot{Q}}{\pi r^3} = \frac{4AV}{\pi r^3} = \frac{4V}{r}$$

$$\dot{\gamma}_{half\ round} = \frac{4V}{maximum\ distance\ from\ centroid}$$

Where: $\dot{Q} = flow\ rate$

$D = diameter$

$r = radius$

$A = area$

$V = velocity$

Cooling time: In order to see how different the cooling time for PET in relation to HDPE is, a cooling time index was calculated with Equation 1:

$$t_c = \frac{h^2}{\alpha\pi^2}\ln\left(\frac{4}{\pi}\left(\frac{T_M - T_W}{T_E - T_W}\right)\right) \rightarrow \frac{t_c}{h^2} = \frac{1}{\alpha\pi^2}\ln\left(\frac{4}{\pi}\left(\frac{T_M - T_W}{T_E - T_W}\right)\right)$$

Where $t_c = cooling\ time$

$h = thickness$

$\alpha = thermal\ diffusivity$

$T_M = melt\ temperature$

$T_W = wall\ temperature$

$T_E = ejection\ temperature$

(Malloy 1994:86)

Thermal diffusivity was obtained by dividing thermal conductivity with density and specific heat (see Table 18). The values for these were taken from Table 4 and Table 9. The vicat softening temperatures, also taken from these tables, were used as the ejection temperatures. For those HDPE values that were given in a range in Table 9, the average was used. The density used for HDPE was that of Exxon Mobil HMA 025: 0,964 g/cm^3. The melt and wall temperatures used in the calculations were the same that were used in the Moldflow simulations (see Table 19). Because the goal was to compare the materials and not to calculate the actual cooling times, values for cooling time divided by the thickness squared were calculated instead. The value obtained for PET was divided by the value for HDPE to get a cooling time index.

Table 18. Thermal diffusivities

	Unit	HDPE	PET
Thermal conductivity (k)	W/mK	0,445	0,24
Specific heat (C_p)	J/kgK	2400	1050
Density (ρ)	kg/m^3	964	1330
Thermal diffusivity (α) k/ρC_p	m^2/s	1,92 *10^{-7}	1,72 *10^{-7}

Table 19. Temperatures used in the calculations

	Melt temperature °C	Wall temperature °C	Ejection temperature (Vicat softening temperature) °C
HDPE	230	30	122
PET	290	20	80

Energy consumption: The energy needed for melting HDPE and PET was calculated the following way:

$$Q_{total} = Q_1 + Q_2$$
$$Q_1 = mC_p\Delta T$$
$$Q_2 = m\Delta H\chi_c$$

Equation 9. Energy needed to raise temperature and melt plastics

Where:
$Q_{total} = total\ energy\ needed\ to\ melt\ the\ polymer$
$Q_1 = energy\ needed\ to\ change\ the\ temperature$
$Q_2 = energy\ needed\ for\ the\ phase\ transitionof\ the\ crystalline\ regions$
$m = mass$
$C_p = specific\ heat$
$\Delta T = change\ in\ temperature$
$\Delta H = heat\ of\ fusion$
$\chi_c = degree\ of\ crystallinity, weight\ percentage$

Values for heat of fusion were taken from Table 4 and Table 9. The degree of crystallinity values for PET and rPET flakes were taken from Table 8. As mentioned in chapter 3.3, the degree of crystallinity for HDPE is 60-80 %, therefore 70 % was used in the calculations. Again, because the goal is to compare the materials no mass was used in the calculations. Instead the joule per kilogram was calculated. This value for PET was divided by the value for HDPE to get an energy need index. The change in temperature used in the calculations was the temperature difference between the melt temperatures, the same as used in the mould flow simulations, and 20 °C (room temperature).

Prices: Two kinds of price indices were calculated by using price information obtained from various sources. One index was the price per volume unit of the material because if the tray would be manufactured out of some PET or rPET material and the design of the tray would not be changed, more material would be needed for these materials. The other index was solely based on the price per weight unit. The use of TiO_2 was ignored in these calculations.

5 RESULTS

In this chapter the results from each method are presented in separate chapters.

5.1 Viscosity test

The PET and rPET materials were slightly unstable in terms of viscosity. The peak pressures could vary so that sometimes a few occasional shots needed slightly higher or slightly lower pressure. Therefore, large variations were ignored and only the results that represented the main threads level of pressure need were documented. But some variations still show in the results. The results can be seen in appendix 6.

The pressure limit was reached at 265 °C, for all speeds for the following materials: PET, PET/rPET and PET/rPET/TiO_2. This means that the actual injection speeds were bit lower for these materials at these conditions. Consequently the shear rates were slightly lower and therefore the viscosities should, in theory, be slightly higher. This would mean that the curves that were pressure limited would have been shifted slightly down, if higher pressure would have been available. The fill time for HDPE was higher than for the other materials, except for the tests that were pressure limited. One reason for higher fill times is most likely due to the difference in shrinkage. As earlier mentioned amorphous PET has a shrinkage percent of 0,2 and that of HDPE is 1,5-3,0, which would mean that a bigger volume of HDPE would need to be injected. This difference in shrinkage does, however, not completely account for the difference in fill time.

Figure 25 shows the results for HDPE. Even though the temperature range is twice as wide, the difference in viscosity due to temperature is a lot smaller than for other materials. Figure 26 displays the results for PET and Figure 27 for PET/rPET and rPET flakes. Figure 28 and Figure 29 contain the results for PET/rPET/TiO_2 and rPET granules respectively. The PET and rPET materials seem to get very viscous at lower speeds especially when injected at 265 °C. One possible reason for this is that the melt had time to cool to the extent that it got very thick. It is interesting that the rPET flakes curve at 275 °C is almost exactly on top of the PET/rPET curve at 285 °C.

