Pre-treatment processing of household plastic packaging waste

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Declaration

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other university.

11th day of September 2016

Abstract

The purpose of this investigation was to investigate whether or not it would be possible to separate blow moulded and injection moulded waste plastics using two techniques; air classification and ballistic separation. Air classification and ballistic separation are two techniques that separate different types of material according to size, shape and density. Previous research, together with new measurements, has suggested that blow mould plastics tend to be thinner in terms of wall thickness than injection moulded plastics meaning that air classification could be used to separate each type of plastic. The material used for the study was supplied by a Romanian recycler and was a mixture of High Density Polyethylene and polypropylene. Two additional samples, one Polyethylene rich and the other polypropylene rich, were also included in the research.

The first part of the study involved measuring different characteristics of the material to determine how to go about performing the different air classification experiments. The second part of the study focused on separating the different material samples using different air classifier systems and a ballistic separation system. The third part of the study focused on processing the samples from part 2 (air classification) into test specimens for further mechanical and melt flow property measurements.

After measuring the mechanical and melt flow properties of the different samples it was found that air classification did not substantially improve the mechanical or melt flow properties of the material. The study did, however, show that there is a strong correlation between polymer type and melt flow properties. High Density polypropylene is generally used for blow mould applications whereas polypropylene is generally used for injection mould applications. Separating the material according to polymer type therefore means that the material is, to an extent, also sorted according to melt flow properties.

Acknowledgements

I would like to thank my supervisors Dr Lizelle Van Dyk, Dr Norbert Fraunholcz and Ms Bernadette Sunjka for their support and guidance. I would also like to thank Prof. Peter Rem at Delft University of Technology for giving me access to the laboratory facilities at the university, and for his invaluable advice. Finally, I would like to thank Mr. Jaap Vandehoek for the internship position that allowed me to complete this research in the Netherlands.

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Nomenclature

Polymer – a macromolecule that is composed of a number of repeating units or monomers

Polyolefin – any polymer that is part of the alkene group

Melt Flow Index – the measure of the viscosity of a material

Virgin Polymer – primary polymer materials synthesised from hydrocarbons such as oil and gas

Plastic – the general term for polymer based products

Monomer – a molecule that has the ability to bind to other molecules

Polyethylene – a polymer derived from the ethylene monomer

Polypropylene – a polymer derived from the propylene monomer

Polystyrene – a polymer derived from the styrene monomer

Polyethylene Terephthalate – a polymer derived from the ethylene terephthalate monomer

Recyclate – recycled material

NIR spectroscopy – Near Infrared spectroscopy

Rheology – the study of the flow of materials in a liquid state

Chemical recycling – recycling by means of chemically breaking down a material into its individual molecules and re-synthesizing them into a new material

Mechanical recycling – recycling by means of mechanical technologies

List of acronyms

PP – Polypropylene

PE – Polyethylene

HDPE – High density polyethylene

LDPE – Low density polyethylene

LLDPE – Linear low density polyethylene

MFI – Melt flow index

MFR – Melt Flow Rate

MDS – Magnetic density separation

EU – European Union

P1 – Magnetic Density Separation polypropylene product

P2 – Magnetic Density Separation Polyethylene product

FTIR – Fourier Transform Infrared Spectroscopy

DSC – Differential Scanning Calorimetry

PS – Polystyrene

PVC – Polyvinylchloride

PET – Polyethylene Terephthalate

CHAPTER 1

1 Introduction

Ever since the discovery of synthetic polymers during the early decades of the 20th century, plastics have become an integral part of modern society. Plastics are relatively cheap, easy to manufacture and durable making them the choice material for applications in a number of industries such as agriculture and plastic packaging. Plastics are ideal materials for packaging applications and are used to package almost every consumable product on the market today. This makes the plastic packaging sector the largest plastic consumer – it accounts for 39% of the total European plastics market (Plastics Europe, 2015).

Plastic packaging products can be manufactured from a range of different plastics depending on the intended application. Figure 1-1 outlines the most common packaging polymers and their typical applications. The most widely used polymers in the packaging industry are Polyethylene Terephthalate (PET), High Density and Low Density Polyethylene (HDPE & LDPE) and Polypropylene (PP).

Figure 1-1 Common packaging plastics and their associated resin codes (Ellen Mac Arthur Foundation, 2016)

Despite these polymers having many favourable physical properties, the majority of packaging products are designed for single usage after which it is subsequently discarded. The result is that plastic packaging accounts for the majority of plastic waste ending up in the total waste stream; most of these plastics then end up in landfills or in our natural environment with only 2% being closed-loop[1] recycled and 8% being cascade[2] recycled (see Figure 1-2). The overwhelming majority of the value locked in packaging materials is lost to the economy every year; the reclamation and recycling of these materials is therefore becoming an increasingly important topic for many industries and governing bodies across the globe.

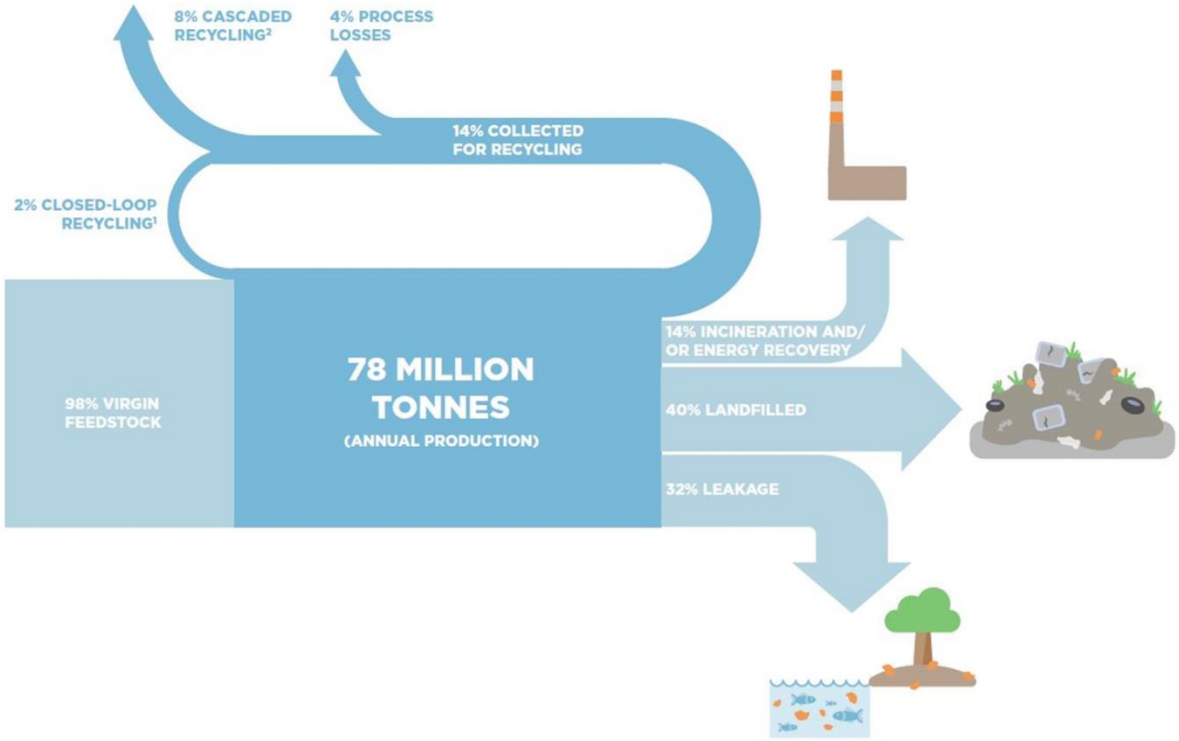


Figure 1-2 Plastic packaging flows (Ellen Mac Arthur Foundation, 2016)

Plastic recycling is undertaken by one of two methods: chemical recycling or mechanical recycling. Mechanical recycling is the favoured approach as it is less energy and cost intensive. Mechanical recycling is the process of sorting mixed plastics into homogeneous plastic fractions so that it may be melted and formed into new products. Referring back to Figure 1-1, resin codes[3] are often imprinted onto packaging products to assist recyclers in sorting mixed plastics into homogeneous plastic fractions. In order to achieve closed loop recycling the purity of the recyclate should, depending on the polymer in question, be in the order of 90% or higher.

[1] Closed loop recycling is the process of using recycled materials to produce a product of a similar quality compared to the original product

[2] Cascade recycling is the process of using recycled materials to produce a product of a lower quality compared to the original product

[3] Resin codes refer to polymer type

In conjunction with separating plastics according to polymer type, plastics need to be sorted according to other physical properties such as colour and melt flow (rheological) properties[4] to produce recyclates that closely resemble the physical characteristics of the original or virgin material.

Viscosity, with regards to plastics, refers to the melt flow or rheological properties of a molten polymer at a given temperature. Viscosity is an important physical property when it comes to the manufacturing of different plastic products because different manufacturing processes, such as blow moulding and injection moulding, require polymers with different viscosities in molten form. Typically, injection moulding applications require polymers with low viscosities in molten form whereas blow moulding applications require polymers that are far more viscous in molten form (see section 2.4 for more information). If two or more different polymers with different melt flow properties are melted down together the result is a product with melt flow properties that are not suitable to either manufacturing process.

For all the research focused on plastic recycling, very little research has been carried out on how to separate plastics based on their melt flow properties; more specifically, how to separate plastics that were initially blow moulded from plastics that were initially injection moulded. In this study two techniques were used to attempt to separate a plastic recyclate mixture into a blow mould rich fraction and an injection mould rich fraction. After separating the material, the physical properties of each fraction were measured to determine to what degree the physical properties and melt flow properties were improved or worsened.

1.1 Project background

1.1.1 Magnetic Density Separation

This research was conducted in conjunction with another project that focused on sorting different polymers according to polymer type by using a newly developed technology known as Magnetic Density Separation. Magnetic Density Separation (MDS), developed by the European Commission funded 'Waste to Plastics' project, has the proven ability to separate complex mixes of plastic waste into a number of high quality products in a single step. One of its strong applications is the separation of mixed polyolefin[5] waste into high purity Polyethylene (PE) and polypropylene (PP) recyclates. But to create a truly versatile recyclate the material must also be sorted according to its melt flow or rheological properties. Figure 1-3 is a simple flow diagram of the proposed process.

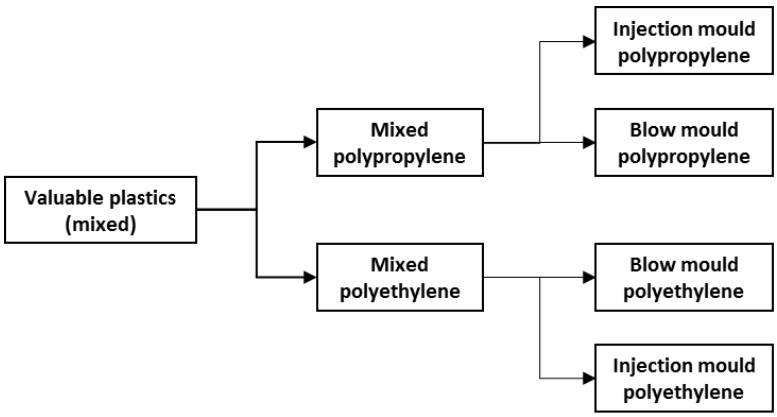


Figure 1-3 Plastic separation overview (developed by author)

[4] Melt flow (rheological) properties refer to the behaviour of the polymer in molten form

[5] Polyolefin refers to any plastic synthesised from an alkene monomer (PP and PE are both polyolefin's)

1.1.2 Melt Flow Index

The Melt Flow Index (MFI) of a polymer is the measurement of the viscosity of a molten polymer or the ease of flow of a molten polymer. It is defined as the mass of a molten polymer that flows, in ten minutes, through a capillary under a specific pressure and has the units, $g/10min$ (Shenoy and Saini, 1986). This term will be used repeatedly throughout the report when referring to melt flow (rheological) properties.

For the purposes of this study, the two grades of plastic will be referred to as blow mould (BM) grade and injection mould (IM) grade. BM and IM grade plastics have different MFI's and can only be used for either blow moulding or injection moulding applications.

1.1.3 Recycling facility

The sample material for this project was supplied by a recycling facility that is in the process of integrating an MDS system into their recycling line. The recycling facility is located in Romania and it currently produces four products by means of manual hand sorting, namely:

1. HDPE blow mould grade (mixed colours)
2. PP injection mould grade (black)
3. PP injection mould grade (mixed colours)
4. HDPE blow and injection mould grade (mixed colours)

Figure 1-4 is a simple process flow diagram of the operation at the recycling facility in Romania.

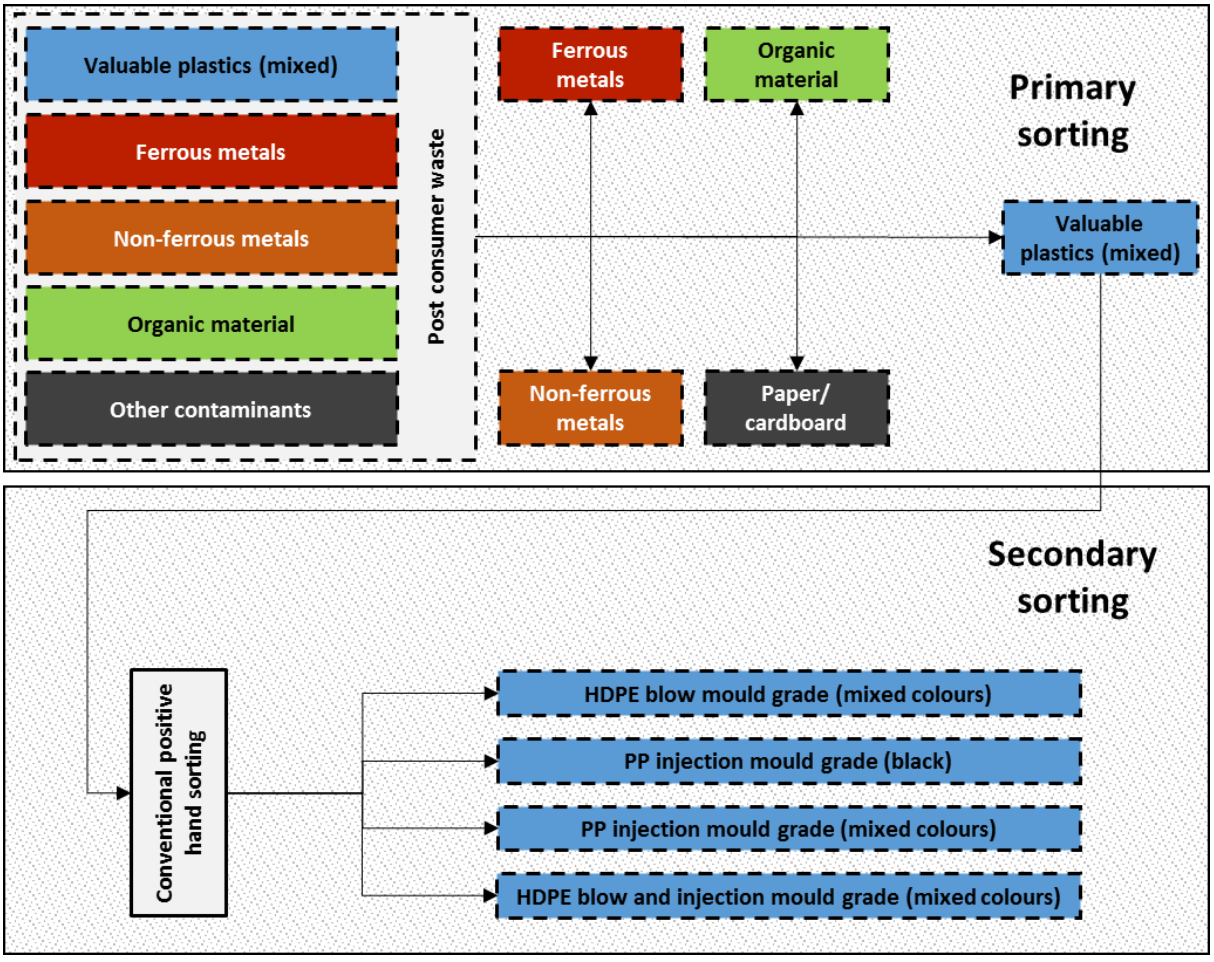


Figure 1-4 Recycling plant process overview (developed by author)

Material sourced from municipal waste collection services enters the facility without any prior treatment. It is fed, as is, into the primary sorting facility where the rubbish bags are opened to liberate the contents. It passes through a series of sorters that remove most of the organic materials, non-ferrous and ferrous metals, paper and cardboard. The pre-screened material is fed onto two conveyor lines where hand-sorters sort out different types of plastics. The different plastics are transferred to the secondary hand sorting facility where hand sorters manually sort the mixed into the four products listed at the beginning of this chapter. Manual sorting the material is believed to achieve purities, according to polymer type, of between 80 and 90%.