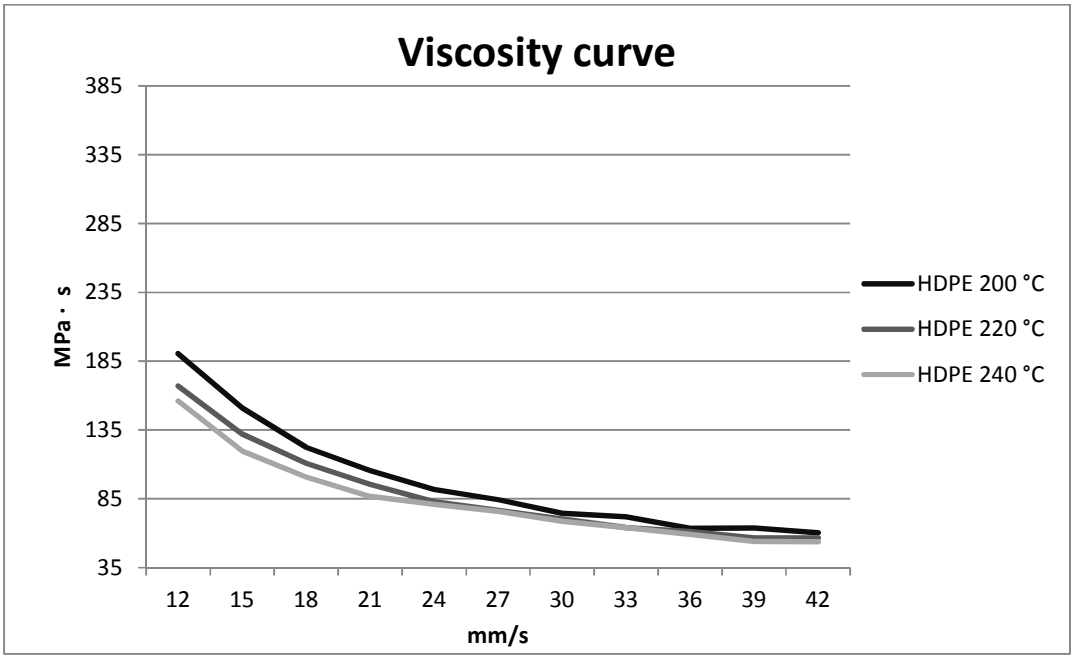

Figure 25. Viscosity curve, HDPE

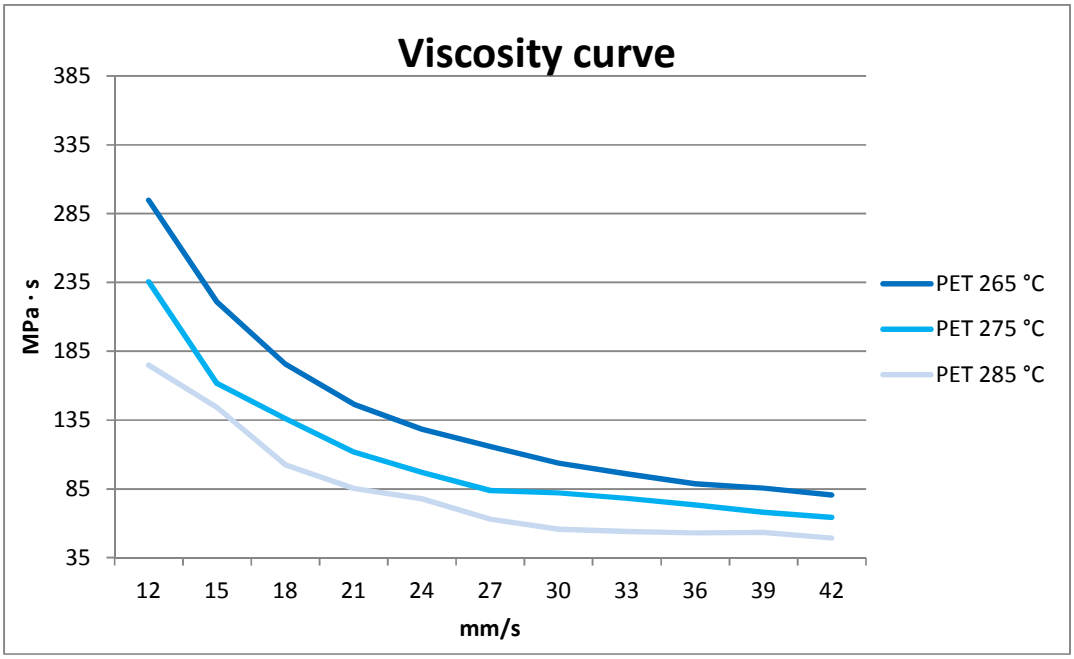

Figure 26. Viscosity curve, PET

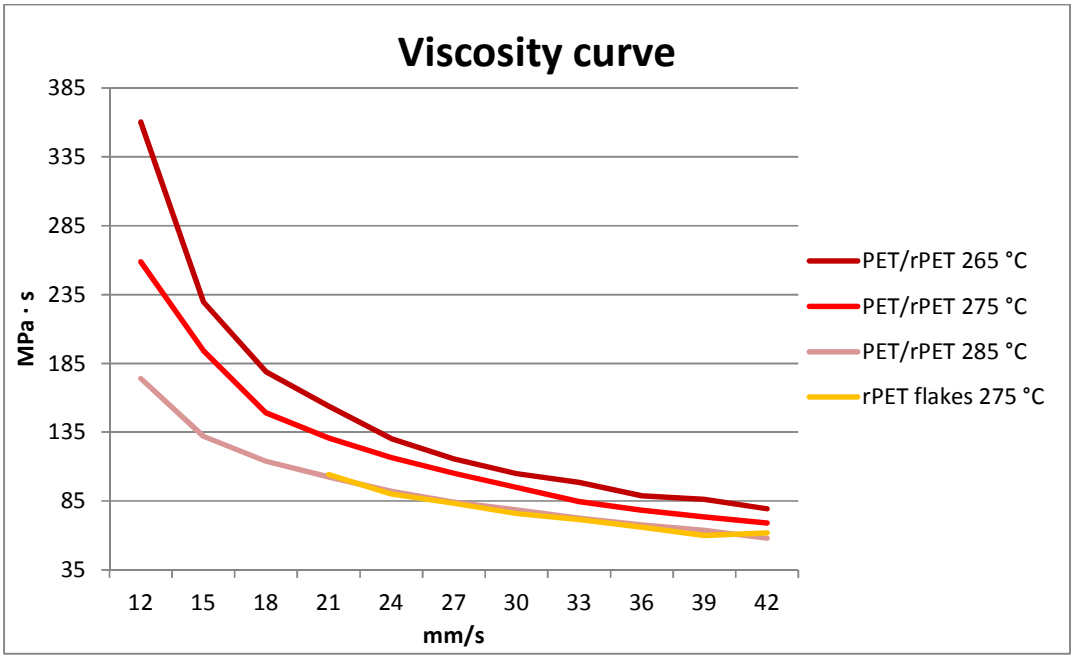

Figure 27. Viscosity curve, PET/rPET and rPET flakes

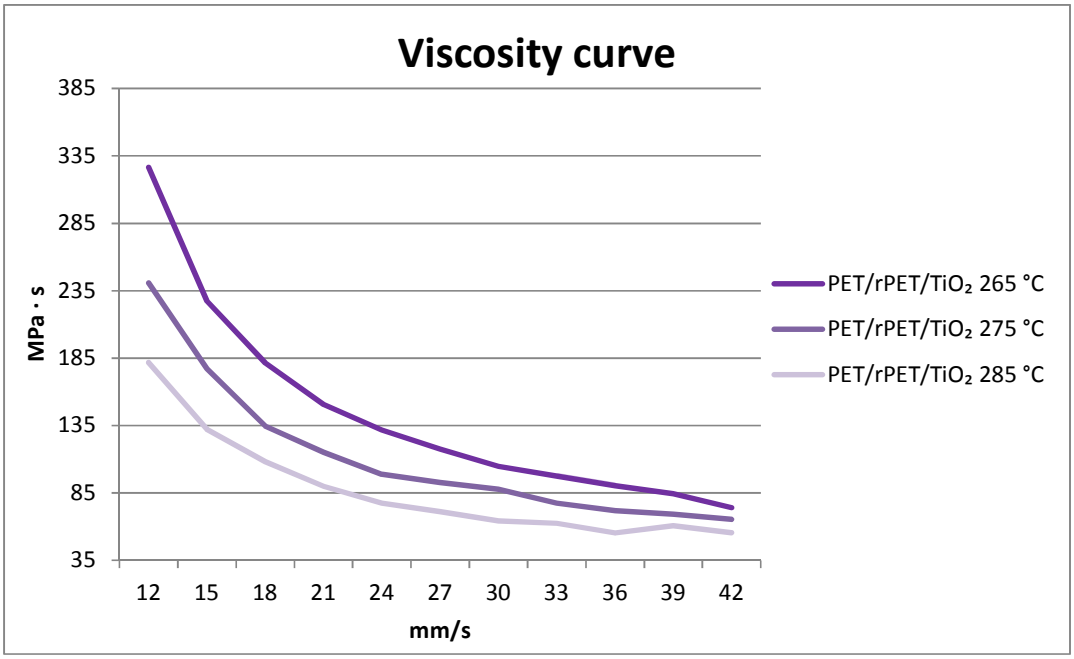

Figure 28. Viscosity curve, PET/rPET/TiO_2

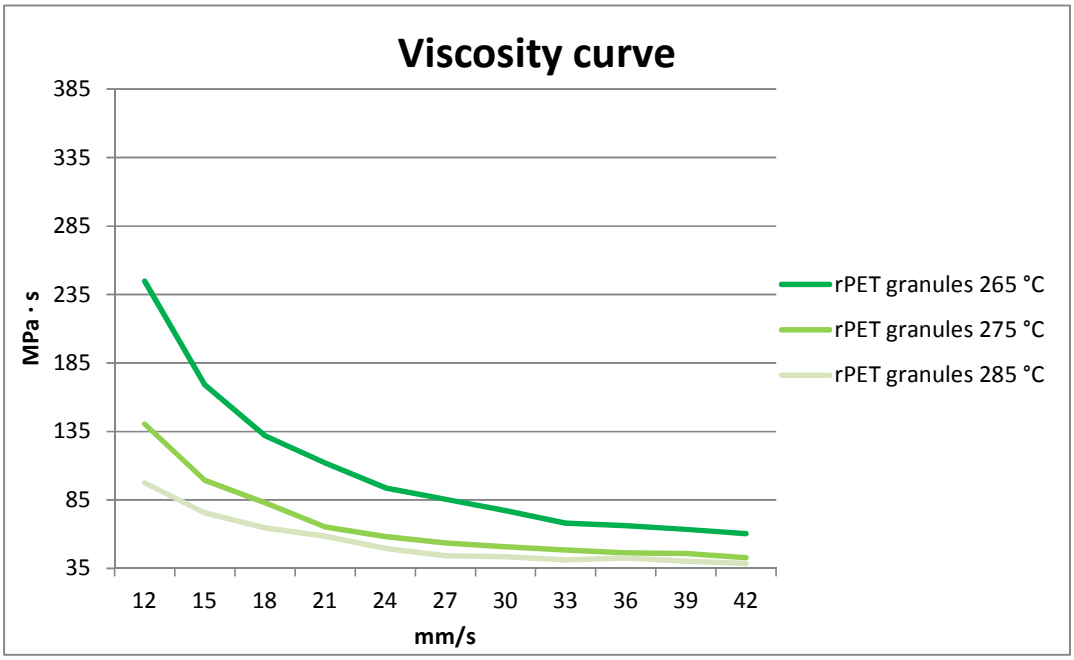

Figure 29. Viscosity curve, rPET granules

As seen in Figure 30, the viscosity of PET/rPET/TiO_2 is slightly lower than that of PET/rPET.

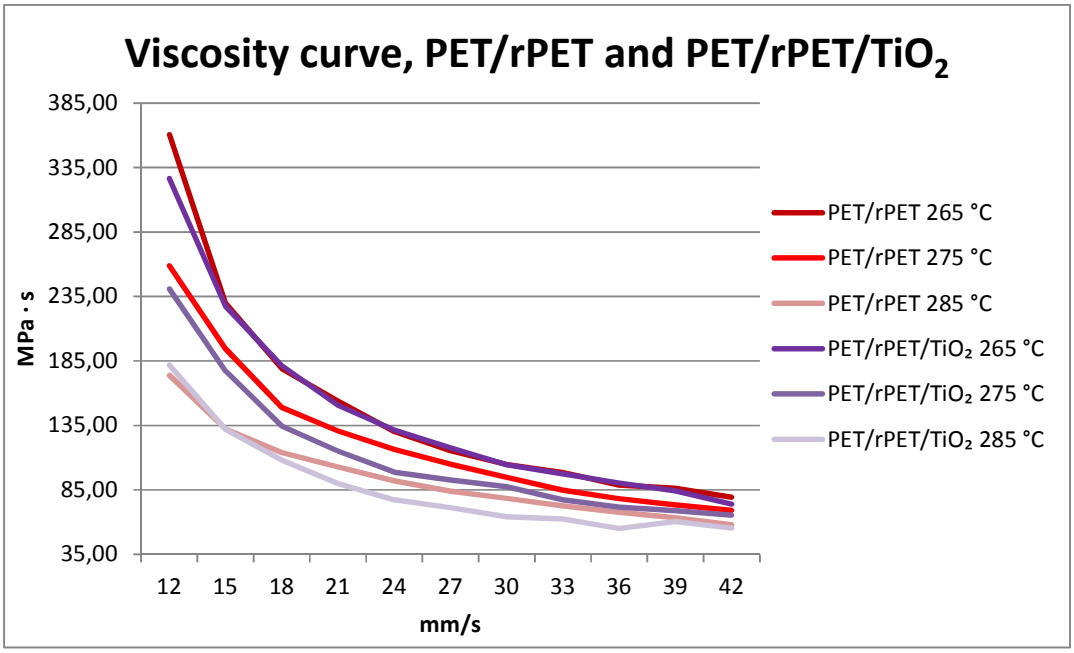

Figure 30. Viscosity curve comparison of PET/rPET and PET/rPET/TiO_2

In Figure 31, the average apparent viscosities are shown. In order to get a fair comparison the HDPE curve is based on the temperatures 220-240 °C, making the temperature range as wide as for the rest of the materials. The rPET flakes curve was also placed in this figure although limited data was available. Despite that, it can be seen in Figure 32 that the mid-temperature viscosity curve looks fairly similar to the average viscosity curve. Therefore, the mid temperature viscosity can roughly represent the average viscosity. So even though the data for rPET flakes does not give very accurate results, certain guidelines can be drawn.

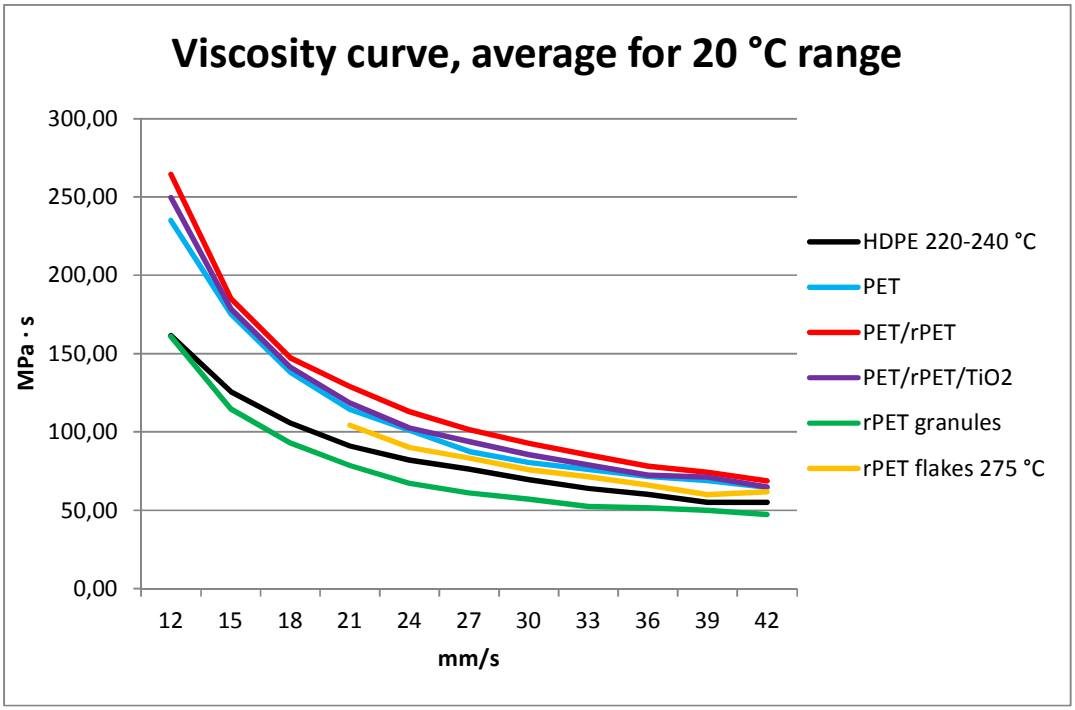

Figure 31. Viscosity curve, average for 20 °C range

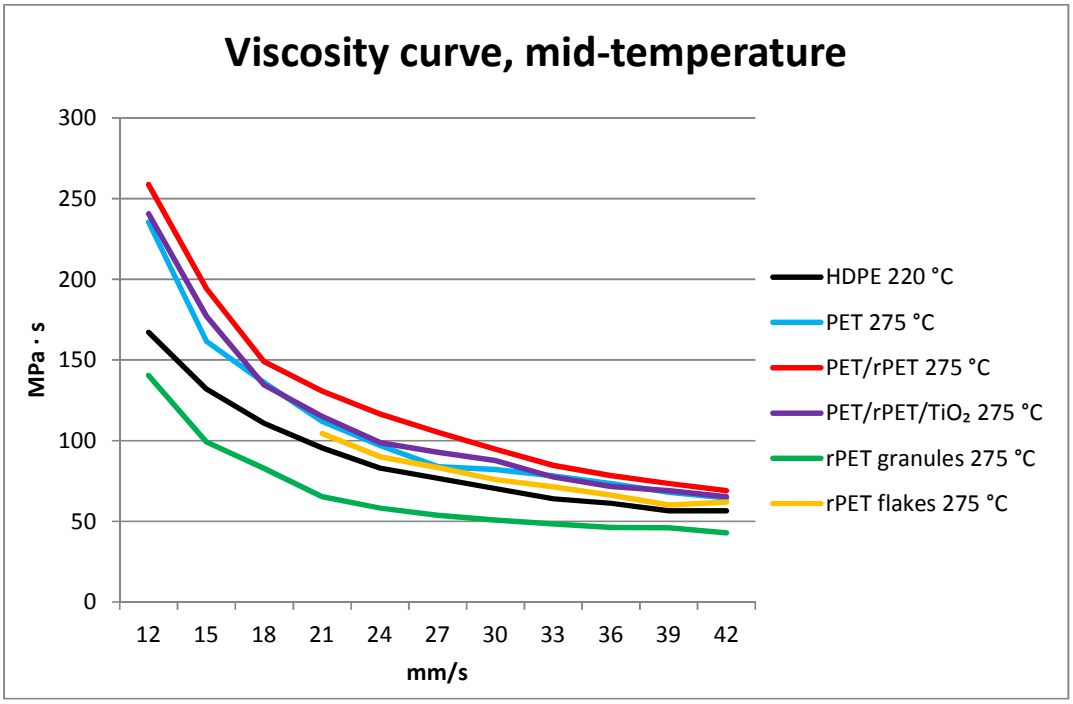

Figure 32. Viscosity curve, mid-temperature

In Figure 33 the curves for the average hydraulic pressure can be seen. Again, the HDPE curve only represents the results for the 220-240 °C range. Here, the curves for PET, PET/rPET and PET/rPET/TiO_2 would be higher if the tests would not have been pressure limited. The rPET flakes curve is once again among the average curves and in Figure 34, where the mid-temperature hydraulic pressure curves are shown, it can be seen that the mid temperature curves can represent the average curves well enough to work as guidelines. It remains uncertain if the rPET flakes tests for 265 °C would have been pressure limited or not. The pressures needed at 275 °C were clearly lower than that of PET, rPET/PET and PET/rPET/TiO_2.

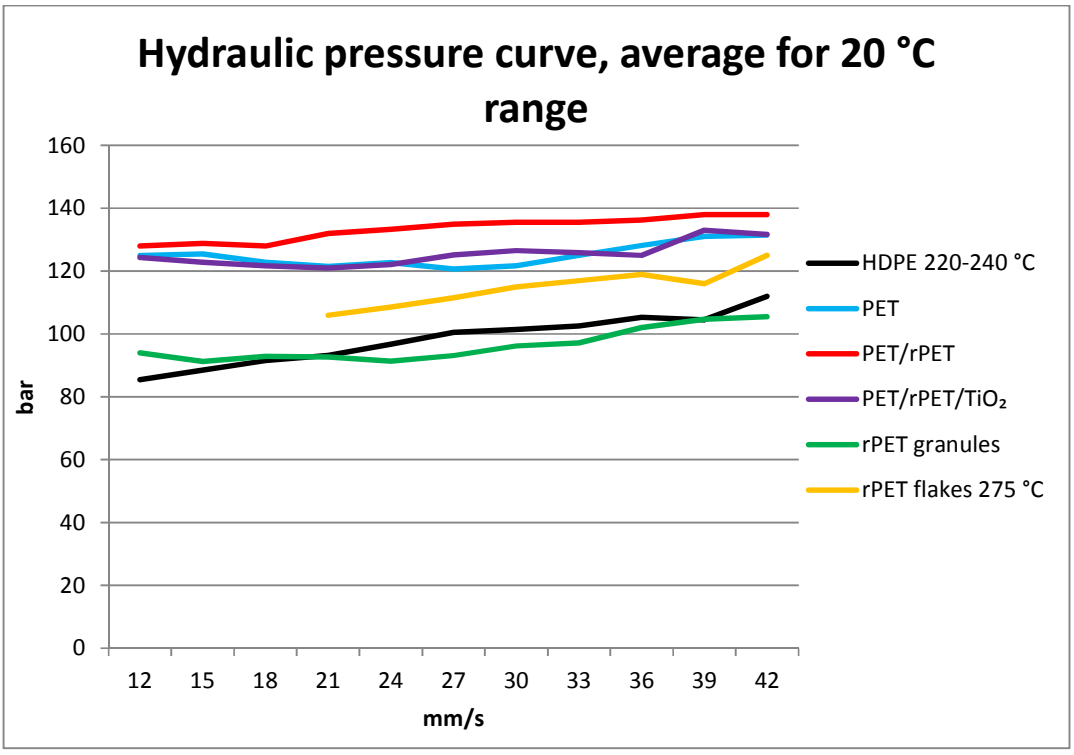

Figure 33. Hydraulic pressure curve, average for 20 °C range

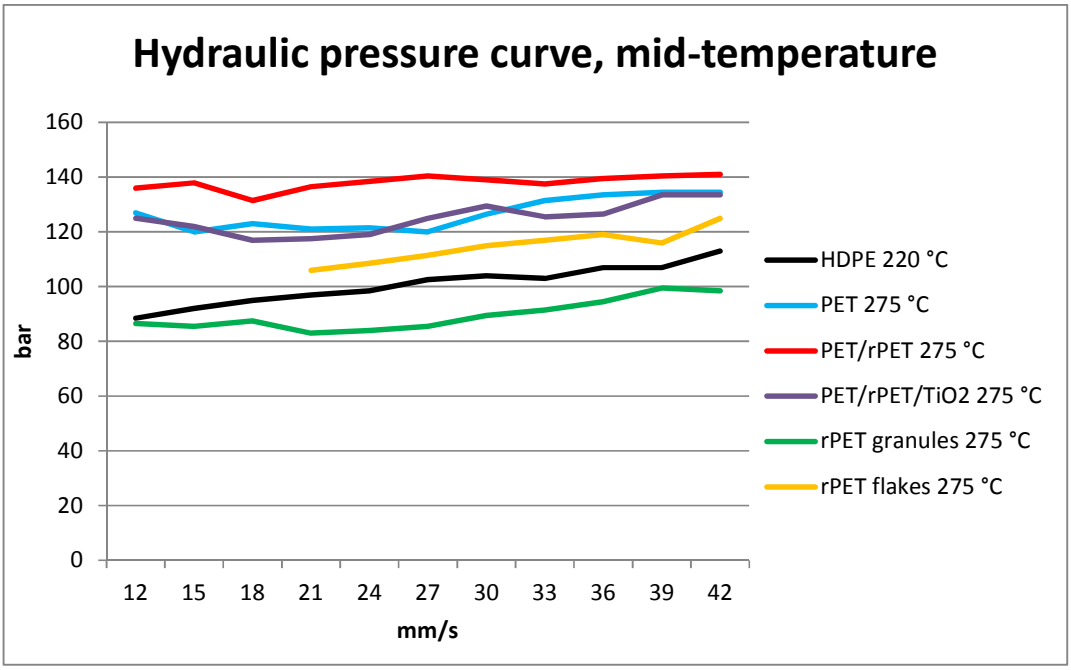

Figure 34. Hydraulic pressure curve, mid-temperature

In Table 20 the average apparent viscosities, average hydraulic pressures as well the results for rPET flakes are shown in numbers. The average apparent viscosities and average hydraulic pressures of each PET and rPET material were divided with that of HDPE for each injection speed, to get a viscosity and pressure index (the viscosity and pressure relationship to HDPE). All the indices for each material were summed together and divided by the number of injection speeds to get an average index. The purpose for this was to get an overall picture of how different the viscosities and pressure needs within all tested shear rates and temperatures are. The indices can be seen in Table 21. If all speeds would have been tested with rPET flakes, the average index would most likely have been slightly higher for both apparent viscosity and hydraulic pressure.

Table 20. Average apparent viscosities and hydraulic pressures

mm/s	HDPE, 220-240 °C average values		PET, average values		PET/rPET, average values		PET/rPET/TiO_2, average values		rPET granules, average values		rPET flakes values for 275 °C	
	App. visc. (MPa)	Hydr. pressure (bar)	App. visc. (MPa	Hydr. pressure (bar)	App. visc. (MPa	Hydr. pressure (bar)	App. visc. (MPa	Hydr. pressure (bar)	App. visc. (MPa	Hydr. pressure (bar)	App. visc. (MPa	Hydr. pressure (bar)
12	161,5	85,5	235,0	125,0	160,9	94,0	264,4	128,0	249,6	124,3		
15	125,9	88,5	175,6	125,5	114,6	91,2	185,4	128,8	178,8	122,8		
18	105,7	91,5	138,2	122,8	93,1	92,8	147,3	128,0	141,3	121,7		
21	91,1	93,3	114,6	121,5	78,6	92,7	129,1	132,0	118,5	121,0	104,4	106,0
24	81,9	96,8	101,0	122,7	67,2	91,3	113,0	133,3	102,6	122,2	90,1	108,5
27	76,3	100,5	87,5	120,7	61,1	93,2	101,6	135,0	93,9	125,2	83,4	111,5
30	69,5	101,5	80,5	121,7	57,1	96,2	92,7	135,5	85,4	126,5	75,9	115,0
33	64,0	102,5	76,0	125,0	52,5	97,2	85,3	135,5	79,0	125,8	71,4	117,0
36	60,2	105,3	71,7	128,2	51,7	102,0	78,2	136,3	72,4	125,0	66,1	119,0
39	55,2	104,5	69,0	131,0	49,9	104,7	74,4	138,0	71,3	133,0	60,0	116,0
42	55,2	112,0	64,7	131,5	47,4	105,5	68,8	138,0	64,9	131,7	61,9	125,0
Average	**86,0**	**98,4**	**110,3**	**125,1**	**75,8**	**96,4**	**121,8**	**133,5**	**114,3**	**125,4**	**76,7**	**114,8**

Table 21. Apparent viscosity and hydraulic pressure index

mm/s	HDPE, 220-240 °C		PET		PET/rPET		PET/rPET/TiO_2		rPET granules		rPET flakes 275 °C	
	App. visc.	Hydr. pressure	App. visc.	Hydr. pressure	App. visc.	Hydr. pressure	App. visc.	Hydr. pressure	App. visc.	Hydr. pressure	App. visc.	Hydr. pressure
12	1	1	1,46	1,46	1,64	1,50	1,55	1,45	1,00	1,10		
15	1	1	1,40	1,42	1,47	1,46	1,42	1,39	0,91	1,03		
18	1	1	1,31	1,34	1,39	1,40	1,34	1,33	0,88	1,01		
21	1	1	1,26	1,30	1,42	1,42	1,30	1,30	0,86	0,99	1,15	1,14
24	1	1	1,23	1,27	1,38	1,38	1,25	1,26	0,82	0,94	1,10	1,12
27	1	1	1,15	1,20	1,33	1,34	1,23	1,25	0,80	0,93	1,09	1,11
30	1	1	1,16	1,20	1,33	1,33	1,23	1,25	0,82	0,95	1,09	1,13
33	1	1	1,19	1,22	1,33	1,32	1,24	1,23	0,82	0,95	1,12	1,14
36	1	1	1,19	1,22	1,30	1,30	1,20	1,19	0,86	0,97	1,10	1,13
39	1	1	1,25	1,25	1,35	1,32	1,29	1,27	0,90	1,00	1,09	1,11
42	1	1	1,17	1,17	1,25	1,23	1,18	1,18	0,86	0,94	1,12	1,12
Average index			**1,25**	**1,28**	**1,38**	**1,36**	**1,29**	**1,28**	**0,87**	**0,98**	**1,11**	**1,12**

5.2 Moldflow

It proved to be quite challenging to produce results with Moldflow. The reason for this was that the tray is such a complex part with many details. It was very time consuming to generate the meshes and to perform the simulations. It was attempted to reach the required aspect ratio and match percentage but the end result was quite far from them. It was possible to reach the required match percentage by creating very fine meshes with small elements. But by generating very fine meshes other problems arose, such as unoriented elements, and this prevented the simulations. These problems were not success-

fully solved after many trials and errors. Therefore a mesh with lower quality was repaired as much as was managed, and then used in the simulations. Figure 35 shows the appearance of the mesh and Figure 36 shows the mesh statistics.