In order to test the MDS system a 20 tonne sample of material was prepared by the Romanian recycler for processing. This material was also the sample material used in this investigation. The material supplied was a mixture of three out of the four products they produce. The PP injection mould (black) sample was not included because it was deemed unsuitable for MDS processing. The composition of the sample material is shown in Table 1-1. The material was shredded, washed and dried before it was mixed together.

Table 1-1 sample material composition (information supplied by Romanian recycler)

Product name	Percentage of total
HDPE blow mould grade (mixed colours)	50%
PP injection mould grade (mixed colours)	33%
HDPE blow and injection mould grade (mixed colours)	17%

In addition to supplying a 20 tonne sample, the recycling company also supplied 10 kg individual samples of the products listed in Table 1-1.

1.2 Objectives of the study

The primary objective of the project was to investigate the possibility of improving the melt flow and mechanical properties of recycled polypropylene and Polyethylene by separating the material into blow mould rich and injection mould rich fractions – separation based on Melt Flow Index (MFI). Two conventional recycling technologies, air classification and ballistic separation, were investigated to determine which method would yield the best separation results. Blow moulded plastics and injection moulded plastics tend to have different thickness ranges (see Figure 1-5) meaning that air separation can be used to sort the material into two fractions; a thin-walled fraction (blow mould rich) and a thick-walled fraction (injection mould rich).

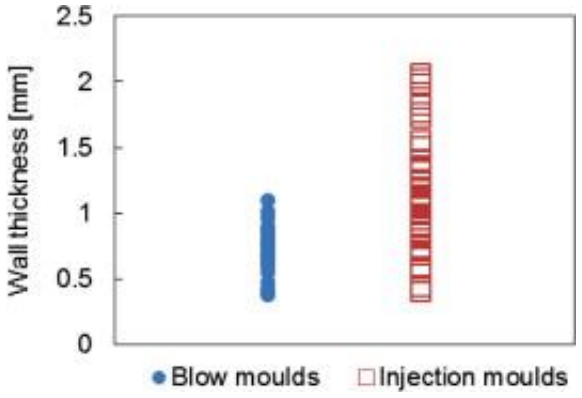


Figure 1-5 Correlation between wall thickness and manufacturing process (Hu et al., 2013)

The method, or separation technology that yielded the best separation results was used to attempt to produce blow mould rich and injection mould rich samples.

To enable this process, it was important to measure the physical characteristics (size, density and thickness characteristics) of the material before and after separation for three purposes:

1. To determine how to optimally configure the air classification and ballistic separation systems
2. To determine mass fractions of each material before and after separation
3. To use as input information in future processing models

Once it was decided which separation technology to use, two processing configurations were investigated; separating the different samples into a thick and thin fractions before MDS processing (see Figure 1-6) and separating them after MDS processing (see Figure 1-7). The samples were then processed into test samples for further mechanical and melt flow property measurements. The aim was to be able to compare which process configuration yielded the best results; specifically, in terms of the melt flow properties of each sample.

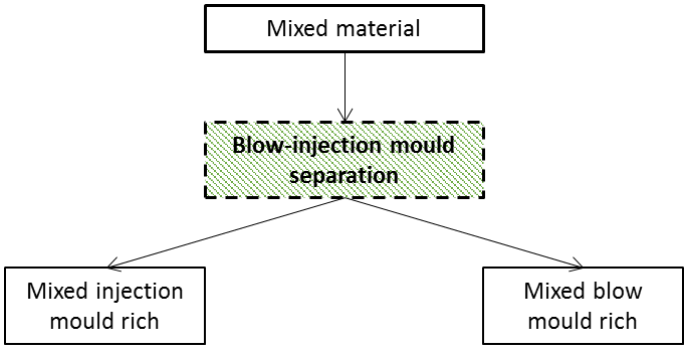


Figure 1-6 Pre-MDS separation

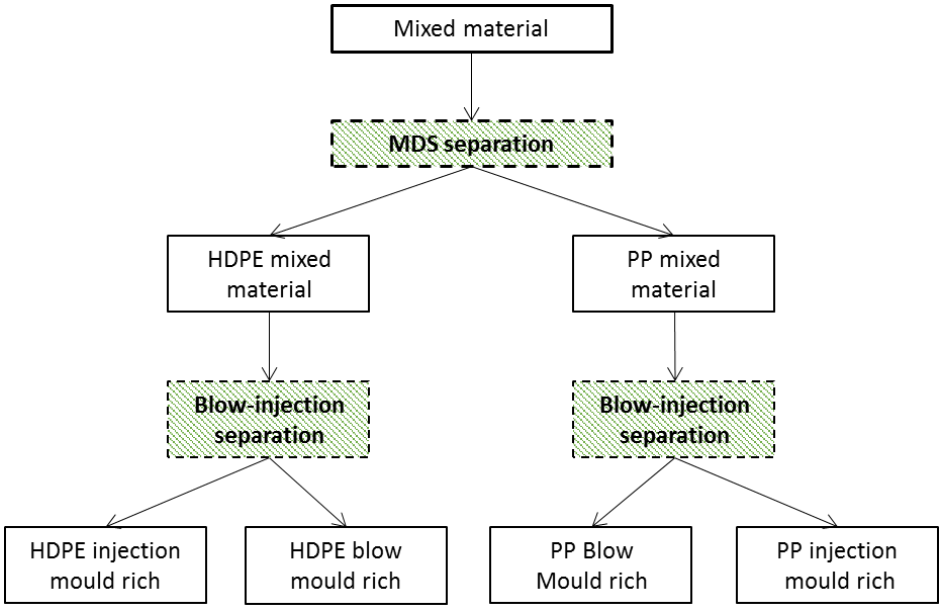


Figure 1-7 Post-MDS separation (developed by author)

The secondary objective of the research was to study the operation and performance of the chosen separation system in more detail to understand the throughput limitations of each system if it were to be implemented into a plastic recycling processing line (see Figure 1-8).

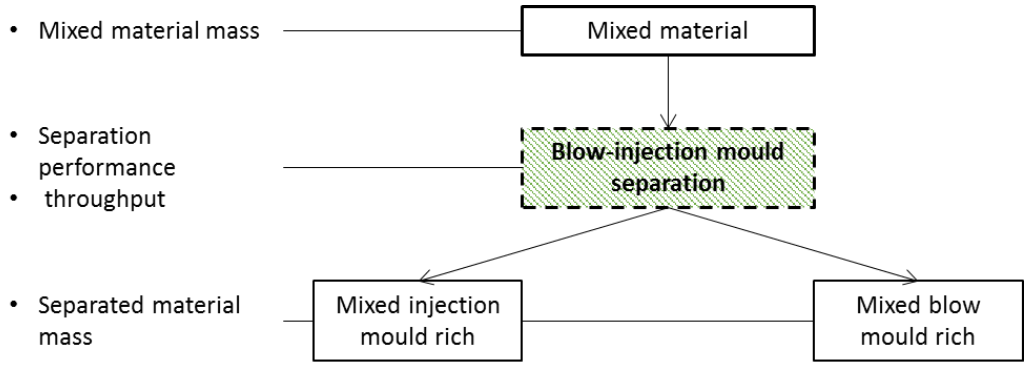


Figure 1-8 System throughput and performance measurement (developed by author)

1.3 Scope of the study

This research focusses specifically on HDPE and PP household packaging waste. PET and other plastics were not included in the test samples. The sample material was supplied by a single plastic recycling facility. The focus area of the study is the European Union (EU) area (EU-27 plus Norway and Switzerland[6]) because the sample material used in this investigation is from a European source.

1.4 Limitations and constraints

Although this research takes an in depth look at the different characteristics of different polyolefin samples, it is limited to one recycling plant in one region of Romania. If this study were to be repeated elsewhere it may yield different results.

The material samples used to conduct this research was also supplied by the recycler shredded, cleaned and dried. The pre-treatment of this material by means of hand sorting means that certain plastic items are intentionally left out of the mix before shredding takes place.

Furthermore, the research report only studied the properties of material samples that had been separated into two wall-thickness ranges; 0.0 and 0.9 mm and $>$ 0.9 mm. A more comprehensive study could separate the material into a number of different thickness ranges to more comprehensively understand the correlation between wall-thickness and melt flow properties.

1.5 Structure of the report

This report comprise of five chapters; Introduction, Literature review, Experimental methods, Results and discussion and Conclusions and recommendations. A short description of each chapter is given below.

CHAPTER 2 – Literature review

The literature review provides important information about plastics, recycling, and air separation.

CHAPTER 3 – Experimental methods

The first part of the experimental methods chapter deals with the measurement and characterization of the plastic material. This serves as important information for the air classification part of the investigation.

[6] EU-27 plus Norway and Switzerland will be considered as Western Europe throughout this report

The air classification and ballistic separation sections describe the experiments conducted on the plastic material.

The final section focusses on the measurement of the mechanical and melt flow properties of material samples from the air classification section.

CHAPTER 4 – Results and discussion

The results and discussion section examines the results of the research and discusses the observed trends in the data.

CHAPTER 5 – Conclusions and recommendations of future work

This chapter provides a brief discussion and some closing remarks on the findings of the research. It also includes a small subsection discussing the potential for further research on the topic.

CHAPTER 2

2 Literature review

2.1 European polymer industry

Europe is one of the biggest producers and converters of polymers with an industry turnover of roughly €320 billion in 2013. The industry directly employs approximately 1.45 million people across Europe, the majority of which operate within the plastics conversion sector of the plastics industry (Plastics Europe, 2015).

In 2013 the aggregated production of plastics in Europe was an estimated 57 Mtonne accounting for 20 % of global plastics production. The demand for plastic products within Europe was approximately 46.3 Mtonne with five countries accounting for the majority of plastics consumption: Germany, Italy, France, the United Kingdom and Spain (Plastics Europe, 2015).

Plastics have become an integral part of nearly all industrial sectors because of their versatility, relatively low production and manufacturing costs, and their ability to be reused through recycling or energy generation. Plastics in Europe are used widely among a number of important markets. Figure 2-1 gives a breakdown of the European plastics market. It can be seen that the largest demand for plastics is for application as packaging material.

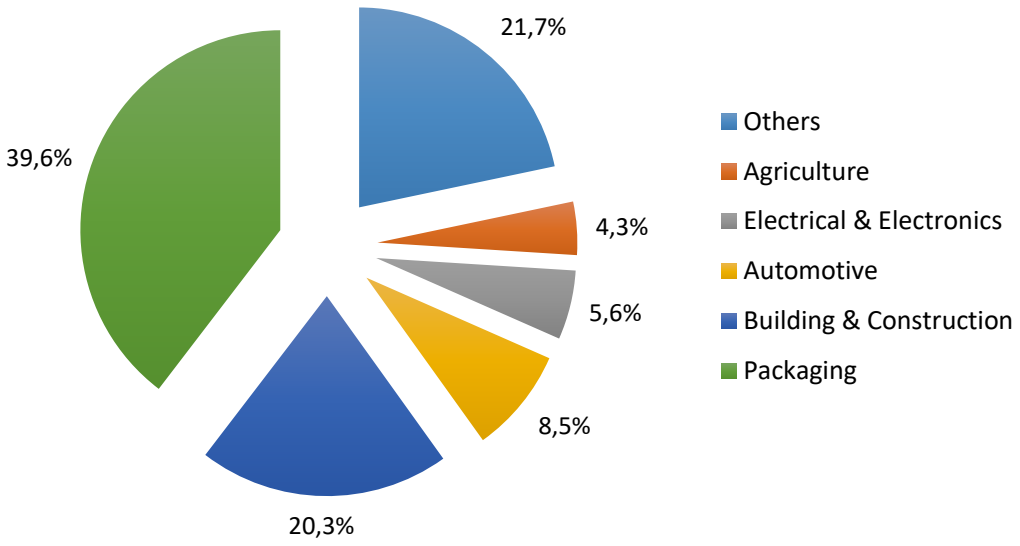


Figure 2-1 Plastics demand by sector in 2013 (plastics Europe, 2015)

2.1.1 Plastic packaging

Plastic packaging accounts for approximately 39% of total plastic demand which are used for primary (sales packaging), secondary (grouped packaging) and tertiary (transport packaging) applications (APME, 2001). Plastics are manufactured from a variety of polymers with varying mechanical and physical properties. Different applications require different properties such as mouldability, barriers to moisture and other environmental elements, transparency and temperature protection (Erlöv et al., 2000). The plastics that are predominantly used for the manufacturing of packaging materials are

polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET). PE consumption can be categorized further according to its specific type; low density PE (LDPE), linear low density PE (LLDPE) and high density PE (HDPE). Other notable polymers utilized in smaller fractions are polyvinyl chloride (PVC), polystyrene (PS) and polyurethane (PUR) (Plastics Europe, 2015). Figure 2-2 provides a breakdown of European plastics demand by polymer type for the purposes of packaging manufacturing.

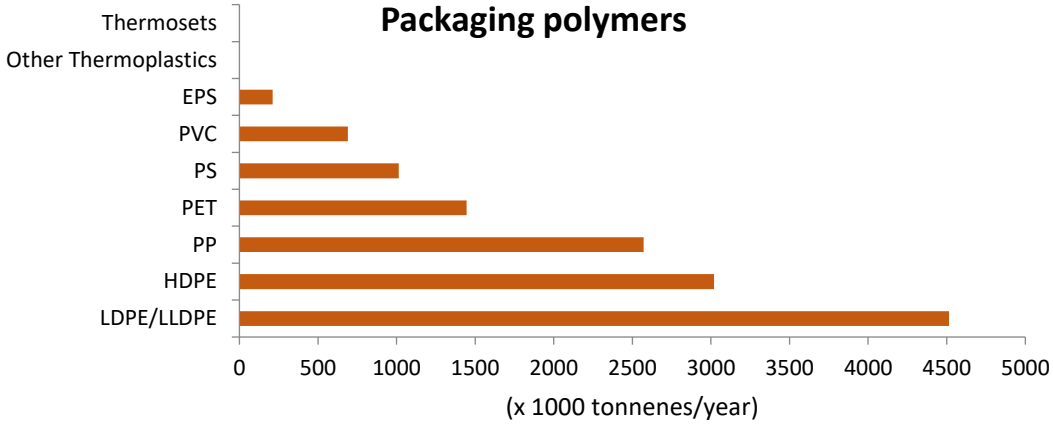


Figure 2-2 Packaging plastics consumption by polymer type in Europe 1999 (APME, 2001)

Furthermore Figure 2-3 provides insight into exactly what these polymers are converted into and the means by which they are manufactured.

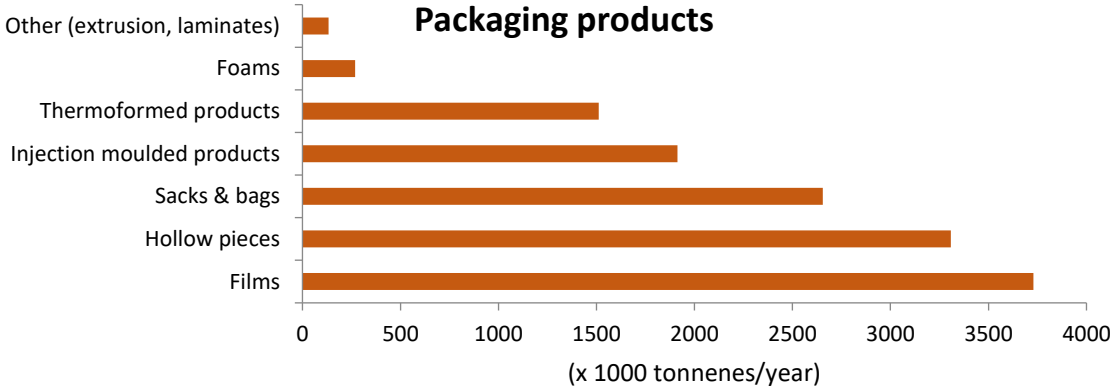


Figure 2-3 Packaging products (APME, 2001)

2.1.2 Waste management

Plastic recycling has, since the 1980s, become an increasingly important topic for the EU as it attempts to reduce and reuse post-consumer waste materials. Waste management remains a major challenge

for Europe and as a result the EU has developed a general waste management hierarchy for EU member states to follow (Gascoigne and Oglivie, 1995):

- Prevent wastes generation at the source
- Reuse the materials through recycling and energy generation
- Effectively dispose of waste residues that cannot be reused

Figure 2-4 illustrates the various options available in terms of plastic waste management. Regarding recycling there are two options; mechanical recycling or feedstock recycling. Mechanical recycling refers to processes that mechanically sort and separate plastic waste streams to recover different types of polymers. Feedstock recycling refers to the process of chemically converting waste plastics into valuable chemicals or monomers that may be resynthesized into usable plastic products.