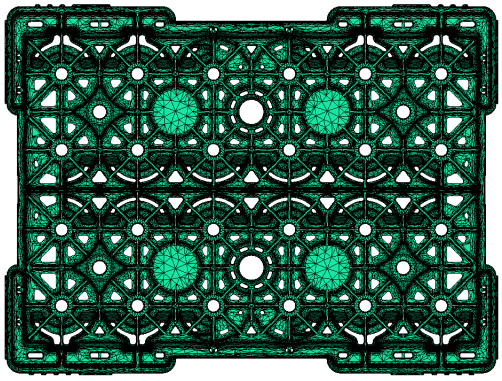

Figure 35. The mesh

```
Entity counts:
    Triangles:      275798
    Connected Nodes:        138711
    Connectivity regions         1

Area:
    Surface Area:       9068.88 cm^2

Volume:
    Triangle:   984.392 cm^3

Aspect Ratio:
                  Max    Average    Min
                184.3      3.97     1.16

Edge details:
    Free edges                   3996
    Manifold edges               411699
    Non-manifold edges           0

Orientation details:
    Elements not oriented        0

Intersection details:
    Element intersections        23
    Fully overlapping elements   0

Match percentage:
    Match percentage             68.0%
    Reciprocal percentage        55.2%
```

Figure 36.Mesh statistics

The simulation results were compared with the previous simulation and although they only had a few similarities, it was decided that the results are sufficiently accurate to be used for comparing the materials. Possible reasons for the results being different are the difference in mesh quality, different process parameters and different dimensions for the runners and gates.

Results for shear rate and shear stress are displayed at a point of time just before the cavity is filled because the values remain fairly constant until this point and then go

down when the filling is completed. As the values are similar at the bottom of the part and no cutting plane shows any different values, only one view was necessary for displaying the results. The values that are on the colour scale bars should represent the range of values that the test produces. However, some of the values that the bars show for temperature at flow front, shear rate and shear stress could not be found. The reason for this could be that some very small areas or individual elements within the mesh could be giving a completely false representation of the part. Therefore these results were manually inspected. The lowest values for temperature at flow front as well as the highest values for shear rate and shear stress that were found are displayed separately. Each material and injection time is referred to as following: HDPE4, HDPE3, PET4 and PET3 (the numbers represent the injection time).

Figure 37 displays how the melt progresses with time until the filling is completed. Although the injection times were set at 3 and 4 seconds the fill times were slightly higher and different for the materials. For HDPE4 the fill time was 4,462 s and for HDPE3 it was 3,339 s. For PET4 and PET3 they were 4,614 s and 3,413 s respectively. The nominal flow rates can be seen in Table 22.

Table 22. Nominal flow rate

	HDPE4	HDPE3	PET4	PET3
Nominal flow rate (cm^3/s)	235,68	314,24	235,68	314,23

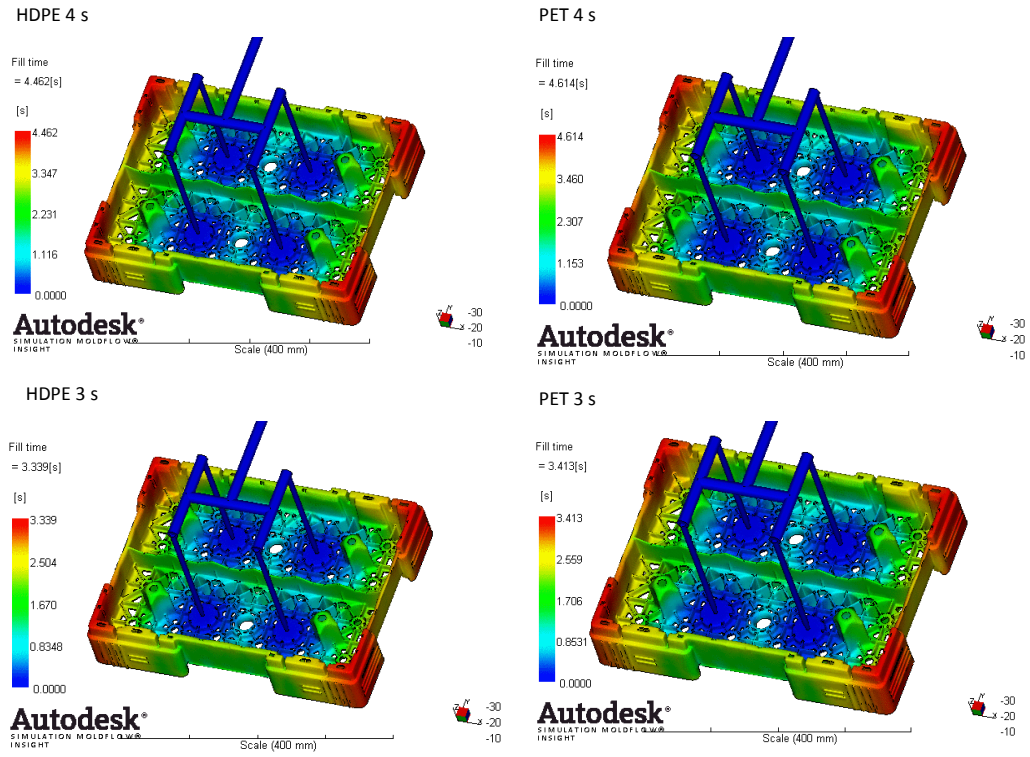

Figure 37. Fill time

The pressure throughout the cavity as well as the peak pressure can be seen in Figure 38. V/P (velocity/pressure) switchover is when injection stops and holding pressure is applied. For HDPE4 the peak pressure reached 64,74 MPa and for HDPE3 it rose to 68,95 MPa. It is interesting that in contrast to the results for HDPE the peak pressure for PET4, 81,65 MPa, was lower than for PET3, 78,66 MPa. One reason could be, as it was mentioned in chapter 3.6, that shorter fill times might lead to a lower pressure loss due to shear thinning. Another reason could be that the melt has more time to cool at the slower injection rate and hence becomes more viscous. The temperature of the flow front can be seen in Figure 39. The melt temperature range found for PET4 is 48,1 °C whereas it is only 32,2 °C for PET3. For PET4 the melt temperature had dropped under the melting point of PET. This indicates that it would be important to fill the mould as quickly as possible. The range found for HDPE4 was 41,1 °C and for HDPE3 25,6 °C, with temperatures inside the processing range for both injection speeds.

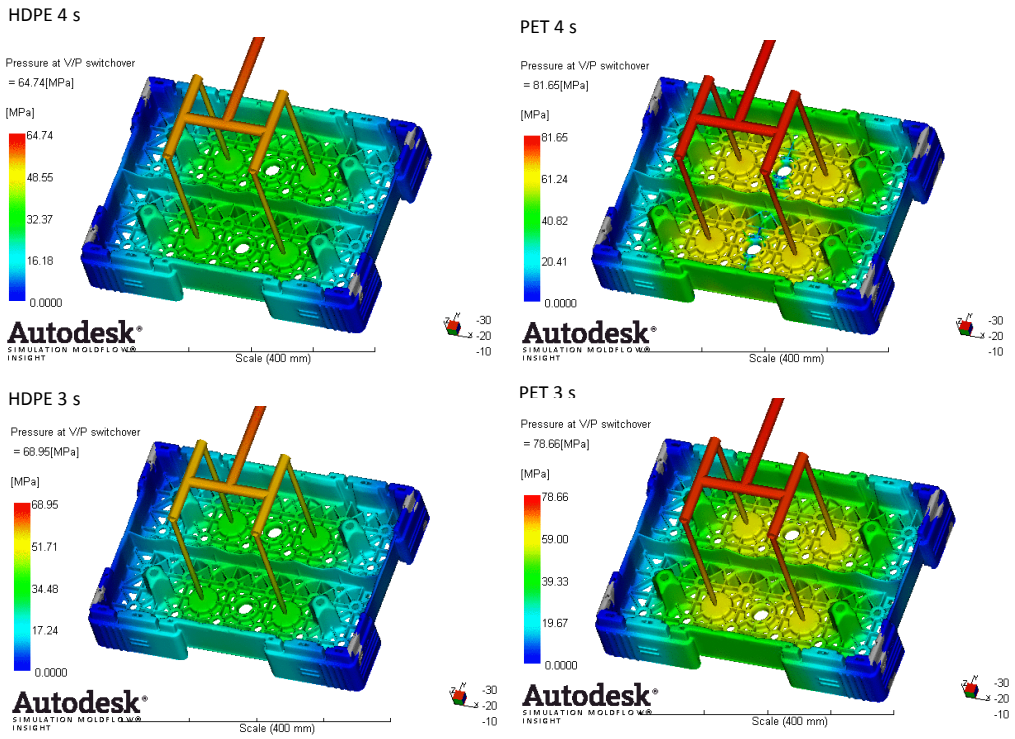

Figure 38. Pressure at V/P switchover

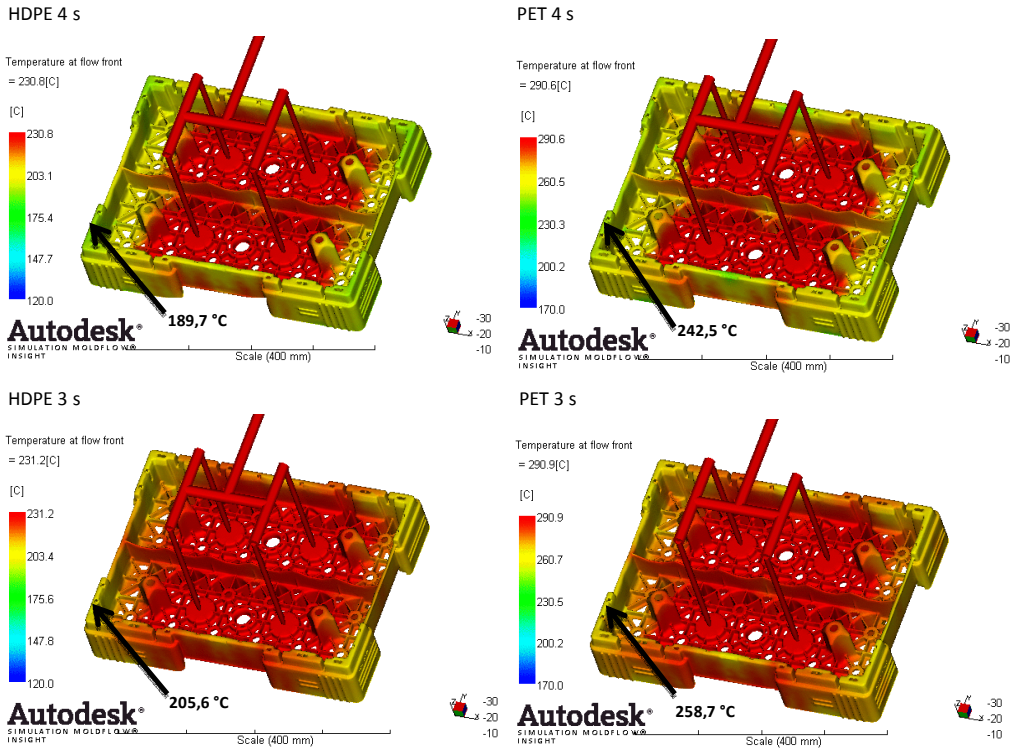

Figure 39. Temperature at flow front

The results for shear rate can be seen in Figure 40. The maximum shear rate for HDPE is 40 000 1/s and for PET it is 50 000 1/s, meaning that the materials can withstand shear rates this high. The shear rates for these conditions are much lower. The highest for HDPE4 and PET4 is about 3 000 1/s and that of HDPE3 and PET3 is around 4 000 1/s. The results for shear stress (see Figure 41) were more alarming. The maximum shear stress for HDPE and PET is 0,2 MPa and 0,5 MPa respectively. Values above the maximum shear stress were found in every simulation. Maximum for HDPE3 was 0,44 MPa but generally shear stress was below 0,30 MPa. For HDPE4 it was slightly lower, generally below 0,26 MPa and the maximum found was 0,37. For the PET simulations, both had shear stress values generally below 0,5 MPa. The values were slightly lower for PET4 with a maximum shear stress of 0,77 MPa. The maximum for PET3 was 0,81 MPa. According to the results, significant material degradation due to shear stress would occur for HPDE at both injection times whereas for PET it would only occur minimally at both fill times.

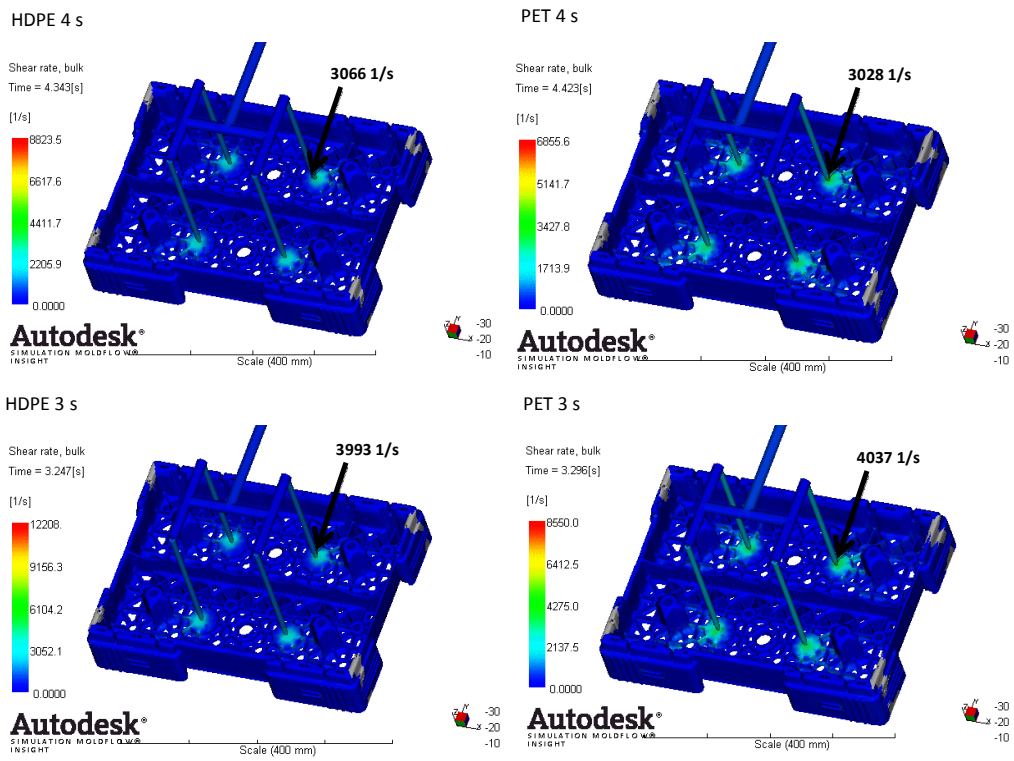

Figure 40. Shear rate

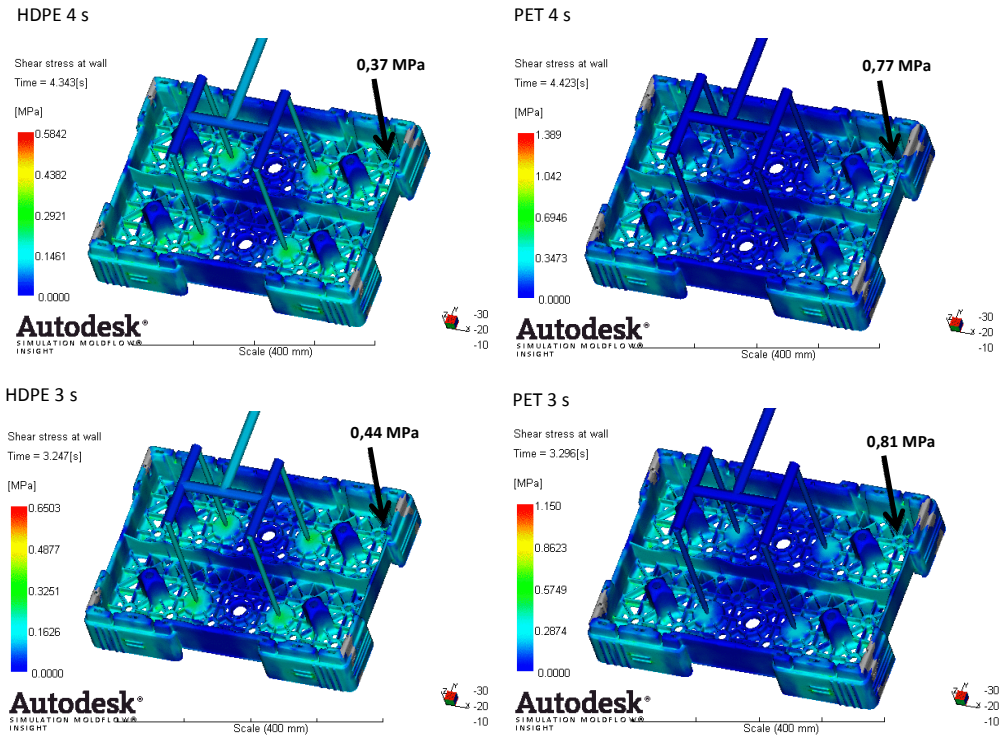

Figure 41. Shear stress

The results for clamping force are quite inconclusive and might not be very reliable. For all simulations back flow occurs at the V/P switchover which can be seen in Figure 42, by the drop in the curves. It is interesting that the maximum clamp force for both HDPE4 and HDPE3 is reached after the V/P switchover. For PET4 and PET3 it is reached before the switchover. For these reasons it might be better to ignore the results beyond the V/P switchover point. The maximum clamp forces during filling were the following: HDPE4 221 tons, HDPE3 214 tons, PET4 411 tons and PET3 369 tons.

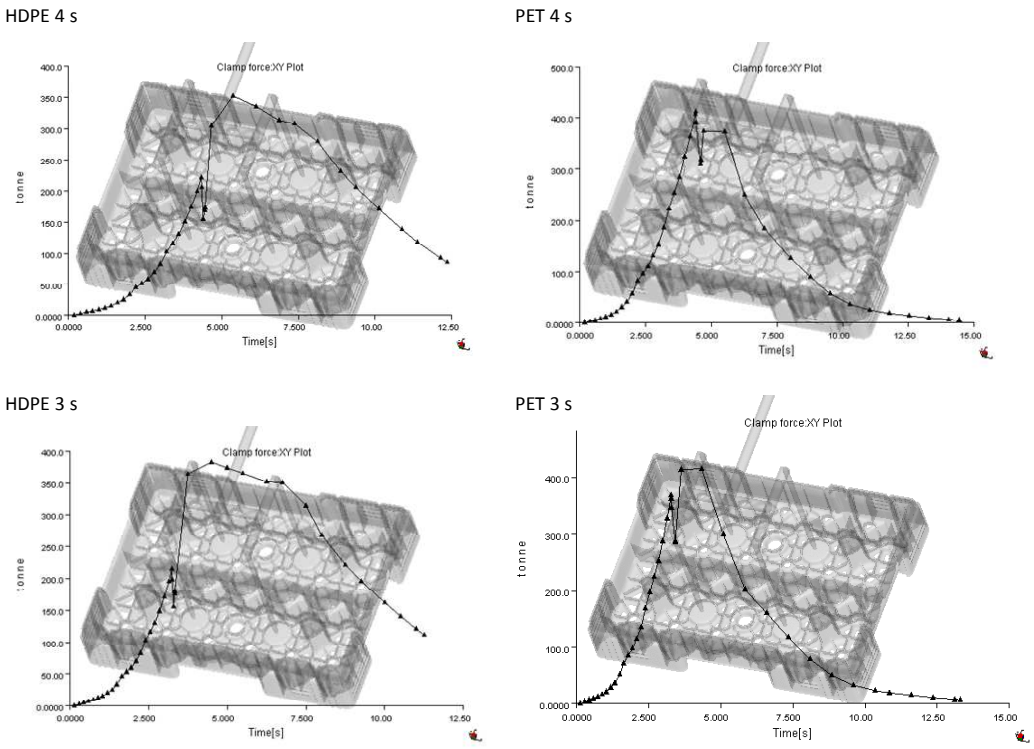

Figure 42. Clamp force

5.3 Tensile test

The injection moulded test specimens were not completely filled; there was a small sink groove along the narrow part of the specimen. This was most likely caused by rapid freezing of the gate, as the gate was very thin and the processing temperature window of PET is so narrow. This prevented extra plastic to be pushed in for shrinkage compensation. Higher hold pressure could have been a possible solution for this problem. But as this was the case for all the tested materials and all test specimens looked the same, it did not change the relative results between the materials. And because the main goal for the tensile test was to compare the materials, this was ignored. Consequently the cross sections used in the calculations for stress and Young's Modulus were in reality smaller. This would mean that the actual values for stress at yield and Young's Modulus would be slightly higher. Table 23 contains the results for the tensile test. As can be seen, the

mechanical properties were fairly similar for all materials. No notable change in property or appearance due to higher mould temperature was seen.

Table 23. Tensile test results

Material	Stress at yield (MPa)	Young's Modulus (MPa)	Nominal strain at break (%)
PET	52,0	1059	244
PET 30 °C	50,5	1041	250
PET 40 °C	50,6	1088	248
PET/rPET	54,5	1089	243
PET/rPET/TiO_2	53,1	1045	255
rPET granules	53,5	1075	264
rPET flakes	54,0	1025	254

Figure 43, Figure 44 and Figure 45 displays the results and standard deviations for stress at yield, nominal strain at break and Young's Modulus respectively.