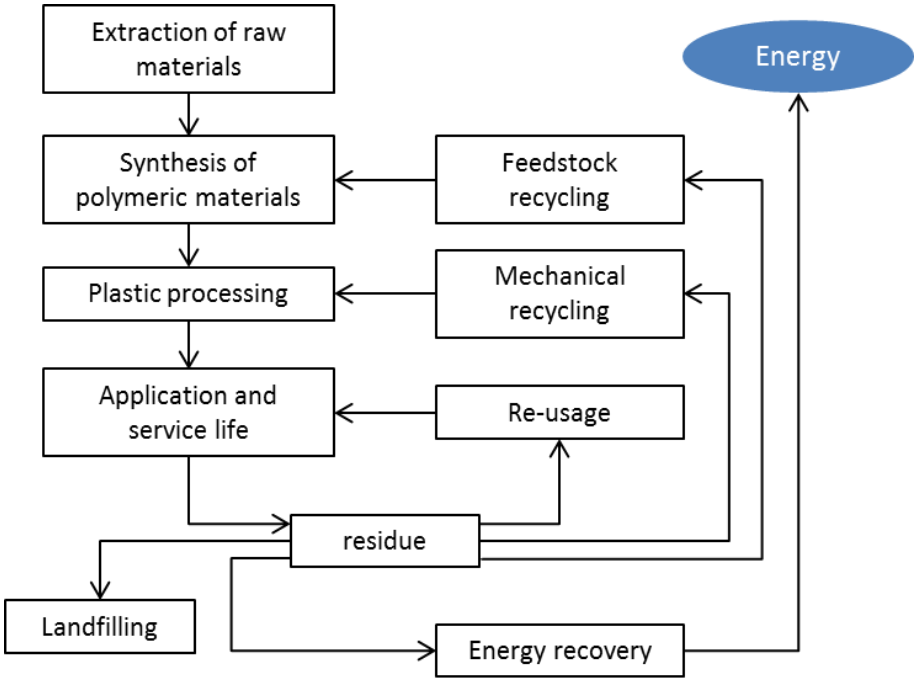


Figure 2-4 Plastic waste management (Vilaplana and Karlsson, 2008)

Mechanical recycling technologies are not yet able to remove all plastics from complex waste streams meaning that a large fraction of material containing valuable plastics ends up being incinerated for energy production, or being deposited on a landfill site.

Legislation and environmental policies driven by the European Commission have helped move Europe away from landfilling all post-consumer waste but there is still a long way to go (see Figure 2-5).

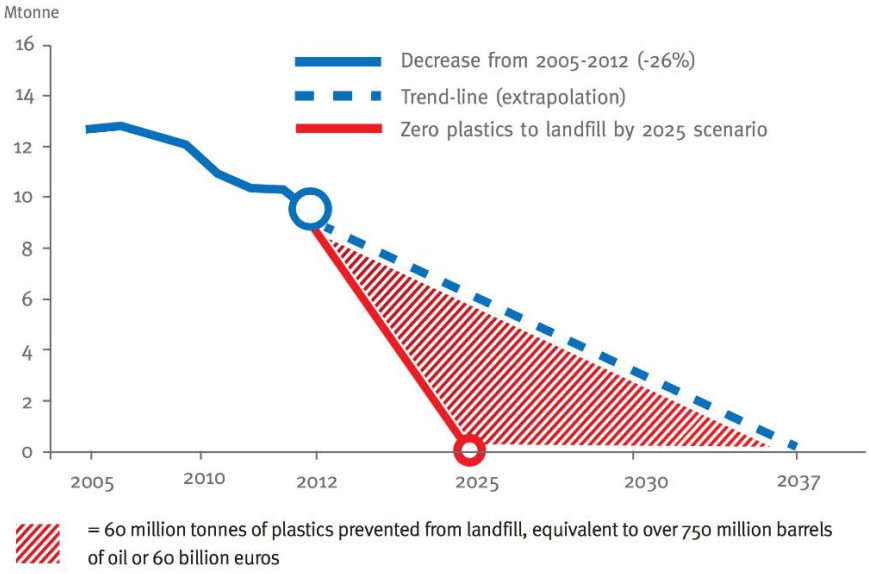


Figure 2-5 European landfill scenarios (Plastics Europe, 2015)

2.1.3 Plastic recycling

Sorting and recycling of complex polymer waste streams remains a difficult and costly process and is the reason why only a small fraction of post-consumer plastics are recycled. The value of the recyclate is also lower than the value of the virgin material[7]. Manufacturing processes, exposure to the elements and mixing different types and grades of polymers renders a secondary material with inferior properties compared with virgin polymers. Virgin polymers used by plastics converters generally conform to strict product standards that ensure the finished products adhere to standards imposed by standards authorities, manufacturers and consumers of products packaged in plastics. In addition to product quality, manufacturing machinery require polymers that adhere to strict technical specifications to guarantee desired operational performance. In most cases recyclates do not meet the required specifications for the production of most primary packaging products.

Additionally, it is mostly the easy-to-sort materials that are fully recycled such as PET bottles and plastic drinks crates because of their homogenous nature and ease of identification by conventional recycling technologies. Other plastic packaging materials are more difficult to sort. Many packaging products that look similar may indeed be manufactured from different polymers or may contain additives and pigments that make them non compatible with one another; the recycled product therefore does not resemble the quality of the virgin material (Luijsterburg and Goossens, 2014). Subsequently, the market value of recyclates is significantly lower than virgin polymers because the value of recyclates are directly linked to the market value of virgin polymers.

The European Commission is aware of the problem and understands the scale of the value locked in packaging waste. As a result, the European commission has provided funding for a number of projects aimed at increasing the fraction of plastics that are recycled. Additionally, they want to establish a circular economy whereby materials that are recyclable are reused several times for the same purpose thus reducing the demand for virgin polymers.

[7] Commonly referred to as downcycling or cascade recycling; the value of the recyclate is lower than the value of the original product

One of the projects funded by the European Commission's FP7 programme (titled "W2Plastics[8]") has developed a unique and powerful technology that has the ability to separate a complex polyolefin flake stream by polymer type in one step: Magnetic Density Separation (MDS) is able to sort these complex waste streams into attractive secondary products of high quality and in economically feasible volumes (Serranti et al., 2015).

2.2 Magnetic Density Separation

Magnetic Density Separation (MDS) is a specialized method of separating polymer flakes according to their density. Different polymers have different densities; separating on density thus separates polymer flakes according to polymer type. In this case, the polymer sample is a polyolefin mixture of PP and PE. Figure 2-6 shows a cross-sectional diagram of an MDS system.

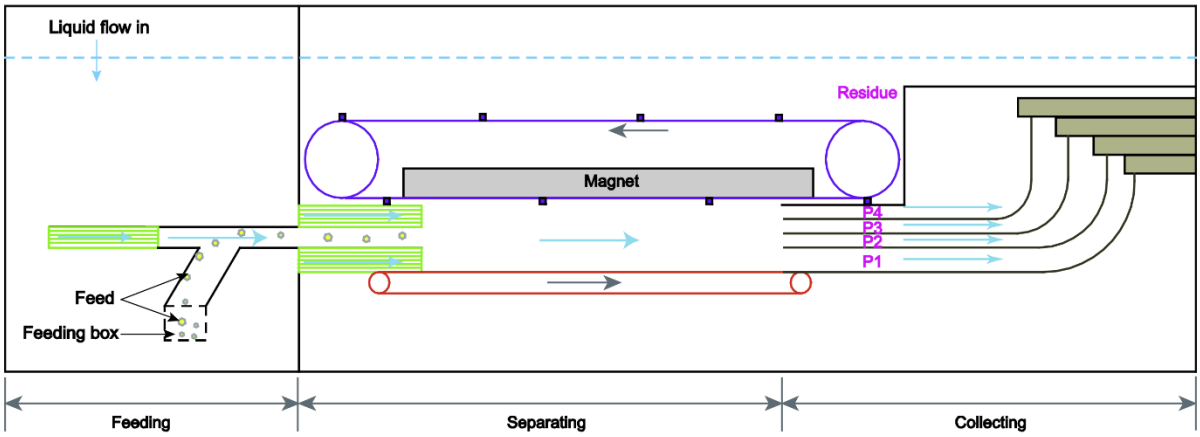


Figure 2-6 Magnetic Density Separation (Serranti et al., 2015)

MDS works by creating an artificial gravitational field using specialized permanent magnets that influence a magnetic fluid[10] (Figure 2-7). The magnetic fluid is then channeled slowly over the magnets by conveyor belts to ensure that the flow remains laminar. Polymer flakes are fed into the MDS system at one end and as they pass over the magnets the flakes will translate vertically as the gravitational and buoyancy forces reach equilibrium. The flakes will settle at a fluid height that corresponds to its density and the density of the fluid at that height (Serranti et al., 2015). Once the flakes reach the other end of the separation channel they are collected.

Preliminary tests have proven that MDS technology has the potential to accurately separate complex waste streams quickly and cost effectively. A trial of Dutch and Romanian household waste showed that the MDS system was able to generate high purity products. In certain instances it generated a PE product with 100% purity and a PP product with 94% purity (Serranti et al., 2015).

The trials on the MDS system were under controlled circumstances where waste samples were cleaned of all foils and only blow moulded and injection moulded PE and PP materials were selected (Serranti et al., 2015). It is important to note that research concerning MDS technology and the pre or post-treatment processing of the material is ongoing. The goal is to develop a robust process model that is

[8] See http://www.w2plastics.eu/ for more information

[10] The Magnetic fluid is made up of Iron Oxide particles (magnetite) which are roughly 10-20 nm in size suspended in water HU, B. 2014. *Magnetic Density Separation of Polyolefin Wastes.* Post Doctoral Dissertation, Delft University of Technology.

able to separate complex polyolefin waste streams into high purity products quickly and cost effectively.

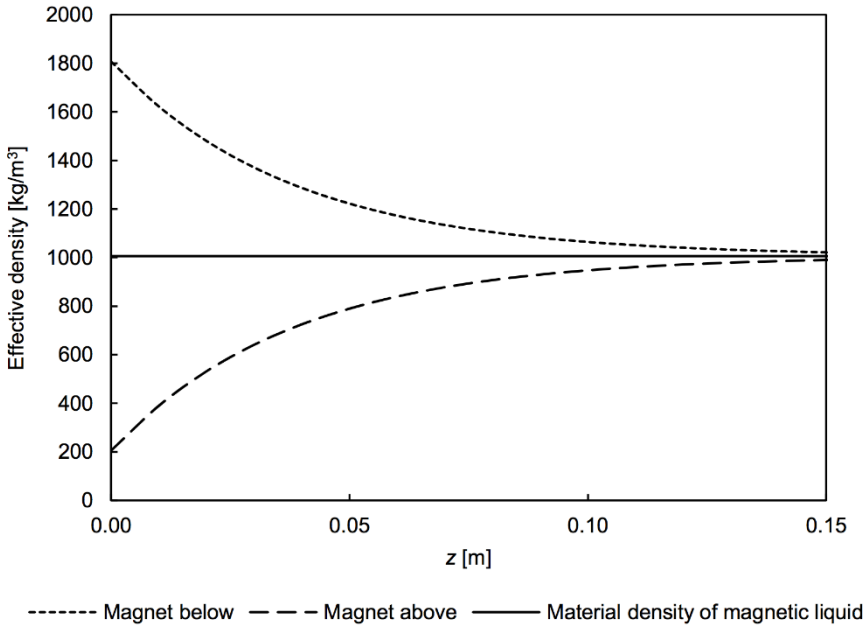


Figure 2-7 Density gradient of magnetic fluid in the presence of a magnet (Hu, 2014)

2.3 Polymers

Polymers have become an integral material in modern society with plastics being used for various applications in a number of industries ranging from consumer goods to building and construction. The unique range of physical properties and relatively low costs attributed to polymers makes them a versatile group of materials for both manufacturers and designers.

2.3.1 Types of polymers

Polymers are either referred to as natural or synthetic polymers. Natural polymers are materials such as starch, rubber and cellulose and occur naturally whereas synthetic polymers (the focus material for this report) refer to all polymers that have been synthesized from feedstocks such as crude oil.

Synthetic polymers are more commonly referred to as plastics and are divided into two main groups: thermoplastics and thermosetting plastics. Thermoplastics account for approximately 80% of total plastic consumption because of their durability and manufacturing versatility (Biron, 2012). Thermoplastics soften when heated and solidify when cooled and undergo a physical transformation that is reversible. Thermoplastics are suited for recycling applications because the process of softening and solidifying may be repeated without compromising the mechanical and chemical integrity of the plastic (Biron, 2012); however, if thermoplastics are exposed to high temperatures, for instance well above the melting temperature of a specific thermoplastic, it may lead to degradation of the polymer (Callister, 2007).

Examples of common thermoplastics are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) and polystyrene (PS). PE (of differing densities), PP, PS and PVC make up 70% of total plastics production because of their relatively low costs, durability and versatility that make them ideal for plastic packaging applications (Xanthos, 2005).

Thermosetting plastics refer to the group of polymers that are liquid at low temperatures and as they solidify they undergo a chemical reaction that is irreversible. Once they have taken their desired form they cannot be reheated or melted and formed into another shape. Examples of thermosetting plastics are polyurethanes and epoxy resins. This group of plastics remains challenging to recycle because it is not possible to melt and reform them again (Biron, 2012). For recycling purposes, only thermoplastics are considered in this investigation; it is therefore important to understand the physical and chemical properties of different thermoplastics.

2.3.2 Properties of thermoplastics

2.3.2.1 Polymer molecules

Polymers are groups of simple monomers such as ethylene or propylene that bond together during the reaction in the presence of an initiator and a catalyst. Figure 2-8 illustrates the transformation from an ethylene monomer to ethylene polymer. The polymer molecule in Figure 2-8 is the repeating unit in a particular polymer chain. Polymer chains can vary in length but still have the same repeating unit; paraffin wax and polyethylene are both made from ethene but have very different chain lengths giving each very different mechanical properties (Blackman et al., 2012).

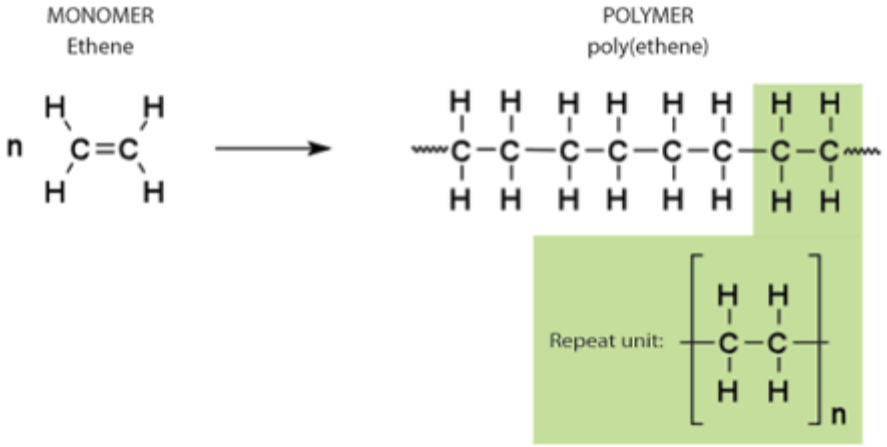


Figure 2-8 Ethylene transformation to polypropylene (University Of Cambridge)

2.3.2.2 Molecular weight

Molecular weight is an important property of a polymer. Molecular weight or molecular mass refers to the length of a polymer chain; the longer the polymer chain, the higher the molecular weight. During polymerization polymer chains grow to different lengths depending on the process itself and the intended application of the polymer. As a general rule the melt transition temperature of a polymer increases as the length or molecular mass of the polymer chain increases. Mechanical properties also depend on the molecular mass of a polymer; elastic modulus and tensile strength increases as molecular mass increases (Callister, 2007).

2.3.2.3 Molecular shape and structure

The molecular shape of a polymer is an important property as a number of characteristics of the polymer depend on the shape of the polymer. Because single chain bonds have the ability to rotate in three dimensions, a polymer chain can bend and twist entangling itself into something that resembles a bowl of spaghetti. This property allows a certain degree of rotational flexibility making the polymer tougher. Polymers with double carbon bonds or large side groups tend to have a higher rotational rigidity making them more brittle (Sivasankar, 2008).

The structure of a polymer refers to the manner by which polymer chains join together. Figure 2-9 shows common polymeric structures; linear, branched, cross-linked and network structures.

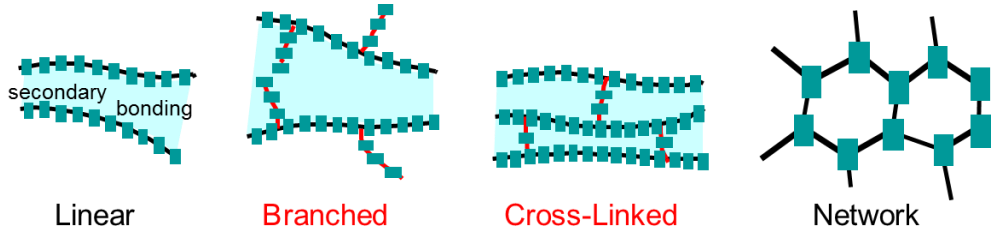


Figure 2-9 Polymer structures (Adapted from Callister, 2007)

The structure of a polymer is a characteristic of the polymer that develops during its synthesis. Different processes are designed to achieve certain polymer structures in order to produce a material with desired properties and characteristics such as density and tensile strength. Polypropylene and polystyrene are linearly structured whereas polymers such as Polyethylene (LDPE and HDPE) are branched polymers (Callister, 2007).