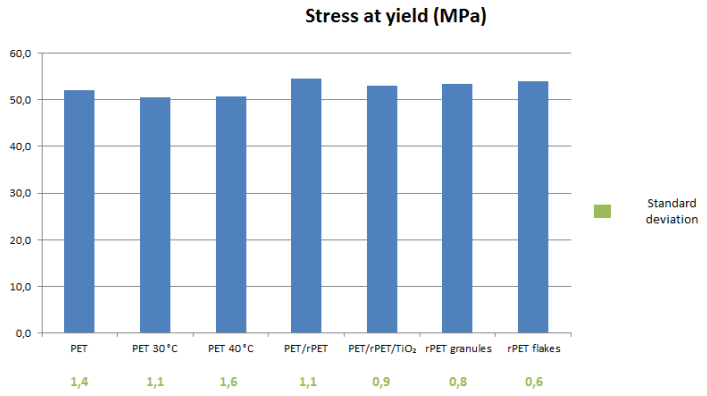

Figure 43. Stress at yield

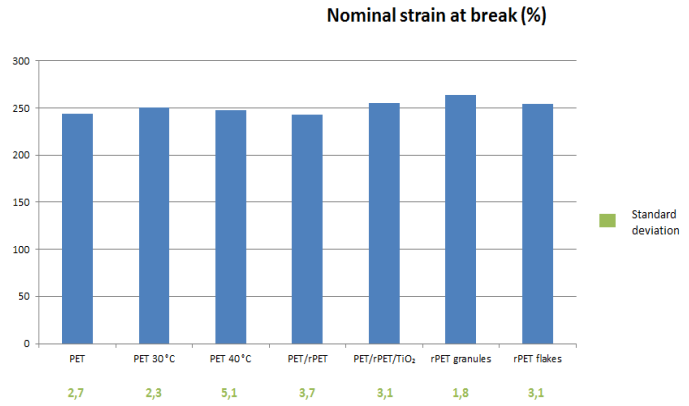

Figure 44. Nominal strain at break

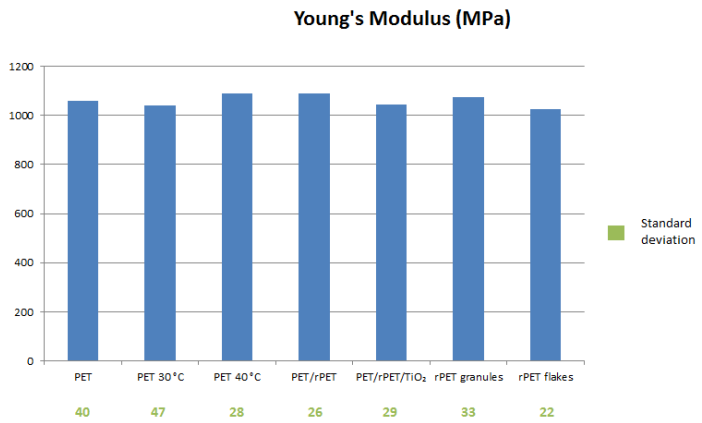

Figure 45. Young's Modulus

5.4 Melt flow index (MFI)

Table 24 contains the results and test conditions. Figure 46 also displays the results along with the standard deviations.

Table 24. Melt flow index conditions and average results

Material	Weight (kg)/ temperature (°C)	Melt flow index, average (g/10 min)
HDPE	2,16/190	8
HDPE	2,16/230	13
PET	2,16/280	40
rPET flakes	2,16/280	48
rPET/TiO_2 (99/1)	2,16/280	51
rPET granules	2,16/280	36

The PET and rPET materials have significantly higher melt flow indices than HDPE. RPET/TiO_2 has a slightly higher MFI value than rPET flakes, but also has a higher standard deviation. Likewise, the MFI of rPET granules is slightly lower than that of PET but the standard deviation is quite big for rPET granules. PET and rPET granules have values clearly lower than rPET flakes and rPET/TiO_2. The results indicate roughly that PET and rPET granules have a molecular weight that is higher than that of PET/rPET and PET/rPET/TiO_2.

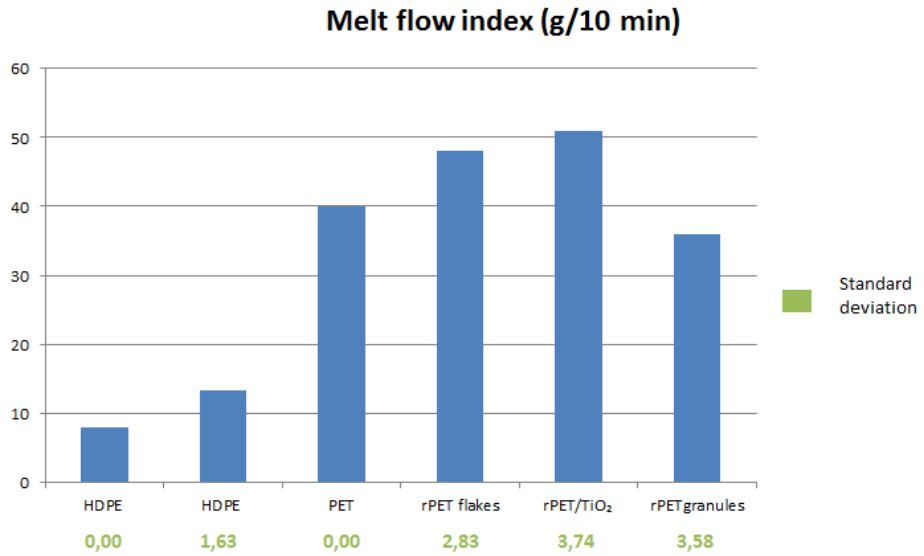

Figure 46. Melt flow index results and standard deviations

5.5 Interviews

According to Markku Hirn, injection compression moulding would not be a suitable production method for this purpose. He states the following reasons as hinders:

> ”1. The product contains shapes that are done with the use of side action. The force that is needed cannot be developed. 2. The flow lengths and the wall thickness will lead to quick cooling of the raw material. The force needed would be unreasonable high and as high as the clamping force required by the projected area. In practice, the injection and compression would have to be done simultaneously and still no advantages would be gained.”

He thinks that injection moulding would be the best method, but explains that the machine should have a very effective and dynamic injection unit. (Hirn 2013)

5.6 Calculations

The shear rates for the test specimen mould for all injection speeds used in the test can be seen in Table 25. Because of the small size of the gates, very high shear rates occurs there. The range of all the shear rates is 335-18 750 1/s.

Table 25. Shear rates for the viscosity test

Injection speed (mm/s)	Shear rate (1/s)				
	Runner	Runner/2	Gate	Broad section	Narrow section
42	2577	1288	18750	1172	3711
39	2393	1196	17411	1088	3446
36	2209	1104	16072	1004	3181
33	2025	1012	14732	921	2916
30	1840	920	13393	837	2651
27	1656	828	12054	753	2386
24	1472	736	10714	670	2121
21	1288	644	9375	586	1856
18	1104	552	8036	502	1590
15	920	460	6697	419	1325
12	736	368	5357	335	1060

The results for cooling time and energy consumption can be seen in Table 26. The cooling time index for PET was 1,92 (HDPE=1) which means that according to the equation used, the cooling time for PET can be expected to be 92 % higher than that of HDPE. When heating from room temperature, the energy per kilogram needed to raise the temperature of PET to 290 °C is 51,3 % of the energy needed to raise the temperature of HDPE to 230 °C. For rPET flakes, heated to 290 °C, the energy needed is 48,3 % of the energy need of HDPE. The value is slightly lower for rPET flakes than for PET, because of the lower degree of crystallinity within the flakes.

Table 26. Cooling time index and energy consumption

	Unit	HDPE	PET	rPET flakes
Cooling time index		1	1,92	1,92
Total energy consumption for reaching target temperature	kJ/kg	675,5 (230 °C)	346,5 (290 °C)	326,0 (290 °C)
Energy consumption/kg index		1	0,513	0,483

The results for the price and density indices calculations can be seen in Table 27. As can be seen, even though the prices for rPET is significantly lower than for HDPE its density will bring the material costs up.

Table 27. Price and density indices

	HDPE	PET	PET/rPET	rPET flakes	rPET granules
Price/weight unit index	1,000	0,986	0,774	0,561	0,790
Density index	1,000	1,380	1,380	1,380	1,380
Price/volume unit index (Price index * Density index)	1,000	1,360	1,067	0,774	1,090

6 DISCUSSION

In this chapter the research methods and their limitations are discussed.

The viscosity test was unique in the sense that no studies that have been using the in-mould rheology test this way could be found. It is, as previously mentioned, primarily used to determine the optimal injection speed for a specific mould. While this made the test interesting it also leaves room for some uncertainties whether this is a good way to do comparable viscosity measurements or not. One way of looking at this test is that it is similar to pushing melt through a pipe with constant cross section and measuring the pressure loss. In this mould the cross section is not constant and the shape of the channels changes, of course, but the principle remains the same. And as the geometry of the mould and the machine parameters (except for temperatures) were the same for all materials the only thing that should, in theory, differ is the viscosity. There were however, some practical things that affected the quality of the results. The variations in viscosity for PET and rPET were slightly problematic and even though most of the extreme values were excluded from the results this still, more or less, increased the margin of error.

On the other hand, this could just be the nature of PET and what should be expected when processing this material. Another unfortunate thing was that some of the tests were limited by pressure. Furthermore the difference in fill time is not a good thing either. It would be better to make sure that the same volume of melt is injected rather than the weight percentage and thus having a more similar fill time. Still, the difference in fill time could have been accounted for other things than shrinkage. Perhaps the screw was just able to move and accelerate faster for PET than for HDPE as PET is significantly less viscous at low shear rates, which was proven by the melt flow index test. Nonetheless, the viscosity curves should accurately show the amount of resistance exhibited by the materials even if the injected volumes were different. After all, whatever the reason for shorter fill times for PET is this would most likely be the case for any mould. And the pressure curves still show the difference in pressure need and thus compensate the viscosity curves, in the case of any misperception. It was also a shame that rPET flakes were only tested partially as it seemed to be one of the better materials. Because the theory suggested that the quality of 100 % flakes would be poor, it was therefore decided to mix the flakes with virgin material. Nevertheless it was good that the remaining material was used and that 100 % flakes was included in the tests as the results obtained were sufficient to draw guidelines from.

It should be remembered, that by doing this test with different moulds the results would probably be quite varying because different shear rates would be in use. Therefore if someone would wish to compare results obtained with different moulds, it should be done with caution. This is the reason the shear rate table was done, which contains 55 different shear rates, so that the results could be roughly correlated to moulds with similar shear rates. In addition to these shear rates there is also a big range of different shear rates at the area between the broad and narrow section of the test specimen that are not included in the table. These shear rates are somewhere between the shear rates of the broad and narrow sections. So by taking the average viscosities and pressure needs, overall values that represent a very wide range of shear rates as well as a wide temperature range are obtained. In fact the 20 °C injection temperature range and whatever the lowest flow front temperature is for the slowest speeds at the lowest injection temperature, offers a temperature range not too far away from that of the Moldflow results. At least for the simulations with faster fill time. The viscosity test shear rates are also most-

ly within the same range as the Moldflow simulations, except for the shear rates at the gates. But the gates only represent a very small portion of the mould. Considering all of this, it should be possible to correlate the results obtained from the Moldflow simulations with the results from the viscosity test.

As for Moldflow, it is obvious that the mesh quality was not optimal. The results probably offer a reliable comparison of the materials but relating them to reality should be done with caution, especially in the case of clamp force.

One drawback for the tensile test would, of course, be that the test specimens were not completely filled. Another would be that the Young's Modulus measurements were not done according to the standard. But as earlier mentioned this should not greatly affect the relative results as the conditions were the same for all materials. The results were quite interesting; there was virtually no difference in the mechanical properties of the PET and rPET materials. It was suspected that the rPET materials would have had weaker mechanical properties, especially the flakes that had been re-melted twice.

The shear rate calculations only offer approximate values due to the fact that the cross sections of the channels within the cavity will start to decrease as soon as plastic enters the cavity and gradually starts to freeze along the walls. But be that as it may, this is the case for all moulds and therefore it should be possible to correlate results to other moulds. Furthermore, it was not sure if the shear rate for a half round cross section was calculated with the proper equation. But it should still be a good approximation.

7 CONCLUSION

In this chapter the results are analyzed and the research questions are answered.

7.1 Does PET have too poor flow properties to be used for producing trays through injection moulding?

According to the results it should be possible to produce the tray out of PET or rPET, through injection moulding. There could be one preventing factor though: premature

freezing of the melt. A warning for this was given by the uncompleted filling of the test specimens. On the other hand, the gates only had a thickness of 0,5 mm and according to the Moldflow results it would be possible to fill the mould with both fill times 4,614 s and 3,413 s. But with the latter, the melt temperature would stay within a safe range and the pressure needed would be lower. This implies that it would beneficial to inject PET or rPET rather faster than slower.

According to the results for the viscosity test and Moldflow simulations PET is more viscous than HDPE when injection moulded, at least for these moulds. At low shear rates HDPE is significantly more viscous than PET, as proven with the MFI test.

According to the mould flow results PET needs 26,1 % higher pressure than HDPE for the slower fill time. For the faster fill time, PET needs 14,1 % higher pressure. If the tray is now produced with a fill time similar to 4,462 s and trays out of PET would be produced with a fill time of 3,413, PET would need 21,5 % higher pressure. According to the viscosity test results, the overall pressure need for all temperatures and shear rates tested would be 28 % higher for PET. It is also evident that the difference in pressure need is smaller at the fast end of injection speeds than for the slow end. In conclusion, the pressure needed to produce a tray out of PET through injection moulding would be 10-30 % higher than that of HDPE, depending on the fill time.

7.2 Do the rPET materials have better flow properties and weaker mechanical properties than PET? How does TiO_2 affect flow properties?

When using 100 % rPET, both the granules and flakes have better flow properties than PET. It is very interesting that the rPET granules had so much lower viscosity than the rest of the PET and rPET materials, especially when it had the lowest MFI of these materials. The flow properties were even slightly better than that of HDPE. Although the flakes (100%) were less viscous than PET, the PET/rPET mix was the most viscous material. Adding TiO_2 did have a positive effect on flow properties according to both the viscosity and MFI test, although the effect was quite marginal. The conclusion is that rPET has better flow properties than PET, but there is no point in mixing PET and rPET

in order to improve flow properties or mechanical properties. TiO_2 will improve the flow a little and could be used if the product should be white, but otherwise it is not very beneficial to use.

7.3 Would rPET be a more suitable material than HDPE, in terms of material performance and from the economic and ecologic viewpoint?

It is difficult to give any absolute answers about which material would be the most suitable. This thesis has not gone through every single aspect concerning the material selection. The areas that can be assessed based on this thesis, however, are: Mechanical properties, material price, ecological benefits, flow properties, weathering resistance and cooling times. In Table 28 and Table 29 relative scores have been given for these areas. Every area has also been given a score for its importance, according to my own opinion on what is important in order to produce a successful product. The first table contains scores for the materials, assuming that the design would be the same for all materials. The second table shows how the scores would be if the tray design for the PET and rPET materials would be changed and thereby reduce the weight of the tray. This could maybe not be done by making the overall wall thickness thinner, which would make the filling of the mould even more difficult, but as PET is a remarkably stiffer material some wall supports could for example perhaps be removed. The amount of material that could be removed remains uncertain though. Although it was mentioned in the theory part that the flakes are usually pelletized before injection moulding it could still be possible to insert them directly into the injection moulding machine. Because this remained uncertain it is was not taken into consideration when giving scores. If the flakes would need to be pelletized prior to injection moulding, the score for this material would be lower in both tables.

The scores given in Table 28 are motivated the following way:

1. Mechanical properties: PET has about twice as high tensile strength and is a lot stiffer. Although HDPE has higher impact strength, which is one of the most important mechanical properties for the tray, PET still is a quite tough material and therefore receives a higher overall score.

2. Material price: The price per volume unit index is used as a base for the scores. The cost of TiO_2 is ignored as the amount added to the material is so small.
3. Ecological: Energy needed for melting is a lot lower for the PET and rPET materials. Drying is needed for the PET and rPET materials. The energy used for producing the raw material is similar for HDPE and PET but significantly lower for the rPET materials. More energy is needed to produce rPET granules than flakes. If the design remains the same, more material would be used for the PET and rPET materials. Still by using rPET materials, resources are saved.
4. Flow properties: Scores are given based on the average hydraulic pressures.
5. Weathering resistance: All materials should remain tough at cold outdoor temperatures. HDPE is UV-sensitive and PET has good UV-resistance.
6. Cooling time: The cooling time for the PET and rPET materials is almost twice as high as for HDPE.

Table 28. Score table, same design

Property	Importance (1-10)	Score (1-10)					
		HDPE	PET	PET/rPET	PET/rPET/TiO_2	rPET granules	rPET flakes
Mechanical properties	7	8	10	10	10	10	10
Material costs	10	6	1	5	5	4,5	9
Ecological	6	5	3	5	5	6	8
Flow properties	10	10	2	1	2	10	7
Weathering resistance	5	5	10	10	10	10	10
Cooling time	10	10	3	3	3	3	3
Total score		**371**	**198**	**240**	**250**	**331**	**358**
Percentage of maximum score		**77,3**	**41,3**	**50,0**	**52,1**	**69,0**	**74,6**

The scores given for mechanical properties, material price and ecological is different for the PET and rPET materials in Table 29 and are motivated the following way:

1. Mechanical properties: With the new design for the PET or rPET tray would perform at the same level as the HDPE tray.
2. Material price: New design reduces the amount of material used and therefore brings the material costs down.
3. Ecological: New design reduces the amount of material used and therefore makes the tray more ecological.

Table 29. Score table, new design

Property	Importance (1-5)	Score (1-5)					
		HDPE	PET	PET/rPET	PET/rPET/TiO_2	rPET granules	rPET flakes
Mechanical properties	7	8	8	8	8	8	8
Material costs	10	6	3	7	7	6,5	10
Ecological	6	5	5	8	8	9	10
Flow properties	10	10	2	1	2	10	7
Weathering resistance	5	5	10	10	10	10	10
Cooling time	10	10	3	3	3	3	3
Total score		**371**	**216**	**264**	**274**	**355**	**366**
Percentage of maximum score		**77,3**	**45,0**	**55,0**	**57,1**	**74,0**	**76,3**

Top 5:

1. HDPE: 77,3 %
2. rPET flakes, new design: 76,3 %
3. rPET flakes, same design: 74,6 %
4. rPET granules, new design: 74 %
5. rPET granules, same design: 69 %

According to these scores, HDPE is the most suitable material, even if the design is changed. Still the score for rPET flakes comes very close to HDPE, both for the old and new design, and could be as good as HDPE if injection moulding could be done with

flakes directly. The rPET granules also come quite close with a lighter design but have a slightly lower score if the same design is used.

7.4 Would injection compression moulding be a more suitable production method?

It seemed clear after the interview that this would not be a suitable method. Maybe it could be possible if no side action would be used, but probably there would be nothing to gain from it.

8 SUGGESTIONS FOR FURTHER WORK

Another way to do the viscosity test would be to use a mould cavity with constant cross section. This way the shear rates could be quite accurately calculated and by recording the peak pressure and then using the pressure loss equation, the viscosity could be obtained. Thereby viscosity versus shear rate curves could be created with an injection moulding machine. It could prove useful for companies that want to test and compare materials themselves. The results obtained this way could be compared with results produced with a rheometer to check the reliability. Erland Nyroth, lab engineer at Arcada, suggested a mould cavity shown in Figure 47 that would be suitable for this purpose. The challenges in this would be the following:

- The cross section starts to decrease during injection due to that the melt freezes along the walls. Therefore the shear rates would change during injection.
- It would be important to control the temperature as precisely as possible.
- It would be important to control the injected volume as precisely as possible.
- Injection speed should remain as constant as possible.

Some research on how to solve or get around these challenges would have to be done in order to make the tests as reliable as possible.

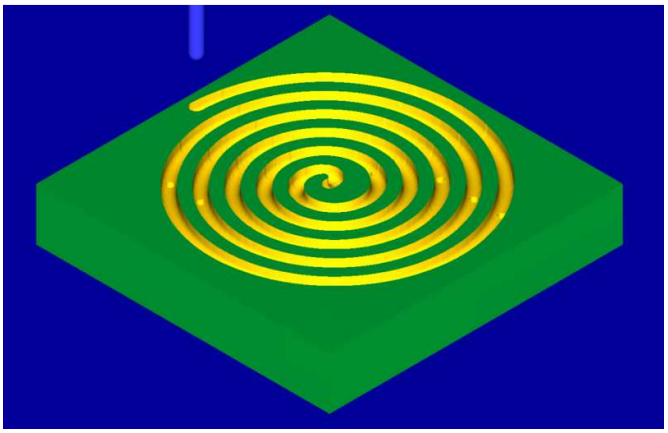

Figure 47. Spiral cavity mould (Erland Nyroth, 2013)

Another interesting area that could be researched is moisture absorbing additives. By mixing these with PET it could maybe be possible to avoid hydrolysis to a greater extent and even reduce the drying requirements.

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APPENDIX 1/1 (6)

Material:	HDPE Exxon Mobil HMA 025							
	1	2	3	4	Melt	Mold		
Temperature (°C)	200	210	210	210	200	30		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,80	96,00	190,08	1,79	97,00	190,99	190,54	96,5
15	1,37	100,00	150,70	1,36	101,00	151,10	150,90	100,5
18	1,09	99,00	118,70	1,10	104,00	125,84	122,27	101,5
21	0,91	106,00	106,11	0,91	105,00	105,11	105,61	105,5
24	0,79	107,00	92,98	0,79	104,00	90,38	91,68	105,5
27	0,70	108,00	83,16	0,70	111,00	85,47	84,32	109,5
30	0,63	107,00	74,15	0,63	108,00	74,84	74,50	107,5
33	0,58	111,00	70,82	0,58	114,00	72,73	71,78	112,5
36	0,52	109,00	62,35	0,52	113,00	64,64	63,49	111
39	0,49	119,00	64,14	0,49	118,00	63,60	63,87	118,5
42	0,46	120,00	60,72	0,45	121,00	59,90	60,31	120,5
Intensification ratio	11							

Material:	HDPE Exxon Mobil HMA 025							
	1	2	3	4	Melt	Mold		
Temperature (°C)	220	230	230	230	220	30		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,70	88,00	164,56	1,73	89,00	169,37	166,96	88,5
15	1,30	92,00	131,56	1,31	92,00	132,57	132,07	92
18	1,06	95,00	110,77	1,06	95,00	110,77	110,77	95
21	0,89	97,00	94,96	0,90	97,00	96,03	95,50	97
24	0,76	99,00	82,76	0,77	98,00	83,01	82,89	98,5
27	0,68	102,00	76,30	0,68	103,00	77,04	76,67	102,5
30	0,61	104,00	69,78	0,62	104,00	70,93	70,36	104
33	0,57	101,00	63,33	0,56	105,00	64,68	64,00	103
36	0,52	109,00	62,35	0,52	105,00	60,06	61,20	107
39	0,48	107,00	56,50	0,48	107,00	56,50	56,50	107
42	0,46	111,00	56,17	0,45	115,00	56,93	56,55	113
Intensification ratio	11							

Material:	HDPE Exxon Mobil HMA 025							
	1	2	3	4	Melt	Mold		
Temperature (°C)	240	250	250	250	240	30		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,70	82,00	153,34	1,74	83,00	158,86	156,10	82,5
15	1,28	84,00	118,27	1,28	86,00	121,09	119,68	85
18	1,04	88,00	100,67	1,04	88,00	100,67	100,67	88
21	0,88	89,00	86,15	0,88	90,00	87,12	86,64	89,5
24	0,78	94,00	80,65	0,77	96,00	81,31	80,98	95
27	0,70	99,00	76,23	0,70	98,00	75,46	75,85	98,5
30	0,63	98,00	67,91	0,63	100,00	69,30	68,61	99
33	0,57	102,00	63,95	0,57	102,00	63,95	63,95	102
36	0,52	104,00	59,49	0,52	103,00	58,92	59,20	103,5
39	0,48	99,00	52,27	0,48	105,00	55,44	53,86	102
42	0,45	114,00	56,43	0,43	108,00	51,08	53,76	111
Intensification ratio	11							

APPENDIX 1/2 (6)

Material: PET Lighter C 88

	1	2	3	4	Melt	Mold		
Temperature (°C)	265	275	275	275	265	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,86	144	294,62	1,86	144	294,62	294,62	144
15	1,38	145	220,11	1,4	144	221,76	220,94	144,5
18	1,1	144	174,24	1,12	144	177,41	175,82	144
21	0,93	144	147,31	0,92	144	145,73	146,52	144
24	0,81	144	128,30	0,81	144	128,30	128,30	144
27	0,73	144	115,63	0,73	144	115,63	115,63	144
30	0,66	144	104,54	0,65	144	102,96	103,75	144
33	0,6	144	95,04	0,61	144	96,62	95,83	144
36	0,56	144	88,70	0,56	144	88,70	88,70	144
39	0,55	144	87,12	0,53	144	83,95	85,54	144
42	0,52	145	82,94	0,49	145	78,16	80,55	145
Intensification ratio	11							