2.3.2.4 Polymer crystallinity

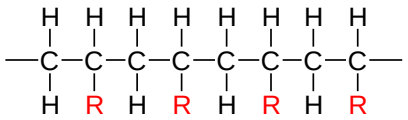
Crystallinity in any material refers to the ordering of the molecules of a specific material in its solid phase. Metals are a good example of crystalline materials as they are almost always crystalline in solid phase. Polymers, however, have a more complicated structure in solid form. The relative size and complexity of polymer molecules means that crystallization is only possible under certain conditions. To achieve crystallinity, polymer melts need to cool slowly allowing time for the polymer chains to align themselves into a lattice configuration. Linearly structured polymers are fairly easy to crystalize because there are few restrictions to alignment whereas branched polymers have significant restrictions making it more difficult for polymer chains to align (Callister, 2007).

Most polymers are therefore semi crystalline; polymers with crystalline regions embedded in the amorphous phase of the polymer. Crystallinity may have an influence on the mechanical and physical properties of a specific polymer; polymers with a high crystallinity are generally stronger and more resistant to heat and dissolution (Callister, 2007).

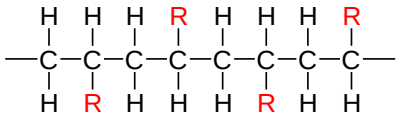
2.3.2.5 Stereoisomers

Stereoisomers refers to monomer molecules that have the same formula that are joined together uniformly from head to tail but differ in their three dimensional arrangement. Three spatial configurations are possible: isotactic, syndiotactic and atactic (see Figure 2-10).

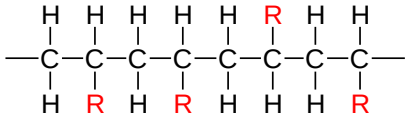
Typically, a given polymer is not defined or characterized as having a single configuration; the configuration of a polymer is usually a combination of the above with the dominant configuration resulting from the method of synthesis (Callister, 2007).



Isotactic configuration: R groups[11] on the same side of the chain



Syndiotactic configuration: R groups on alternate sides of the chain



Atactic configuration: randomly ordered R groups

Figure 2-10 Tacticity (Adapted from Callister, 2007)

2.3.2.6 Polymer densities

Understanding the density differences between different thermoset plastics is important because a number of mechanical recycling techniques rely on the plastics density for separation. It should also be noted that manufacturers are moving towards using plastics of lower densities for economic reasons (World Economic Forum, 2016) Table 2-1 lists the densities the various polymers.

Table 2-1 Density ranges of various polymers adapted from (Mark, 2007)

Chemical name	**Density (kg/m^3)**
Low density polyethylene (LDPE)	910 – 925
Linear low density polyethylene (LLDPE)	918 – 935
High density polyethylene (HDPE)	941 – 965
Polyethylene terephthalate (PET)	1330 – 1420
Polyporopylene (PP)	850 – 920
Polystyrene (PS)	1040 – 1090
Polyvinyl Chloride (PVC)	1300-1450

2.3.2.7 Mechanical properties

Polymers can have very different mechanical properties depending on their molecular structure. Plastic packaging polymers need to be tough and ductile to ensure they do not fracture or tear. Other applications, such as computer keyboards, require a material that is harder and stiffer than flexible polymers. The mechanical properties of the typical packaging polymers of are listed in Table 2-2.

Table 2-2: Mechanical properties of common polymers adapted from (Callister, 2007)

Material	**Elastic Modulus (GPa)**	**Yield Strength (MPa)**	**Tensile Strength (MPa)**	**Percent Elongation**
LDPE	0.172-0.282	9.0-14.5	8.3-31.4	100-650
HDPE	1.08	26.2-33.1	22.1-31.0	10-1200
PET	2.76-4.14	59.3	48.3-72.4	30-300
PP	1.14-1.55	31.0-37.2	31.0-41.4	100-600
PS	2.28-3.28	-	35.9-51.7	1.2-2.5
PVC	2.41-4.14	40.7-44.8	40.7-51.7	40-80

[11] R groups refer to any atom or side group other than Hydrogen

2.3.3 Virgin polymer production

Synthetic polymers are polymers whose chemical makeup is based on the carbon atom. Synthetic polymers are therefore mostly synthesized from natural resources such as coal, natural gas and crude oil. The process of polymer manufacturing begins by separating the hydrocarbons from the raw material input. Once the desired hydrocarbons have been extracted they are then converted into monomers such as ethylene or propylene through a process commonly known as cracking (Chauvel and Lefebvre, 1989). In this form, the individual monomers can be chemically bonded into chains through one of two basic mechanisms: condensation or addition reactions (Ghosh, 2001).

Condensation reactions are chemical reactions where two monomers join together to form a larger molecule with a smaller molecule being eliminated. Condensation reactions are used to produce materials such as polyamides, polyesters, polycarbonates and polyurethanes; typically, thermoset plastics. Addition reactions are chemical reactions where monomer units bond together without the elimination of any atoms. Addition reactions are used to produce materials such as polyethylene and polypropylene; typically, thermoplastics (Blackman et al., 2012).

2.3.3.1 Polyethylene production

Addition reactions are used to manufacture PE and are carried out in the presence of a catalyst. LDPE is produced in the presence of peroxide catalysts whereas Ziegler-Natta[12] systems are common commercially used systems for the production of HDPE (Blackman et al., 2012).

LDPE has a density range between 910 and 925 kg/m^3 with a melt transition temperature of approximately 115°C. LDPE has a lower density compared to HDPE as a result of the chains of LDPE being highly branched. As a result, LDPE cannot be used in applications where it is exposed to temperatures in excess of its melt transition temperature. 65% of LDPE is used for the manufacturing of films for the packaging of consumer goods (Blackman et al., 2012).

HDPE is a much stronger material than LDPE with a density range of approximately 941 to 965 kg/m^3 and a melt transition temperature of approximately 133°C. The improved strength comes from the fact that HDPE is more crystalline than LDPE; less branching yields a material that is far more crystalline with stronger intermolecular forces. HDPE is used in applications where strength is important such as bottles, bottle caps, rigid food packaging containers and hard hats (Blackman et al., 2012).

2.3.3.2 Polypropylene production

polypropylene is also the product of an addition reaction where the asymmetric propene alkene is polymerized. Since propene is asymmetrical its polymerization may result in three types of polypropylene associated with the arrangement of its ethyl branch; isotactic polypropylene, syndiotactic polypropylene and atactic polypropylene. Isotactic polypropylene is the type of polypropylene that exhibits desirable commercial properties. It is produced in the presence of a modified Ziegler-Natta catalyst and results in a material with high strength and stiffness (Blackman et al., 2012). As a result, PP tends to be stiffer, and more rigid than HDPE (Ghosh, 2001).

2.3.4 Polymer additives

Additives play an important role in polymer manufacturing. Additives refer to any material or compound that is added to the polymer mix that modify its properties. Additives include fillers, colorants, stabilizers and plasticizers. Additives for plastic recycling purposes are beneficial as certain types of additives have the ability to improve the recyclability of a polymer (AlMaaded et al., 2014).

[12] Ziegler-Natta catalysts are Titanium based catalysts used to support addition reactions.

Additives are also used for cosmetic reasons such as pigments that give a particular plastic object a desired colour.

2.3.4.1 Fillers

Fillers refer to organic or inorganic particles or fibres ranging from nanoparticles to continuous fibres of varying shapes and profiles that are added to a given polymer during manufacturing. One of the primary reasons for adding fillers is to reduce the overall volume fraction of the more expensive polymer; this makes manufacturing cheaper as less polymer material is used (Xanthos, 2005). Fillers can also be added to reinforce a polymer; adding fillers can help to increase the modulus and strength of a polymer (La Mantia, 1998b). If improved electrical or thermal conductivity properties are required, the addition of a conductive filler may help to improve these properties. The addition of fillers can assist in manufacturing; certain fillers can help to prevent warpage during manufacturing (Xanthos, 2005).

Fillers are mostly used for plastics in the following industries: building and construction, automotive and consumer goods. Packaging materials do not usually contain fillers. Fillers do, however, play an important role in plastic recycling. Fillers can be added to recycled PP to improve the elastic modulus and tensile strength (La Mantia, 1998a); however, in terms of density separation, the presence of fillers can have a negative impact. Fillers change the density of a polymer; exploiting the density differences of a recyclate mix is no longer possible if the densities are modified.

2.3.4.2 Colourants

Colourants are added to plastics to change their colour, mostly for aesthetic purposes. Colourants are typically organic and inorganic pigments or synthetic dyes but significant progress has been made regarding the development of polymeric colorants (Miley, 1996). The appropriate type of colorant needed depends on the application of the plastic object; certain dyes are toxic making them unsuitable for food packaging, however, dyes and pigment colorants are still used in packaging materials raising questions as to the safety of such practices (Robertson, 2012).

In terms of mechanical properties, the addition of colorant additives does not have significantly adverse effects. In a study focusing on PP it was found that, in some instance, the addition of organic and inorganic pigments actually improved the Elastic Modulus and Tensile Strength (Kanu et al., 2001). However, colourants create a significant challenge when it comes to plastic recycling. Recycling different coloured plastics together renders a grey coloured product which limits its commercial versatility.

2.3.4.3 Stabilizers

Polymers in general are often susceptible to degradation when exposed to heat or ultraviolet light during manufacturing or exposure to sunlight (Hinsken et al., 1991). To prevent or hinder degradation, stabilizers - such antioxidants or UV absorbers - can be added to the polymer. In some instances, stabilizers are added to monomers to prevent premature polymerization during the conversion of monomers to a polymer.

Stabilizers are important additives regarding plastic recycling. Repeated processing can lead to considerable chain scission increasing the Melt Flow Index (MFI) of the recyclate (La Mantia, 1998a). Chain scission can be reduced by adding a stabilizer before each recycling step (see Figure 2-11). Stabilizers are therefore important additives concerning the recycling of polyolefin's.

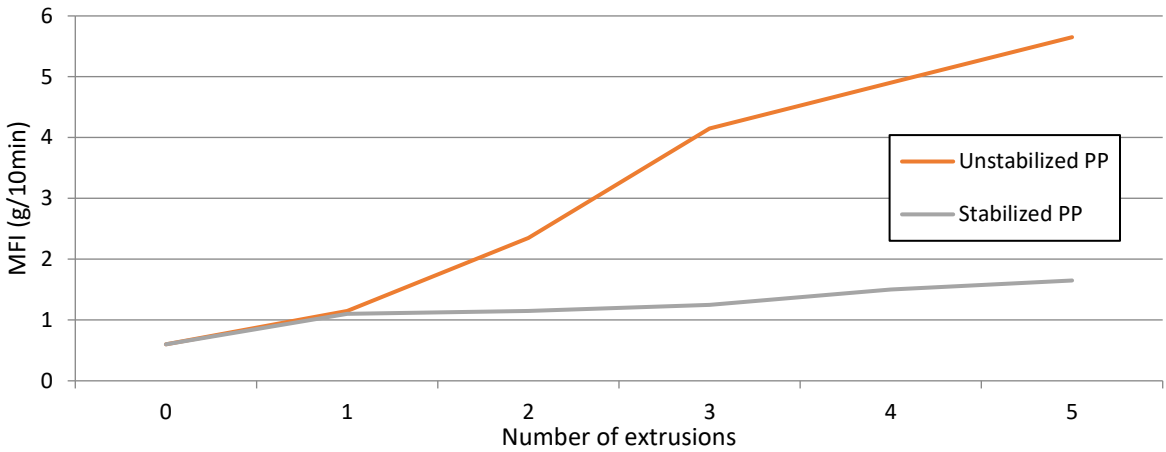


Figure 2-11 Impact of stabilizers on recycled PP - Adapted from (La Mantia, 1998a)

2.3.4.4 Compatibilization

Polymers of different types have different properties defined by an array of characteristics unique to each polymer; density, molecular characteristics, polarity and degree of crystallinity to name a few. The unique characteristics of different polymers also dictate their degree of compatibility or miscibility if blended with another polymer or group of polymers. Polymers are said to be miscible if they resemble a single phase material in solid phase and immiscible if they separate into phases of the individual fractions of each original polymer (Robeson, 2007).

Polymers made up of combinations of different polymers are known as polymer blends. Polymer blends are produced because they often have superior mechanical and physical properties compared to the original constituents. An example of a commercial polymer blend is Nyrol® that was developed in the 1960s by General Electric. Nyrol® is a poly(2,6-dimethyl-1,4-phenylene oxide)-polystyrene blend and is used in electronics, and coating applications. It has a higher glass transition temperature than its individual constituents as well as improved impact resistance and tensile strength (Robeson, 2007).

Compatibilization refers to the practice of processing immiscible polymers in such a way that they resemble a single phase material in solid state. There are two main compatibilization practices: block or graft copolymer addition and reactive compatibilization (Robeson, 2007).

Block or graft copolymer addition refers to the process of adding a copolymer to a binary polymer blend in order to lower the interfacial tension between each phase. Lowering the interfacial tension between each face improves adhesion between each phase, stabilizing its morphology and improving its mechanical properties (Robeson, 2007).

Reactive compatibilization is the practice of creating a continuous single phase polymer blend between two highly immiscible polymers by adding a reactive polymer to the mix. The reactive polymer is miscible with one of the polymers in the blend and reactive to certain functional groups on the other polymer. It leads to the formation of in-situ graft or block copolymers that reduce interfacial tension and improve dispersion leading to an improvement in mechanical properties (Robeson, 2007).

Polymer compatibilizers are especially important when it comes to plastic recycling. Post-consumer packaging waste is a complex mixture of a number of different types of plastic; most of which are immiscible in one another. Separating complex mixes of post-consumer waste into “pure” fractions of each type of polymer remains challenging and even the smallest amount of contaminant material can compromise the properties of the recyclate. Compatibilizers therefore make it possible to recycle different polyolefin’s together to render a recyclate with acceptable mechanical properties.

2.4 Rheology of plastics

Rheology is the science of the flow of matter in molten form or as a soft solid that deform plastically instead of elastically under the influence of an applied force. The applied force can be compressive, tensile, torsional, shear or a combination of all four resulting in a specific type of flow. For the purposes of this report only shear flow (see Figure 2-12) and extensional flow (see Figure 2-13) will be considered as these are the fundamental flow mechanisms regarding injection moulding and blow moulding applications (Wilkes, 1981)

2.4.1 Shear flow

The shear force acting on a polymer melt results in the chains of the polymer to slide past one another. The degree to which these layers deform relative to on another is known as shear strain and is denoted as the symbol $\gamma = X/Y$ (Figure 2-12). The rate at which these layers slide past one another is termed the shear rate and is usually denoted as the symbol $\dot{\gamma} = d\gamma/dt$ (s^{-1}) (Wilkes, 1981).

Taken one step further the resistance to fluid flow can be described by its viscosity and is often denoted by the symbol, η. Viscosity is a function of the applied shear force and the shear rate, $\eta = \tau/\dot{\gamma}$ $(Pa \cdot s)$ which is a linear function. It is important to note that polymer melts deviate from this rule and are categorized as non-Newtonian fluids when in molten form (Wilkes, 1981).

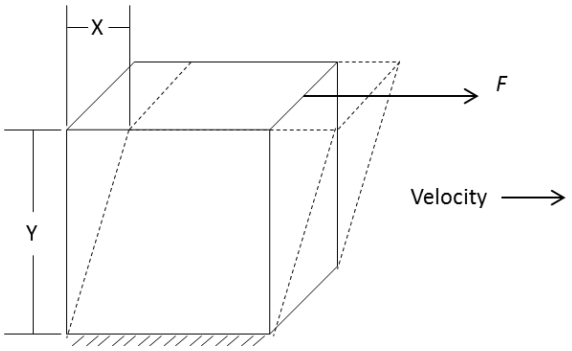


Figure 2-12 Deformation by shear - adapted from (Wilkes, 1981)

2.4.2 Extensional flow

Extensional flow is the result of a polymer melt experiencing elongation in molten form during processing. Extensional flow is either uniaxial, biaxial or planar (Figure 2-13) in nature depending on the forces acting on the polymer (Aho, 2011).

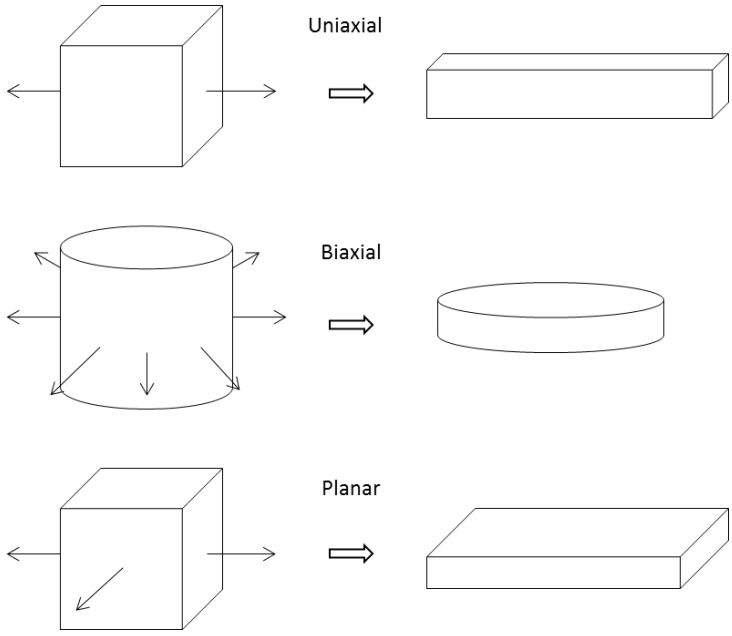


Figure 2-13 Extensional flow of a polymer melt - adapted from (Aho, 2011)

2.4.3 Viscosity and Melt Flow Index (MFI)

The viscosity of a polymer melt is dependent on a number of factors and can be categorized as being either external or internal factors. External factors refer to variables that act on a particular polymer such as temperature, pressure and time. Internal factors refer to properties intrinsic to the polymer such as molecular weight, molecular shape and molecular architecture (Wilkes, 1981).

The Melt Flow Index (MFI) of a polymer is the measurement of the viscosity of a molten polymer or the ease of flow of a molten polymer. It is defined as the mass of a molten polymer that flows, in ten minutes, through a capillary under a specific pressure and has the units, g/10 min. The apparatus used to test for MFI is known as an extrusion rheometer (Shenoy and Saini, 1986).

2.4.3.1 Standardised MFI testing – ISO 1133-1:2011

The standard test used by most polymer manufacturers and converters for testing the MFI of a given polymer is the ISO 1133-1:2011 international standard. The standard is used to test both PE and PP polymer types. It is a simple process of heating the polymer (190°C for PE and 230°C for PP) for a set time and then forcing it under a standard mass (usually 2.16kg) through a die of standard length and cross-sectional area and profile. After a set period of time a sample is taken to be weighed (Shenoy and Saini, 1986).

2.4.4 Manufacturing and recycling considerations

The internal factors of a virgin polymer are synthesized and manipulated to render a product with specific mechanical and rheological properties suited for various applications and manufacturing processes. Concerning manufacturing type, different grades of polymers are used for different applications. Injection moulding requires low viscosity (high MFI) raw materials whereas blow moulding requires high viscosity (low MFI) raw materials. For injection moulding and extrusion applications shear thinning rheological properties are exploited whereas extensional rheological properties are exploited for secondary processing applications such as blow moulding (Aho, 2011).

2.4.4.1 Virgin polymer melt flow properties

Polymer producers manufacture various polymers for use by plastics converters who process virgin polymers into usable products such as drink bottles and food packaging. Different applications require polymers suited for the application and the manner in which the product is manufactured; in this case either injection or blow moulded. Many commercial polymer producers therefore have extensive polymer product ranges suited for a number of uses and processing applications. Focusing on melt flow properties most polymer producers offer a variety of products with different melt flow properties suited to a specific manufacturing application. Table 2-3 gives MFI information for virgin polymers manufactured by three major virgin polymer producers in Europe.

Table 2-3 MFI properties of virgin polymers (generated by author)

Application	Total	Basell Orlen	Chevron Phillips
Injection mould grade	2.0-110	4.0-100	4.5-35
Blow mould grade	0.2-20	0.3-6.5	0.3-2.0

Note: All values are standard MFI units (g/10min) tested using the ISO 1133 testing procedure

Table 2-3 clearly shows the correlation between MFI (or viscosity in molten form) and manufacturing process. Polymers with higher MFI's are generally better suited to injection moulding applications whereas polymers with lower MFI's are generally better suited to blow moulding applications. There is, however, an overlap where polymers can be used for both manufacturing processes. Depending on the sophistication of the manufacturing equipment and the type of product being manufactured, a given polymer may be used for blow and injection moulding purposes; however, this study attempts to determine by what factor the BM and IM fractions can be improved.

2.5 Plastic packaging characterisation

Since the discovery of polymers mid-way through the 20th their use has become ubiquitous in modern society. The unique and diverse range of mechanical, thermal and manufacturing properties of polymers (specifically polyolefin's such as PE and PP) make them the ideal raw materials for the production of plastic packaging products; plastic packaging's account for almost 40% of the plastics market share (Hu et al., 2013).

Unfortunately, most of these plastic packaging materials are used once before being discarded - after the product inside the packaging has been removed it is usually disposed of along with other plastics or waste materials (depending on the waste disposal legislation and infrastructure of a given region). The value of plastic packaging waste materials is largely lost because only a small fraction of the total waste stream is effectively recycled and reintroduced into the market. This is changing as a result of clear directives from the European Union regarding the recovery and reuse of waste materials by means of reuse and recycling.

Recycling is an obvious solution; however, it has its own set of fundamental challenges. Part of the challenge regarding plastic recycling is the separation of a mixed waste stream into homogeneous fractions. In order to realize the full economic value of waste plastics it is important to understand the composition and characteristics of the waste stream. New and existing technologies exploit a number of intrinsic polymer properties in order to sort them according to type and colour; by understanding the physical and geometrical characteristics of the waste stream, new and conventional recycling technologies and processes may be optimized to achieve good separation.

2.5.1 Density distribution

One of the most important characteristics of a polyolefin, and key to the success of Magnetic Density Separation, is the density-type correlation of common polyolefin's. A study looking at Romanian household waste clearly identified the correlation between density and plastic type: PP is concentrated in the density range between 880 kg/m^3 and 920 kg/m^3, whereas the density range of PE (specifically HDPE) is between 930 kg/m^3 and 980 kg/m^3 (Hu et al., 2013). Figure 2-14 illustrates the density range of PP and PE for Romanian household waste.

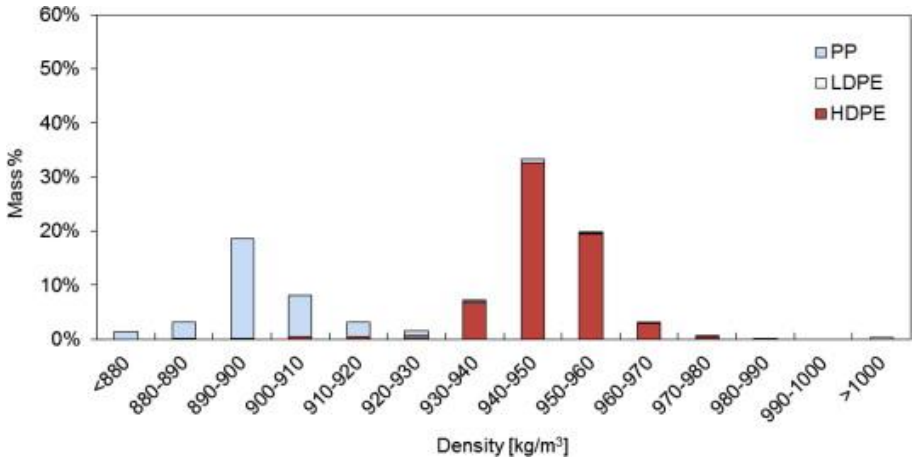


Figure 2-14 Density distribution of Romanian PP and PE (Hu et al., 2013)

2.5.2 Rheological properties

As discussed in previous sections rheological properties are an important parameter when it comes to the processing of a polymer into a usable product; typically, blow moulded polymers have a higher viscosity than injection moulded polymers. What is also clear is that it is important to try and separate waste plastics based on viscosity or Melt Flow Index (MFI) to render a recyclate with the rheological properties that resemble that of a virgin material. This may prove possible as there is a clear correlation between mold type, polymer type and wall thickness distribution (Hu et al., 2013).

2.5.2.1 Polymer type correlation

According to the same study investigating the characteristics of Romanian packaging waste it was found that there was a strong correlation between polymer type and mould type. Figure 2-15 shows that injection moulded plastics are mostly PP (>80%) whereas blow moulded plastics are mostly PE (>80%) (Hu et al., 2013).

2.5.2.2 Wall thickness correlation

The correlation between wall thickness and mould type is somewhat self-evident. Blow moulded plastics are typically fairly thin in comparison to injection moulded plastics. There is however an overlapping region where the thicknesses of blow moulded and injection mould plastics match. Referring again to the study focused on Romanian household packaging waste this assumption was verified by measuring the wall thickness of plastics known to be either blow or injection moulded (see Figure 2-16) (Hu et al., 2013).

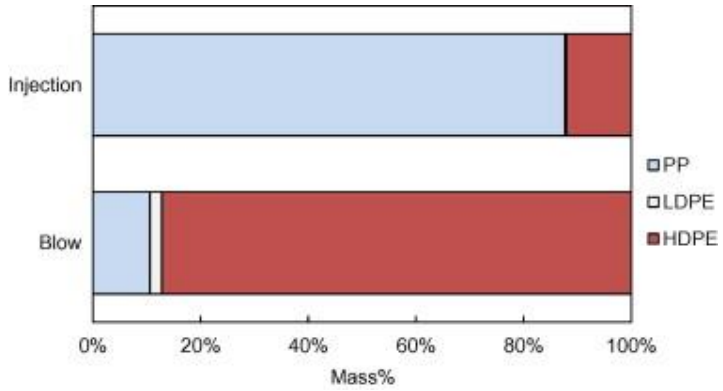


Figure 2-15 Mould type – polymer type correlation (Hu et al., 2013)

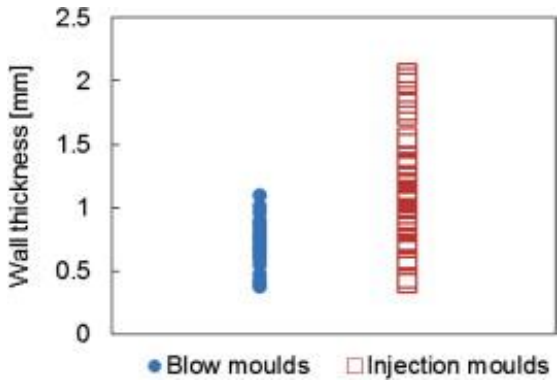


Figure 2-16 Thickness distribution of Romanian blow mould and injection mould plastics (Hu et al., 2013)

2.6 Mechanical recycling

Mechanical recycling of plastic packaging waste is a process involving a number of steps[13] that clean and sort different polymers according to type, colour, density and rigidity. Each step in the process is conducted mechanically and no chemical change of the polymer takes place during the process. The goals of mechanical recycling facilities are to sort different plastics (in this case polyolefin's, PP and HDPE) into cleaned, uncontaminated, homogeneous material streams that are suitable to be processed into new products (see Figure 2-17).

Mechanical recycling is conducted using a number of systems and technologies from rudimentary hand sorting lines to more sophisticated Near Infrared (NIR) spectroscopy[14] sorting systems. Most mechanical recycling plants are integrated process lines that take advantage of a number of technologies and processes to optimally sort different plastics into homogeneous streams. Manufacturing purely homogeneous polyolefin waste streams are possible but difficult to achieve with current technologies; the vast number of different grades, types and colours of plastic packaging materials in circulation makes it a complex task.

[13] Different recyclers have different process lines tailored to the material they are processing

[14] NIR spectroscopy sorting exploits the near-infrared spectral fingerprint of different plastics to sort them by resin type.

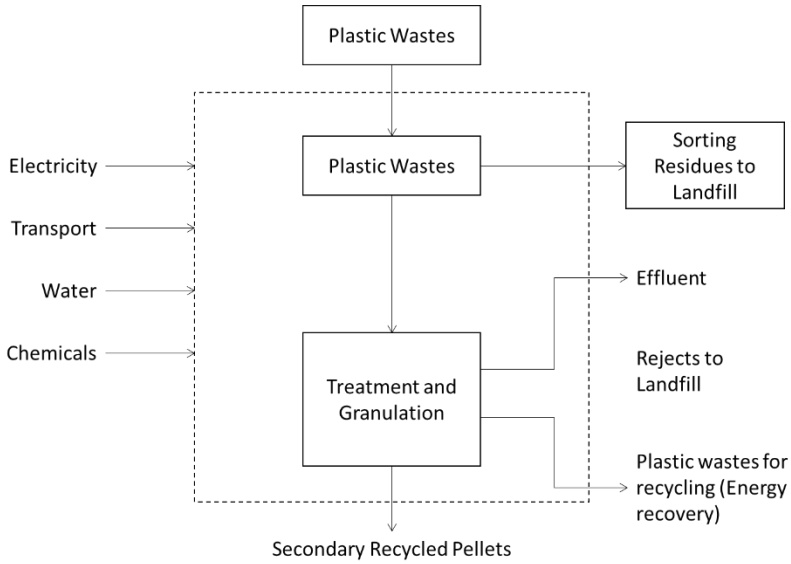


Figure 2-17 Mechanical recycling scenario - Adapted from (Rajendran et al., 2013)

Aside from sorting the waste stream into homogeneous fractions, the challenge remains that the polymer, once processed into a recycled granulate, may not exhibit the same molecular, mechanical and physical properties as exhibited by the virgin material. A number of factors are at play when it comes to the degradation of a polymer - processing conditions, exposure to heat and ultraviolet light during its lifetime and chemical attack are some of the mechanisms that lead to degradation of the polymer. The quality of the recyclate is also affected by the amount of contamination of one type of polymer in another (see 2.3.4.4 regarding polymer compatibility): in the case of Polyethylene Terephthalate (PET) recycling, small amounts of polyvinyl Chloride (PVC) contamination may have severe impacts on the quality of a recyclate (La Mantia, 1996).

The following sections address the topics surrounding polymer degradation and the challenges and opportunities surrounding mechanical recycling.

2.6.1 Polymer degradation

Recyclers are constantly improving their processes and technologies in order to improve the quality of the recyclate to be used for an increasing number of applications. The end goal is to be able to use the same material for the same application a number of times while minimizing waste residues and the reliance on virgin materials. The challenge remains that, no matter how careful the manufacturing process or how sophisticated the disposal and collection system is, the polymer will inevitably become compromised by one or other mechanism. This is known as polymer degradation and is precipitated by a number of factors at different points in a product's lifecycle (La Mantia, 1996).

2.6.1.1 Processing conditions

Polymer parts (plastic packaging specifically) are generally formed under high pressures and temperatures. Injection moulding forces molten plastic into a particular die under high temperatures and pressures to ensure that it fills the mould entirely. Blow moulded and sheet formed parts are also processed under high temperature and pressure conditions. Heat during processing is particularly harmful to the integrity of the polymer; melting the polymer often leads to chain scission of the polymer (causing a reduction in molecular weight) and the formation of crosslinking and branched polymer groups changing its mechanical properties (La Mantia, 2002). Mechanical force has also been observed to result in chain scission during processing (Allen and Edge, 1992). A study comparing the

mechanical properties of virgin and recycled HDPE found that the secondary material's mechanical properties indeed differed from the virgin materials properties (see Table 2-4).

Repeated processing also impacts the quality of a polymer; degradation increases as the number of processing cycle's increases. Table 2-5 shows how, after 15 processing cycles, an HDPE fuel tank's mechanical properties have reduced. Multiple reprocessing also leads to a decrease in the viscosity of a polymer by the reduction of molecular weight caused by chain scission after each processing cycle (see Figure 2-11).

Table 2-4 Mechanical properties of virgin and recycled HDPE - adapted from (La Mantia, 2002)

Property	Virgin HDPE	Recycled HDPE
Modulus (MPa)	596	640
Tensile strength (MPa)	33.7	34.2
Elongation at break (%)	69.7	36.9
Impact strength (N)	135	120

Table 2-5 Change of properties of an HDPE part reprocessed 15 times - adapted from (La Mantia, 2002)

Property	Change in each property, %
Modulus of elasticity	-8.2
Yield stress	-3.0
Elongation at yield	-20.7

Processing of virgin materials and reprocessing of recycled materials is therefore a common cause for the degradation of a polymer's mechanical properties. Fortunately, a number of additives designed specifically to counter the effects of repeated processing are widely available to plastic converters and recyclers (see section 2.3.4).

2.6.1.2 Environmental attack

All plastic packaging materials come into contact with an environmental element at some point during their lifecycle; be it exposure to ultraviolet light, heat, moisture, oxygen, chemical and biological compounds, an applied force or a combination of a number of these elements. Each element has the ability to attack a given polymer causing some degree of chain scission, crosslinking or oxidation degrading the polymer to some extent (Allen and Edge, 1992).

In terms of recycling environmental degradation only complicates the matter further. Since products enter the environment at different times and are exposed to different elements for varying lengths of time it is difficult to anticipate the degree of degradation of a given polymer. Blending a mixture of used plastic packaging material therefore renders a complex product of different materials yielding a product with variability in terms of mechanical properties. Again, the use of additives plays an instrumental role in the recycling of plastics into usable products with good mechanical properties.

2.6.1.3 Mixing and composition

Mixing and reprocessing different types of plastics often leads to a reduction in performance of desired mechanical properties because the polymer blend is most likely incompatible. Most polymer blends tend to be immiscible in one another meaning that at the molecular level there is typically a clear interface between the two polymers which usually translates into poor or less than desirable mechanical properties (Eastwood et al., 2005).

2.7 Fundamentals of particles in a fluid flow

For the purposes of this research project air classification is the mechanism by which particles of varying thickness[15] are to be separated. Before air classification can be discussed the fundamentals of particles in a fluid flow is discussed.