Material: PET Lighter C 88

	1	2	3	4	Melt	Mold		
Temperature (°C)	275	285	285	285	275	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,7	131	244,97	1,67	123	225,95	235,46	127
15	1,22	120	161,04	1,23	120	162,36	161,70	120
18	1	123	135,30	1,01	123	136,65	135,98	123
21	0,84	123	113,65	0,84	119	109,96	111,80	121
24	0,72	119	94,25	0,73	124	99,57	96,91	121,5
27	0,63	122	84,55	0,64	118	83,07	83,81	120
30	0,59	123	79,83	0,59	130	84,37	82,10	126,5
33	0,54	134	79,60	0,54	129	76,63	78,11	131,5
36	0,5	133	73,15	0,5	134	73,70	73,43	133,5
39	0,46	134	67,80	0,46	135	68,31	68,06	134,5
42	0,43	134	63,38	0,44	135	65,34	64,36	134,5
Intensification ratio	11							

Material: PET Lighter C 88

	1	2	3	4	Melt	Mold		
Temperature (°C)	285	295	295	295	285	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,54	105	177,87	1,52	103	172,22	175,04	104
15	1,17	113	145,43	1,17	111	142,86	144,14	112
18	0,93	102	104,35	0,91	101	101,10	102,72	101,5
21	0,78	99	84,94	0,78	100	85,80	85,37	99,5
24	0,69	102	77,42	0,69	103	78,18	77,80	102,5
27	0,59	99	64,25	0,58	97	61,89	63,07	98
30	0,53	91	53,05	0,54	98	58,21	55,63	94,5
33	0,5	101	55,55	0,49	98	52,82	54,19	99,5
36	0,45	101	50,00	0,45	113	55,94	52,97	107
39	0,43	116	54,87	0,42	113	52,21	53,54	114,5
42	0,39	115	49,34	0,39	115	49,34	49,34	115
Intensification ratio	11							

APPENDIX 1/3 (6)

Material:	PET/rPET							
	1	2	3	4	Melt	Mold		
Temperature (°C)	265	275	275	275	265	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	2,04	145	325,38	2,48	145	395,56	360,47	145
15	1,45	145	231,28	1,43	145	228,09	229,68	145
18	1,13	144	178,99	1,13	144	178,99	178,99	144
21	0,96	145	153,12	0,97	145	154,72	153,92	145
24	0,83	145	132,39	0,81	144	128,30	130,34	144,5
27	0,73	144	115,63	0,73	144	115,63	115,63	144
30	0,66	144	104,54	0,66	145	105,27	104,91	144,5
33	0,62	145	98,89	0,62	144	98,21	98,55	144,5
36	0,56	144	88,70	0,56	144	88,70	88,70	144
39	0,53	145	84,54	0,55	145	87,73	86,13	145
42	0,5	144	79,20	0,5	145	79,75	79,48	144,5
Intensification ratio	11							

Material:	PET/rPET							
	1	2	3	4	Melt	Mold		
Temperature (°C)	275	285	285	285	275	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,72	134	253,53	1,74	138	264,13	258,83	136
15	1,28	137	192,90	1,28	139	195,71	194,30	138
18	1,03	135	152,96	1,03	128	145,02	148,99	131,5
21	0,87	135	129,20	0,87	138	132,07	130,63	136,5
24	0,77	138	116,89	0,76	139	116,20	116,55	138,5
27	0,68	140	104,72	0,68	141	105,47	105,09	140,5
30	0,62	139	94,80	0,62	139	94,80	94,80	139
33	0,55	138	83,49	0,57	137	85,90	84,69	137,5
36	0,51	140	78,54	0,51	139	77,98	78,26	139,5
39	0,47	139	71,86	0,48	142	74,98	73,42	140,5
42	0,45	142	70,29	0,44	140	67,76	69,03	141
Intensification ratio	11							

Material:	PET/rPET							
	1	2	3	4	Melt	Mold		
Temperature (°C)	285	295	295	295	285	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,52	103	172,22	1,55	103	175,62	173,92	103
15	1,17	106	136,42	1,15	101	127,77	132,09	103,5
18	0,96	108	114,05	0,95	109	113,91	113,98	108,5
21	0,82	115	103,73	0,81	114	101,57	102,65	114,5
24	0,71	116	90,60	0,72	118	93,46	92,03	117
27	0,64	120	84,48	0,63	121	83,85	84,17	120,5
30	0,58	122	77,84	0,58	124	79,11	78,47	123
33	0,53	122	71,13	0,53	127	74,04	72,58	124,5
36	0,49	122	65,76	0,49	129	69,53	67,64	125,5
39	0,45	126	62,37	0,45	131	64,85	63,61	128,5
42	0,41	128	57,73	0,41	129	58,18	57,95	128,5
Intensification ratio	11							

APPENDIX 1/4 (6)

Material: PET/rPET/TiO_2

	1	2	3	4	Melt	Mold
Temperature (°C)	265	275	275	275	265	20
Test #	1			2		

Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	2,24	144	354,82	1,88	144	297,79	326,30	144
15	1,45	144	229,68	1,42	144	224,93	227,30	144
18	1,13	144	178,99	1,16	144	183,74	181,37	144
21	0,95	144	150,48	0,95	144	150,48	150,48	144
24	0,83	144	131,47	0,83	144	131,47	131,47	144
27	0,74	145	118,03	0,74	144	117,22	117,62	144,5
30	0,66	144	104,54	0,66	144	104,54	104,54	144
33	0,62	144	98,21	0,61	144	96,62	97,42	144
36	0,57	144	90,29	0,57	144	90,29	90,29	144
39	0,52	144	82,37	0,54	145	86,13	84,25	144,5
42	0,45	142	70,29	0,49	144	77,62	73,95	143
Intensification ratio	11							

Material: PET/rPET/TiO_2

	1	2	3	4	Melt	Mold
Temperature (°C)	275	285	285	285	275	20
Test #	1			2		

Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,77	128	249,22	1,73	122	232,17	240,69	125
15	1,31	118	170,04	1,33	126	184,34	177,19	122
18	1,05	117	135,14	1,04	117	133,85	134,49	117
21	0,89	116	113,56	0,89	119	116,50	115,03	117,5
24	0,76	122	101,99	0,75	116	95,70	98,85	119
27	0,68	124	92,75	0,67	126	92,86	92,81	125
30	0,62	130	88,66	0,61	129	86,56	87,61	129,5
33	0,56	123	75,77	0,56	128	78,85	77,31	125,5
36	0,51	124	69,56	0,52	129	73,79	71,68	126,5
39	0,47	134	69,28	0,47	133	68,76	69,02	133,5
42	0,44	134	64,86	0,45	133	65,84	65,35	133,5
Intensification ratio	11							

Material: PET/rPET/TiO_2

	1	2	3	4	Melt	Mold
Temperature (°C)	285	295	295	295	285	20
Test #	1			2		

Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,61	103	182,41	1,57	105	181,34	181,87	104
15	1,17	103	132,56	1,17	102	131,27	131,92	102,5
18	0,94	105	108,57	0,95	103	107,64	108,10	104
21	0,81	101	89,99	0,8	102	89,76	89,88	101,5
24	0,68	103	77,04	0,68	104	77,79	77,42	103,5
27	0,61	104	69,78	0,61	108	72,47	71,13	106
30	0,55	107	64,74	0,55	105	63,53	64,13	106
33	0,53	107	62,38	0,52	109	62,35	62,36	108
36	0,48	103	54,38	0,48	106	55,97	55,18	104,5
39	0,46	125	63,25	0,45	117	57,92	60,58	121
42	0,43	123	58,18	0,42	114	52,67	55,42	118,5
Intensification ratio	11							

APPENDIX 1/5 (6)

Material: rPET flakes

	1	2	3	4	Melt	Mold		
Temperature (°C)	275	285	285	285	275	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12								
15								
18								
21	0,9	105	103,95	0,89	107	104,75	104,4	106,0
24	0,76	107	89,45	0,75	110	90,75	90,1	108,5
27	0,68	111	83,03	0,68	112	83,78	83,4	111,5
30	0,61	118	79,18	0,59	112	72,69	75,9	115,0
33	0,55	116	70,18	0,56	118	72,69	71,4	117,0
36	0,51	121	67,88	0,5	117	64,35	66,1	119,0
39	0,47	113	58,42	0,47	119	61,52	60,0	116,0
42	0,45	125	61,88	0,45	125	61,88	61,9	125,0
Intensification ratio	11							

Material: rPET granules

	1	2	3	4	Melt	Mold		
Temperature (°C)	265	275	275	275	265	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,72	130	245,96	1,73	128	243,58	244,77	129
15	1,28	119	167,55	1,28	121	170,37	168,96	120
18	1,01	118	131,10	1,02	118	132,40	131,75	118
21	0,86	117	110,68	0,86	120	113,52	112,10	118,5
24	0,73	114	91,54	0,74	118	96,05	93,80	116
27	0,65	121	86,52	0,65	118	84,37	85,44	119,5
30	0,59	119	77,23	0,58	121	77,20	77,21	120
33	0,52	119	68,07	0,53	117	68,21	68,14	118
36	0,5	125	68,75	0,49	118	63,60	66,18	121,5
39	0,46	125	63,25	0,46	126	63,76	63,50	125,5
42	0,44	125	60,50	0,43	128	60,54	60,52	126,5
Intensification ratio	11							

Material: rPET granules

	1	2	3	4	Melt	Mold		
Temperature (°C)	275	285	285	285	275	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,47	85	137,45	1,48	88	143,26	140,35	86,5
15	1,05	86	99,33	1,06	85	99,11	99,22	85,5
18	0,85	87	81,35	0,87	88	84,22	82,78	87,5
21	0,72	83	65,74	0,71	83	64,82	65,28	83
24	0,63	82	56,83	0,63	86	59,60	58,21	84
27	0,57	84	52,67	0,57	87	54,55	53,61	85,5
30	0,5	87	47,85	0,53	92	53,64	50,74	89,5
33	0,47	89	46,01	0,49	94	50,67	48,34	91,5
36	0,44	93	45,01	0,45	96	47,52	46,27	94,5
39	0,42	97	44,81	0,42	102	47,12	45,97	99,5
42	0,4	102	44,88	0,39	95	40,76	42,82	98,5
Intensification ratio	11							

APPENDIX 1/6 (6)

Material:	rPET granules							
	1	2	3	4	Melt	Mold		
Temperature (°C)	285	295	295	295	285	20		
Test #	1			2				
Injection speed (mm/s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Fill time (s)	Peak hydraulic pressure (bar)	Apparent viscosity (MPa x s)	Average Apparent viscosity (MPa x s)	Average peak hydraulic pressure (bar)
12	1,36	66	98,74	1,31	67	96,55	97,64	66,5
15	1	69	75,90	1,02	67	75,17	75,54	68
18	0,81	74	65,93	0,8	72	63,36	64,65	73
21	0,7	77	59,29	0,69	76	57,68	58,49	76,5
24	0,61	73	48,98	0,61	75	50,33	49,65	74
27	0,54	73	43,36	0,54	76	45,14	44,25	74,5
30	0,5	81	44,55	0,5	77	42,35	43,45	79
33	0,45	83	41,09	0,46	81	40,99	41,04	82
36	0,43	89	42,10	0,43	91	43,04	42,57	90
39	0,41	88	39,69	0,41	90	40,59	40,14	89
42	0,39	94	40,33	0,38	89	37,20	38,76	91,5
Intensification ratio	11							