2.7.1 Shape considerations

The majority of research covering particles in a fluid flow deals with particles that have been considered spherical in shape for ease of analysis and calculation. This is not a satisfactory approach as the geometric profile of a particle in question may significantly influence the way in which it behaves in a fluid flow (Concha and Barrientos, 1986). It must also be noted that the flow regime (transitional or turbulent) also affects irregularly shaped particles differently to spherically shaped particles (Tran-Cong et al., 2004).

It is therefore important to give the particles in question some form of general classification. Plastic flakes between 12-14mm have varying dimensions and thicknesses. If the shape is not satisfactorily defined by approximating it to a flat cylinder it may be classified as being axisymmetric and orthotropic and can be described graphically as follows (Clift et al., 1978):

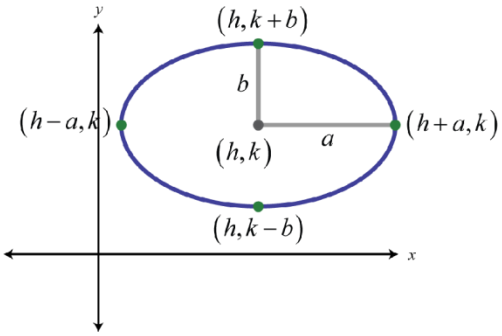


Figure 2-18 Ellipse for representing approximate dimensions of a particle (Clift et al., 1978)

Where $E = b/a$, and $E \to 0$ for disks as the spheroid becomes increasingly oblate. The shape of the particle becomes increasingly important as the Reynold's number of the fluid flow increases.

Irregularly shaped particles generally undergo rotational and translational motion during their fall through a fluid. The translational coefficient of drag and Reynolds number is related to the surface of the particle that moves parallel to the surface plane of the particle. The rotational motion, however, is related to the dimensionless moment of inertia described by (Clift et al., 1978):

$$I^* = \pi\gamma\delta/128a \qquad \text{(Equation 1)}$$

Where:

$I^* = Dimensionless\ moment\ of\ inertia$

$\gamma = Density\ ratio$

$\delta = Thickness\ of\ disk$

$a = Radius\ of\ disk$

[15] The assumption is that particles will be separated based on thickness

2.7.2 Internal flow through a duct

Air classifiers are typically ducts of a specific cross-sectional geometry, length and longitudinal profile (either constant or changing along the length of the classifier). It is important to understand the dimensions of the classifier as it will have influence on the flow characteristics at different velocities. The Reynolds number is the non-dimensionalized number that traditionally describes the nature of the fluid flow. The Reynolds number can be described as (White, 2008):

$$Re = \frac{VL}{\nu} \qquad \text{(Equation 2)}$$

Where:

$V = fluid\ velocity$

$L = length\ of\ the\ channel$

$\upsilon = kinematic\ viscocity$ – for air at 20 degrees Celsius is 1.5×10^{-5} m^2/s (White, 2008)

Generally, the Reynolds number corresponds to a specific flow regime. The kinematic viscosity and the velocity of the air flow for this investigation means that the flow regime is most likely turbulent where there is a slight Reynolds number dependence (White, 2008):

$10^4 < Re < 10^6$ - turbulence, moderate Reynolds number dependence

$10^6 < Re < \infty$ - turbulence, slight Reynolds number dependence

2.7.3 Particles in a fluid flow

Particles immersed in a fluid are acted on by three forces; the force of weight induced by gravity, drag induced by the viscosity of the fluid, and buoyancy induced by fluid displacement. The viscosity of the fluid creates shear forces on the surfaces of a particle leading to a drag force as the particle moves through a fluid. At low velocities this is known as viscous resistance and at high velocities it is known as turbulent resistance (Wills, 2011). The magnitude of the resistance of the immersed particle in a flowing fluid is influenced by a number of factors associated with the particle itself, and the fluid it is immersed in. In terms of the fluid that the particles are immersed in, the parameters that influence their movement are (Taggart and Behre, 1945):

- The flow velocity and direction
- The pressure and any pressure gradients within the fluid
- The viscosity of the fluid
- The temperature and humidity of the fluid

Investigating the manner in which a particle or a collection of particles of the same or differing size behave in a fluid flow is a complex science that requires the use of a combination of fluid dynamics, numerical modelling and experimentation and is beyond the scope of this project.

2.7.4 Terminal (settling) velocity of a particle in the presence of buoyancy force

The terminal or settling velocity of particles in a fluid flow is the velocity at which the drag force and force of gravity equate one another resulting in the particle falling at a constant velocity. Depending on the velocity of the fluid flow the particles will either sink or become entrained in the flow depending on the velocity of the fluid flow and the settling velocity of the particles (Wills, 2011). In terms of separation, heavy particles will continue to fall under their weight despite being in the presence of an air flow flowing in the opposite direction. The lighter particles, having a lower settling velocity than

their heavier counterparts, become entrained in the flow and exit the classifier in the opposite direction.

2.7.4.1 Basic physics

If a particle falls through a fluid under its own weight it reaches terminal velocity when the weight of the particle is balanced by the sum of the drag and buoyancy forces (Brown and Lawler, 2003):

$$W = F_d + F_b \quad \text{(Equation 3)}$$

Where:

$W = weight\ of\ the\ particle$

$F_d = drag\ force$

$F_b = buoyancy\ force$

Furthermore:

$$W = \pi a^2 \delta \rho_s \frac{d^2y}{dt^2} \quad \text{(Equation 4)}$$

$$F_d = C_d \frac{1}{2}\left(\frac{dy}{dt}\right)^2 \pi a^2 \quad \text{(Equation 5)}$$

$$F_b = \rho_f \frac{d^2y}{dt^2} \pi a^2 \delta \quad \text{(Equation 6)}$$

2.7.4.2 Analytical approximation

It is important to consider the mechanism by which particles are separated. The air flow velocity and particle density are important considerations in terms of balancing the forces of buoyancy, weight and friction. Equation 3 simply defines the relationship between these forces and the settling velocity at which these forces balance (Tomas and Gröger, 2001):

$$v_{sink}^2 = \frac{2}{C_d} \cdot \frac{\rho_s - \rho_f}{\rho_f} \cdot \frac{V_p}{A_p} \cdot g \quad \text{(Equation 7)}$$

Where:

$v_{sink} = \frac{dy}{dt} = settling\ velocity$

$g = \frac{d^2y}{dt^2} = gravitational\ force$

$A_p = side\ fed\ cross\ sectional\ area$

$C_d = drag\ coefficient$

$V_p = particle\ volume$

$\rho_f = fluid\ density$

$\rho_s = density\ of\ the\ solid\ particles$

Equation 7 is a simplification of the force balance of the forces described by Equations 4 – 6. This equation defines a specific settling velocity based on a particles terminal velocity in an air flow. It is a simple analytical solution that may be used to quickly approximate the settling velocity of a particle. It

is a rudimentary analytical solution and does not accurately describe the settling velocity of an irregularly shaped particle in an air flow (Tran-Cong et al., 2004).

2.7.5 Ballistic trajectory

The ballistic trajectory or trajectory of a projectile is considered the path that a particle follows after it has been launched by an external force and acted on by an aerodynamic drag component. In the case of material separation ballistic trajectories of different particles can be exploited in order to separate based on particle mass and geometric profile.

To determine the distance travelled of a given particle in the presence of air resistance, Newton's second law is applied and solved for displacement as a function of mass and geometric profile (focusing on horizontal movement) (Bedford and Fowler, 2007):

$$\Sigma F_x = -F_{air} = ma_x \qquad \text{(Equation 8)}$$

Where:

$F_{air} = -kv$ (assuming direct proportionality between air resistance and velocity)

Where $k = \frac{1}{2}\rho_f A C_d$

Integrating the second order equation:

$$s_x = {}^{m}/_{k}\, v_x \left(1 - e^{-\frac{k}{m}t}\right) \qquad \text{(Equation 9)}$$

Equation 9 describes the relationship between mass and displacement of the ballistic trajectory of a particle in the presence of air resistance. As the mass of a particle increases, so does its displacement (assuming the geometric profiles remain the same) (Bedford and Fowler, 2007).

2.8 Air classification

2.8.1 Introduction

Air classification is the process of separating particles in an air flow according to the particles settling velocity, which is a function of the particles size, shape and weight. Air classifiers are either static or dynamic in the way that they function (Altun and Benzer, 2014). Static air classifiers do not have any moving parts whereas dynamic classifiers have a rotating plate onto which the material is fed, imparting a centrifugal force on the particle to assist in separation.

Air classifiers are further defined by the characteristics of the air flow through the system. The fluid flow through an air classifier is dependent on the geometric profile of the classifier and whether the air flow velocity is varied or kept constant (Everett and Peirce, 1990). The composition, particle size range, and relative particle geometry will have an influence on what type of air classifier would be best suited to separate polyolefin flakes of differing thickness and density. Air classification separates material based on one of these parameters meaning that all other parameters should be kept constant to limit the influence of other variables (Tomas and Gröger, 2000)

Typically air classification has been used to separate particles according to particle size rather than sorting a binary mix into two distinct fractions (Taggart and Behre, 1945). Air classification takes advantage of the aerodynamic profile of a particle; perfect separation is not possible for a material feed of particles that differ in shape, size and density (Stessel and Pelz, 1994). Each product from an air classifier will have a degree of contamination.

2.8.2 Types of separation zones

The design of an air classifier depends on the type of material that is to be separated. The separation zone of a classifier is the area where separation occurs. The most common separation zone types are (Shapiro and Galperin, 2005):

- Gravitational counterflow
- Gravitational crossflow
- Centrifugal counterflow
- Centrifugal crossflow
- Cascade classifiers

Cascade classifiers are best suited for the application in question and are discussed in further detail.

2.8.3 Cascade (Zigzag) air classifiers

Cascade air classifiers refer to air classifiers that are constructed from a series of rectangular ducts joined together at a specific angle (Figure 2-19. a). The configuration can be slightly adjusted as is shown in Figure 2-19. b, where angled plates are used to create a zigzag profile. The system can also be used in parallel with horizontal scavenging to improve the cut efficiency (Figure 2-19. c) (Shapiro and Galperin, 2005).

The purpose of introducing a zigzag profile is to create vortices in the flow where coarse particles are captured, thrown to the opposite side of the separation chamber and fall to the bottom of the classifier. Zigzag classifiers have two distinct flow streams; a stream of particles that moves upwards and one that moves downwards at the lower point of each section (Senden, 1980). Cascade classifiers are best suited for this application because of their superior separation sharpness compared to other conventional air classifiers.

Cascade classifiers improve separation but increase operating costs. Cascade classifiers consume large amounts of energy because of the pressure drop they have to overcome as a result of the zigzag profile creating a large pressure drop over the channel.

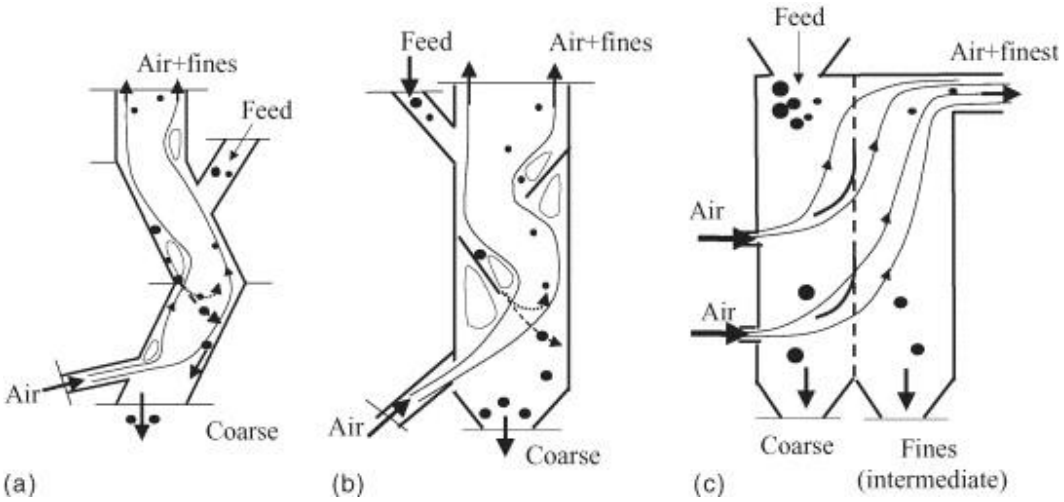


Figure 2-19 Cascade classifiers, (a) zigzag, (b) shelf, (c) horizontal scavenging (Shapiro and Galperin, 2005)

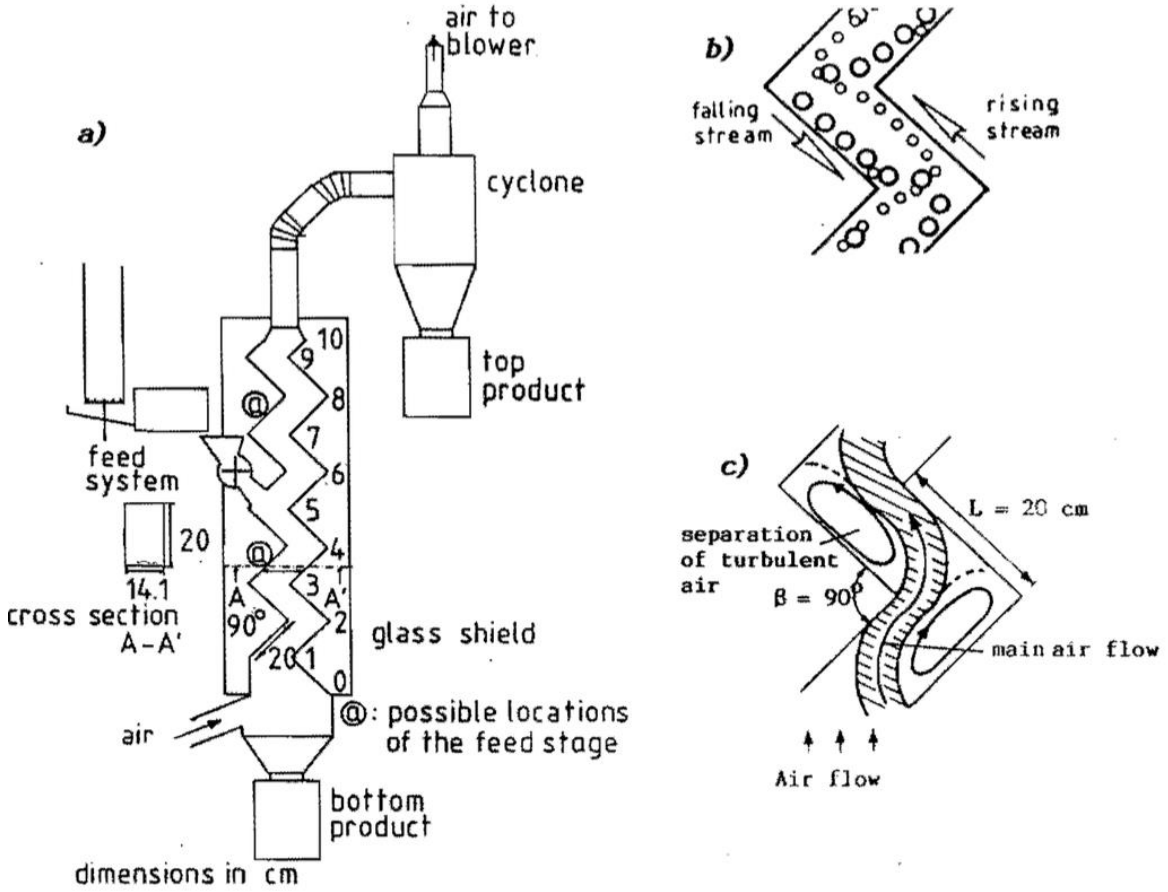


Figure 2-20 Cross section and velocity profile of a typical zigzag air classifier (Rosenbrand et al., 1986)

2.8.3.1 Experimentation with zigzag classifiers

In experimentally studying the sharpness of particle separation for a number of varying configurations it was found that (Rosenbrand et al., 1986):

- The separation sharpness between classifiers of 90 deg. And 120 deg. Were roughly the same but the capacity of the 120 deg. Classifier was larger
- If the classifier channel is broadened the separation sharpness decreases but the capacity increases. This is the same result if the feed point is closer to one of the classifiers exit points
- Wall roughness plays a role in affecting the efficiency of the system by affecting the interactions of the falling particles with the lower zigzag walls of the separators

2.8.3.2 Particle behavior inside zigzag air classifiers

Particle-particle interactions increase as the feed rate increases. When the feed rate increases particles interactions with other particles and the air classifiers walls increases rendering separation less efficient (Rosenbrand et al., 1986).

Transit times of the particles also vary. Heavier particles tend to move downwards in a constant path quicker than the lighter particles moving upwards. The lighter particles also do not follow a constant path profile compared to the heavier particles (Rosenbrand et al., 1986)

2.8.3.3 Zigzag air classifier cut points and performance

Any air classification process is utilised to separate a mixed input material into two or more products (in this case it is a light and a heavy fraction). Air classification is not capable of perfect separation meaning that there will always be some amount of contamination of each product fraction in the other. The point at which the material has a 50% probability of either ending up in the heavy or light fraction is referred to as d(50%) and it is linked to the size or thickness of the particle (depending on what parameter the separation is based on). Therefore the d(50%) point is calculated to determine the cut point meaning that material smaller will most likely end up in the light fraction and material larger will most likely end up in the heavy fraction.

The efficiency of an air classifier can be measured in a number of ways. The first method discussed is based on the masses of the different fractions entering and exiting the air classifier and is considered the general efficiency of an air classifier. The general efficiency equation for air classifiers is given as (Everett and Peirce, 1990):

$$E = \sqrt{\frac{x_e}{x_o}.\frac{y_r}{y_0}}.100 \qquad \text{(Equation 1)}$$

Where E = efficiency; x_e = mass of light particles exiting as lights through the top of the classifier; x_o = mass of light particles entering the classifier; y_r = mass of heavy particles exiting as heavies through bottom of classifier; y_0 = mass of heavy particles entering the classifier.

An important finding was the basis on which the performance of a zigzag separator is measured. If separation is based on efficiency of separation (defined by equation 1) then performance is independent of particle size of the feedstock. If, however, performance is based on operating range (defined by equation 2 where OR refers to the operating range of the classifier, f_1 refers to recovery as a percentage and f_2 refers to contamination as a percentage):

$$OR = \int [f_1(x) - f_2(x)]dx \qquad \text{(Equation 2)}$$

then particle size affects performance. To improve operating range, the input particle size should be small. The operating range also increases with the increase in number of zigzag stages and stage angle (Peirce and Wittenberg, 1984).

Another measure of the performance of air classifiers is the sharpness index, *s.* The sharpness index is the ratio of the d(25%) and d(75%) probabilities and it represents the sharpness of separation; $s = d(75\%)/d(25\%)$ It is calculated independent of the mass of each fraction entering and exiting the air classifier making it suitable for measuring the efficiency of the classifier without knowing the mass of each fraction before and after air classification. Perfect separation is represented by $s = 1$ but most classifiers have sharpness indexes between 0.5 and 0.8 (Klumpar et al., 1986).

In terms of the performance of gravitational-counterflow versus zigzag classifiers, zigzag classifiers are known to have a lower diffusivity (higher efficiency – Equation 1) than gravitational-counterflow classifiers (Biddulph and Connor, 1989).

2.8.3.4 Effect of feed rate and classifier height on air classifier performance

Findings from research showed that tall passive-pulse stacked triangle air classifiers perform better than tall active pulse and nonpulse air classifiers. The study also found that increasing the feed rate also decreased the efficient separation range. Increasing the height of the classifier also showed that it improved the effectiveness of the separation (Hagemeier et al., 2014).

Air classifier performance has also been found to be dependent on the moisture content of the feedstock (Crowe and Peirce, 1988). This is important to note; the plastic feedstock that is to be separated must be cleaned and dried to prevent moisture content impacting air classifier efficiency.

2.9 Literature summary

The most relevant aspects to take note of before progressing to the next chapter are:

- Polymer densities (section 2.3.2.6): important information for section 3.5.3 and 4.3 regarding the density measurements of the plastic samples
- Polymer mechanical properties (section 2.3.2.7): important information for sections 3.9 and 4.8 regarding the mechanical properties of the plastic samples
- Characteristics of plastic packaging (section 2.5): important information for sections 3.5.2, 3.6 and 3.7 regarding the correlations between wall thickness and injection and blow moulded plastic packaging materials
- Characteristics of plastic packaging (section 2.5): important information for sections 3.5.2, 3.6 and 3.7 for air classification purposes
- Air classifier cut points and performance calculations (section 2.8.3.3): important information for sections 3.7 and 3.8 regarding air classification and ballistic separation performance calculations

CHAPTER 3

3 Experimental methods

This chapter provides a detailed description of the equipment, experimental setup and methodology applied to carry out each part of the investigation. The aim of the research is to determine, using conventional recycling technologies, whether or not it is possible to separate blow moulded (BM) from injection moulded (IM) plastics or vice versa using air classification or ballistic separation techniques. As stated in previous sections and in previous studies it has been shown that BM and IM plastics have different thickness ranges providing a parameter that may be exploited in pursuit of separating BM and IM plastics.

3.1 Overview

The flow diagram of the experimental section is shown in Figure 3-1.

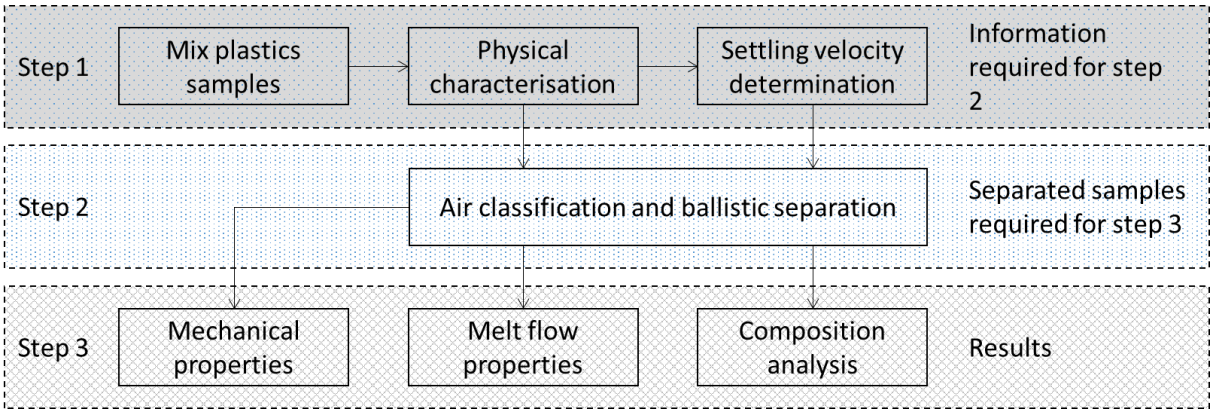


Figure 3-1 Overview of experimental method

Before the air classification and ballistic separation experiments could be carried out, the physical characteristics (wall thickness ranges, size ranges and settling velocity) of the test samples had to be measured. After each sample was separated into two fractions, the new samples were processed into test bars for analysis of mechanical and melt flow properties. The Melt Flow Index (MFI) measurements indicate whether or not sorting on wall thickness affects the melt flow properties of a recyclate by comparing the MFI values of each sample before and after separation.

3.2 Experimental equipment

The experimental equipment used for this research is listed in Table 3-1.

Table 3-1 Experimental equipment

Equipment	Description	Measurement range	Measurement uncertainties
Vernier caliper	Used to measure material wall thickness	$0.00 - 150mm$	$\pm 0.01mm$
Hydrometer	Used to measure liquid density	$0.800 - 1.000$ (specific gravity)	± 0.002
Mass scale	Used to measure sample mass	$0.00 - 3.00$ kg	± 0.01 g
D**rying oven**	Used to dry wet samples		
V**ibrating screen**	Used to sieve samples		
Stopwatch	Used for timing purposes		$\pm 0.2s$
Digital impeller anemometer	Measure air flow velocity	$1.00 - 30.0$ m/s	± 0.20 m/s
Stopwatch	Used to measure drop test time		± 0.2 s
Nihot air classifier	Used for air classification experiments	No measurement device	
Herbold air classifier	Used for air classification experiments	No measurement device	

Note: *Uncertainties were disclosed on the technical data sheet of each piece of equipment and are at a confidence level of 95%.*

The equipment used to measure various parameters were sufficiently accurate with the required measurement resolutions for the purposes of this research.

3.3 Results

To validate the results of the research, the mechanical and melt flow properties of each tested sample are compared with the properties of virgin polymers outlined in the literature as the aim is to produce a recyclate with similar properties to that of the virgin material. The results are also compared with samples that were not processed by means of air classification on density separation to determine, to what degree, each sample was upgraded or worsened.

The performance of the air classifiers is also validated by comparing the separation efficiency results with the results of previous studies outlined in the literature.

3.4 Description of the plastic samples

3.4.1 Pre-Magnetic Density Separation (MDS) samples

The material used to conduct this research was supplied by a Romanian plastic recycling company that produces four distinct packaging recyclates:

- HDPE blow mould grade (mixed colours)
- ***PP injection mould grade (black) – Not included in sample***
- PP injection mould grade (mixed colours)
- HDPE blow and injection mould grade (mixed colours)

The sample that was prepared for testing excluded the PP injection grade (black) product because it is deemed an inferior product and not suitable for MDS processing. To produce the products listed above, a team of hand sorters sort through piles of mixed plastics that have been separated from other materials such as metals, organic materials and paper.

The first group of hand sorters are trained to sort out all plastic bottles (mostly HDPE blow mould bottles with injection moulded PP lids and caps) into a separate bunker. The result is a predominantly HDPE blow mould grade product containing small amounts of PP injection mould grade plastics. The second group of hand sorters are trained to sort out all plastic food containers (mostly PP injection moulded food containers with a small amount of HDPE injection moulded food containers) into a separate bunker. The third group of hand sorters are trained to sort out all the large plastic items such as water drums and drinks crates (a mixture of blow and injection grade HDPE) into a separate bunker. Hand sorting is able to produce products with a purity of between 80 and 90%.

For MDS testing and for this investigation, a 20 tonne sample (a mixture of the three products with a composition corresponding to the ratio outlined in Table 1-1) was supplied by the Romanian recycling company. In addition to the mixed material sample, 10 kg samples of the recycling plants current products as shown in Table 1-1 were also supplied. The size, density and thickness distributions of each of these samples was measured.

Figure 3-2 is an image of the material. It is important to note that the material is irregular in shape and size as a result of the shredding process. For the purposes of the MDS test investigation, the material had to be screened to a nominal size of -10 mm to ensure that it did not cause blockages in the system. The oversized fraction was then re-shredded and mixed back into the mixed sample to avoid changing the composition of the material. Five samples in total were measured for size, thickness and density:

- Mixed sample
- Mixed sample ($<$ 10 mm)
- HDPE blow mould (BM) grade (mixed colours)
- PP injection mould (IM) grade (mixed colours)
- HDPE blow and injection mould (BM + IM) grade (mixed plastics)

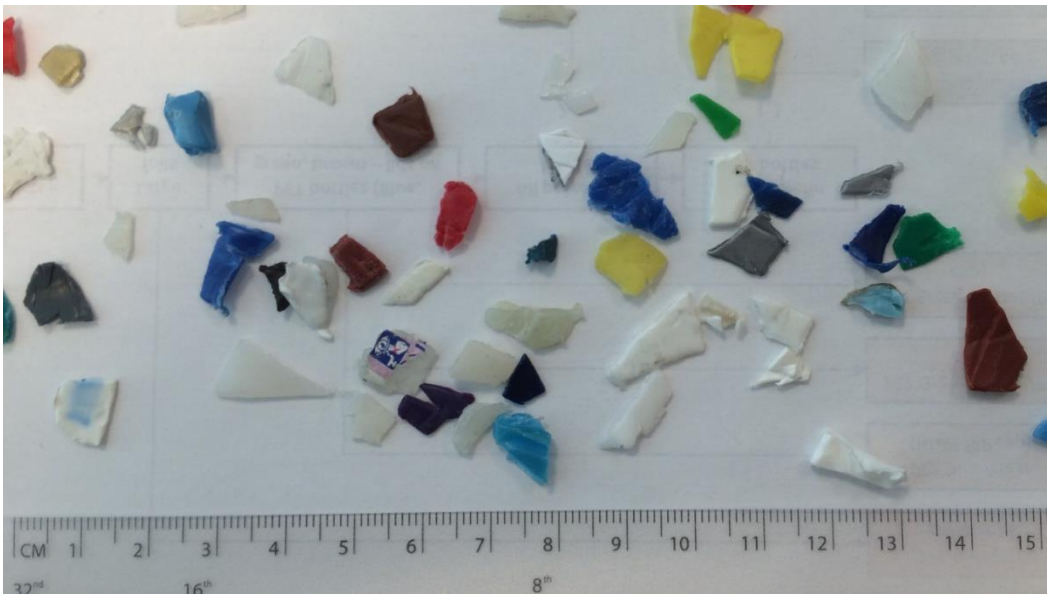


Figure 3-2 Material sample

3.4.2 Test matrix

Section 3.5 describes the tests that were conducted on the different samples described above. The matrix shown in Table 3-2 outlines which tests were conducted on which samples.

Table 3-2 Test matrix

Sample	Size measurements	Thickness measurements	Density measurements	Polymer type/thickness
Mixed sample	X		X	X
Mixed sample ($< 10\ mm$)	X	X	X	
HDPE BM grade	X	X	X	
PP IM grade	X	X	X	
HDPE BM + IM grade	X	X	X	
Sized samples (section 3.5.1)		X	X	

3.4.3 Post-Magnetic Density Separation (MDS) samples

This project was done in conjunction with the MDS project and it was important to also conduct tests on the products from the MDS system to determine whether upgrading before or after MDS was possible. The MDS system has the ability to sort a mixture of PP and HDPE into products with a purity in excess of 90% (Serranti et al., 2015).

Two samples of each product from the MDS project were collected for use in this investigation; a PP product with a purity of approximately 90% and an HDPE product with a purity of approximately 95%.

3.5 Physical characterization of the material

A complete analysis of the material samples received from the recycling plant in Romania was undertaken to understand what is possible in terms of separation; especially separation based on the wall thickness of the material. Specific techniques were used to measure the size, thickness and density distributions of each sample.

3.5.1 Size measurements

Each of the five samples described in section 3.4 were separated into different size fractions to determine the composition of each sample in terms of size. The size of the material is an important parameter with regards to air classification as the drag of a particle immersed in a fluid is a function of the surface area of a particle. Particles with a large surface area generate more drag than particles with a small surface area. To separate the material based on wall thickness alone the settling velocity of each particle, influenced by surface drag forces, should be limited (see section 2.7).

In the case of the material needing to be sorted into different size ranges for air classification purposes, it is important to understand the fraction of each size range for throughput calculations of the recycling system as a whole.

3.5.1.1 Method

The distribution of particle sizes of each sample were determined by separating the material into different size fractions (approximately 0-5 mm, 5-11 mm, $>$ 11 mm) using a laboratory stacked vibrating screen machine with $4\,mm$ and $8\,mm$ square sieves (Figure 3-4). Figure 3-3 shows how material larger than $4\,mm$ and $8\,mm$ is able to pass through these square sieves.

The sieves were stacked with the larger grid size on top. Approximately 1 kg of material, considered a representative sample without overloading the screens, was placed on the top grid before the vibrator was sealed. The vibrator then vibrated the material until it was completely separated into different size fractions (each sample was processed for enough time to ensure complete separation). Each fraction was removed, weighed and weight recorded. This process was repeated for each sample (see Table 3-2). See appendix 1 for a step by step procedure.

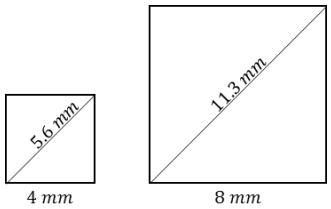


Figure 3-3 Square grid dimensions

Stacked vibrating screen

Square sieves

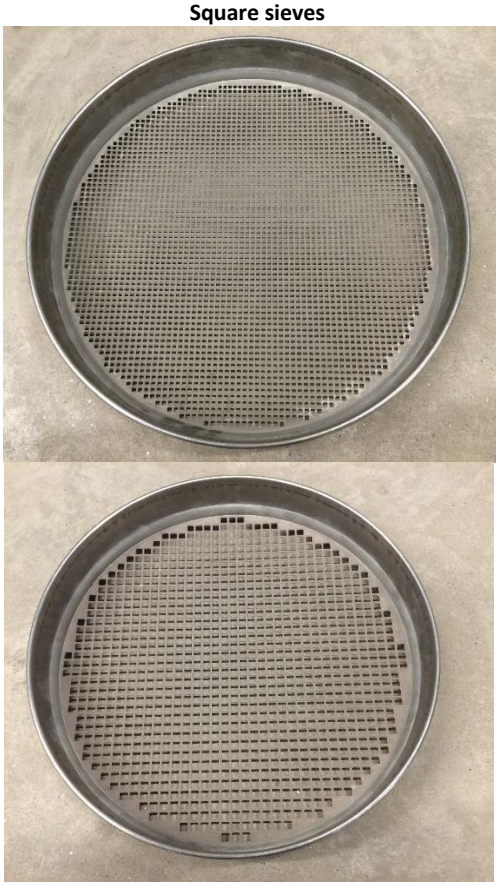


Figure 3-4 Apparatus for size measurement tests

3.5.2 Thickness measurements

The thickness distribution measurements are used to help determine the separation cut points when attempting to separate thin-walled from thick-walled plastics. The thickness distribution measurements also given an indication of the expected masses of each fraction after they have been separated into a thin-walled and thick-walled fraction. Additionally, it also becomes a useful tool when calculating the separation curve charts of air classifiers and ballistic separators (see section3.7). The thickness distributions were measured for all the samples (see Table 3-2).

3.5.2.1 Method

Thickness measurements were conducted by measuring the wall thickness of individual plastic flakes from each sample using a vernier caliper. The measurements were recorded and translated into histograms that graphically display the thickness distribution of each sample. Each column in the histogram represents a thickness interval of 0.1 mm. See appendix 2 for step by step procedure.

3.5.2.2 Correlation between wall thickness and polymer type

Previous research has suggested that different categories of products are made from different polyolefins; blow moulded plastic bottles are generally made from HDPE and injection moulded plastics are generally made from PP (Hu et al., 2013). It was therefore worth investigating the relationship between wall thickness and polymer type. From the same mixed sample used in section 3.5.2, the type of polymer of each flake was recorded using a technique known as Fourier Transform Infrared (FTIR) spectroscopy.

FTIR spectroscopy is a technique that measures how much light (at different frequencies) is absorbed by the sample at which the light is directed (Griffiths and de Haseth, 2006b). The "Fourier Transform" part of the name refers to the exploitation of the mathematical process that converts the raw data into a readable spectrum (Griffiths and de Haseth, 2006a). Once a sample's infrared profile has been analyzed, the system determines the composition of the material by matching it to known materials in the laboratories self-populated database. A PerkinElmer Spectrum FT-IR spectrometer was used for this investigation.

3.5.3 Density measurements

The density distribution for each sample was assessed to determine the mass fractions of PP and HDPE in each of the samples outlined in Table 3-2. A series of simple sink-float tests were undertaken to separate each sample according to the density of HDPE and PP in each sample. Once completed the ratio of each density fraction was calculated.

3.5.3.1 Method

The method used to determine the density distributions of each sample was the same method used in a study that did a similar density distribution analysis on packaging waste material (Hu et al, 2012). Firstly, two solutions of water and pure propanol were prepared so that one solution had a density of 920 kg/m^3 and the other 930 kg/m^3. Material that lighter than 920 kg/m^3 is regarded as PP and material heavier than $930\ kg/m^3$ is regarded as HDPE (see section 2.3.2.6). Sink float tests were conducted on each sample using the solutions described above to separate the material into three density fractions: $<$ 920 kg/m^3, 920 to 930 kg/m^3, $>$ 930 kg/m^3. See appendix 3 for a step by step procedure.

3.5.4 Bulk density measurements

The bulk density of the material represents the mass of the material per volume. It is not an intrinsic property of the material but rather a measure of how much mass of a specific material occupies a given volume. It is important to understand the bulk density of the material as it has implications when determining the economic aspects of a process.

The purpose of the bulk density measurements for this study was to show that bulk density varies according to material wall thickness. The bulk densities of the material before and after air classification were measured for comparison (see section 3.7 regarding air classification).

There are a number of standardized measuring methods for measuring bulk density; mostly oriented to soils and powders (materials of relatively small grain size). For the purposes of this study the bulk density of each material was measured using a simple metal tray and an electronic scale.

3.5.4.1 Method – bulk density measurement

For the bulk density measurement, material is placed into a tray of known volume (6092 cm^3) and weighed. The mass of the material in the tray is then divided by the volume to give the bulk density. This procedure was repeated for each sample.

3.6 Settling velocity measurements

The settling velocity of a particle immersed in a fluid defines the point at which the forces of gravity, buoyancy and frictional drag are balanced. The result is that the particle falls at a constant velocity under free fall or remains somewhat stationary when placed in an air flow stream. The force balance that describes settling velocity explains that settling velocity is a function of a number of properties of both the particle in question and the fluid into which it is immersed. Particle shape, size, density, profile

and surface roughness, and liquid viscosity and density all influence the settling velocity (see section 2.7).

To accurately calculate or compute the settling velocity of irregular particles is challenging and subsequently falls outside of the scope of this project; however, it is possible to experimentally determine the settling velocities of a number of different plastic particles. Because the material is not homogeneous in terms of shape and size, a number of plastic flakes of different size and shape were included in the experiment. What is most important is to determine how the settling velocity changes as the wall thickness of the material changes.

The settling velocity experiment was conducted with material from the mixed sample. The settling velocity was determined by using two different methods:

- dropping individual particles from a height
- constructing a simple air flow chamber that particles can be immersed in

Each method will be discussed individually. For both experiments the same plastic flakes were used in order to compare the results directly.

3.6.1 Material preparation

The thickness and size of individual flakes were measured and the general shape of the flake recorded for each particle from a representative sample of the mixed material. After measurement each flake was placed in a container that corresponded to its thickness. Flake thickness varied from 0.51 to 1.64 mm.

Once a sufficient number of particles had been measured and separated according to thickness, each thickness batch was further sorted down to 5 particles, each having a different shape and size as shown in Figure 3-5.

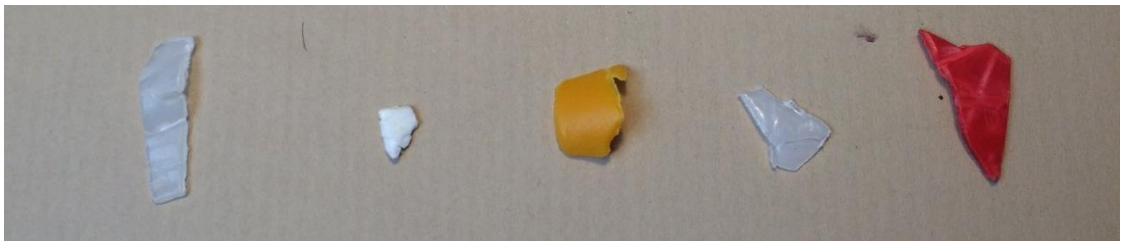


Figure 3-5 Settling velocity flake selection

3.6.2 Settling velocity determination – Drop test

After measurement and sorting a flake was dropped from a height 4.19 m (the height between ground level and the first floor at the laboratory) with all the doors and windows nearby closed. The time taken for the plastic flake to hit the ground was recorded. This step was repeated for each flake.

3.6.3 Settling velocity determination – Flow chamber

The experimental setup for the settling velocity measurements in a laboratory flow chamber is given in Figure 3-6. The flow chamber was a square Perspex air channel with dimensions 45 by 48 mm. A digital impeller anemometer and a flow meter were used to record the air velocity.

To carry out the experiment a single plastic flake was first placed in the flow chamber. The pressure valve was then slowly opened to allow air to flow through the chamber. The valve was opened incrementally until the particle began to gently flutter. The volumetric air flow rate and anemometer

readings were recorded. The average air velocity was calculated for plastic flakes that fell into the same wall thickness range.

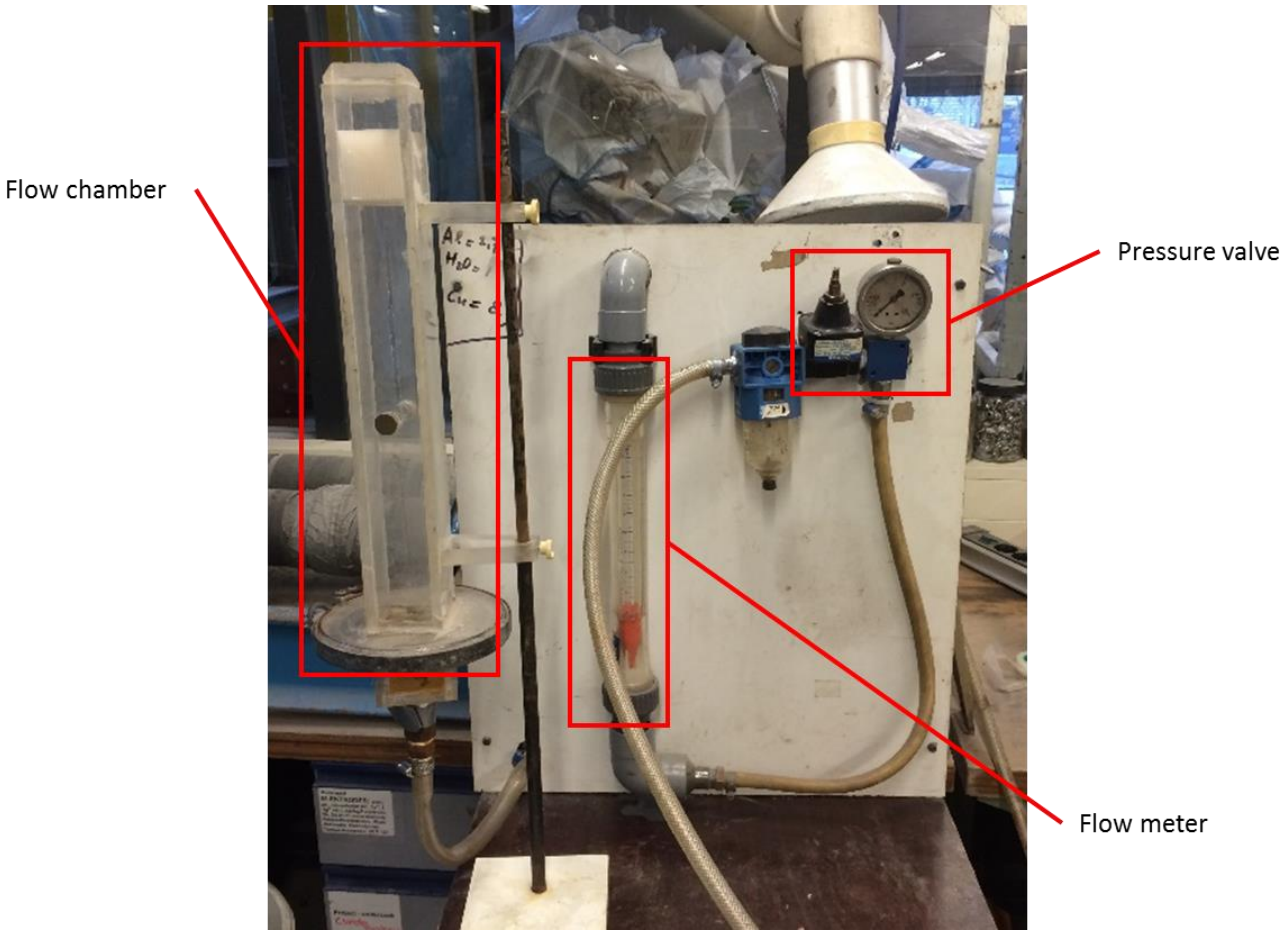


Figure 3-6: Flow chamber setup

3.7 Air classification

Air classification was carried out on the mixed sample material to determine how efficiently the material could be separated into two fractions; one resembling thin-walled (blow mould rich) material and the other resembling thick-walled (injection mould rich) material. The air classification investigation was conducted on (see section 3.4 for more information):

- Mixed sample material (< 10 mm)
- Polypropylene material – MDS product
- Polyethylene material – MDS product
- Mixed sample material (5-10 mm)

The first round of air classification tests was carried out on a Nihot® WS-Z zigzag classifier. The focus of the first round of tests was to determine:

- the effect of air flow rate on the separation cut point,
- what cut points (in terms of wall thickness) were possible on a typical zigzag air classifier setup,
- the corresponding masses of each fraction for each experiment,
- the correlation between particle surface area differences and separation efficiency (see section 2.7 for more information)

The second round of air classification tests was conducted on a more advanced air classification system; the second machine, A Herbold® SZS 630/212 zigzag air classifier, had a much taller zigzag separation chamber, frequency controlled fans and a frequency controlled vibrating feeder. The Herbold® configuration was not as powerful as the Nihot® setup but more precise control of the feed rate and air flow rate was possible. The purpose of the second round of testing was:

- to determine the whether there is a correlation between classifier height and separation efficiency
- to determine effect of feed rate on separation efficiency

3.7.1 Material preparation

3.7.1.1 Mixed material

Mixed material was included in the air classification investigation to determine whether or not it would make practical sense to place the air classification step before density separation (see Figure 3-7). Air classification was also carried out to determine by how much the material can be upgraded before being separated by the MDS system. It also serves as a point of reference for comparison with separation of the MDS PP and HDPE products.

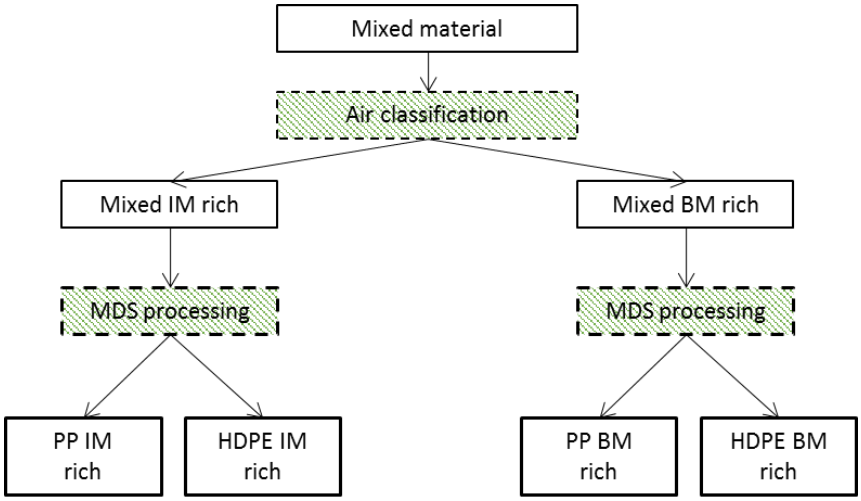


Figure 3-7 Air classification before polymer type separation

3.7.1.2 PP and HDPE MDS products

Air classification on the MDS PP and HDPE products may prove to yield higher quality IM and BM products. The mixed material sample is a polyolefin mix made up of three streams of material produced by Romanian processing plant; it is a mixture of IM grade PP, BM grade HDPE and an IM-BM HDPE mixture (see section 3.4). The MDS system has the ability to separate this material into a PP rich fraction and a HDPE rich fraction. If this information is accurate it means that the PP product is already a product which is an injection mould rich product and the HDPE product is an IM-BM mixture (see Figure 3-8). Air classification could prove to be a refining step that upgrades the product further after MDS processing.

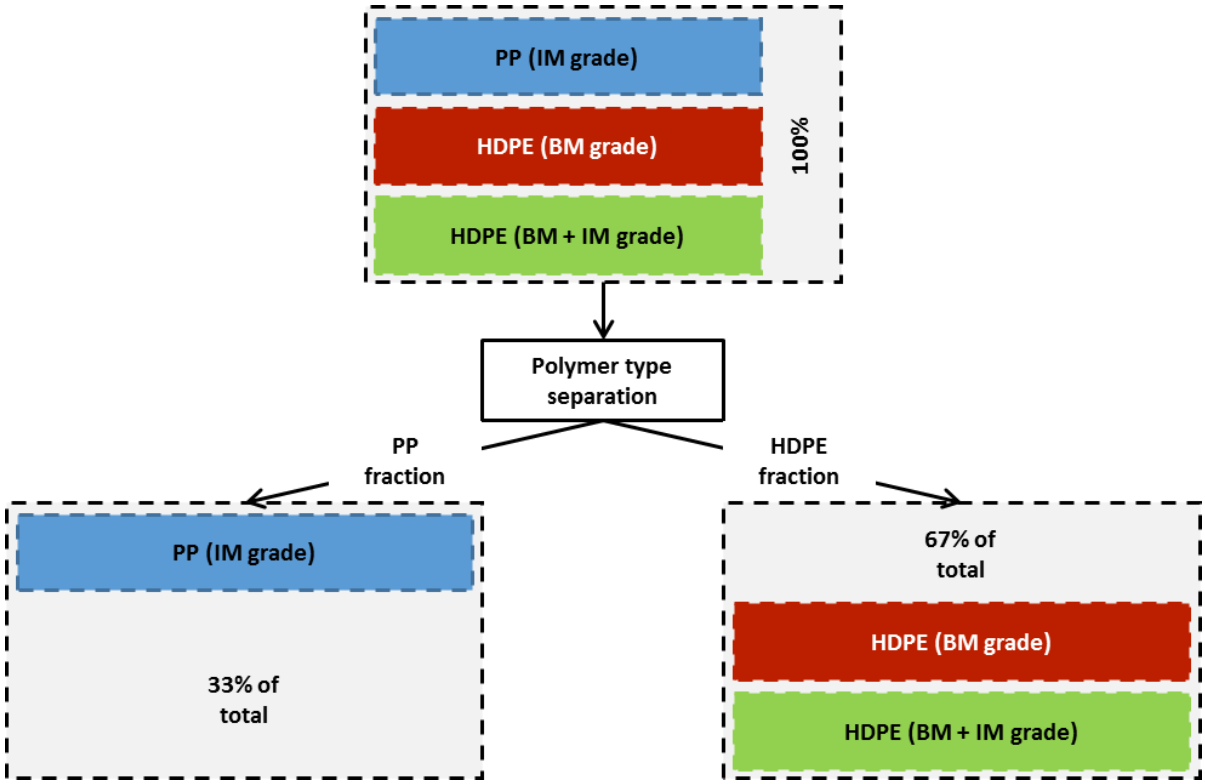


Figure 3-8 MDS processing

3.7.1.3 Mixed material (5-11 mm)

This sample was included in the study to determine the impact flake size has on separation efficiency. By reducing the nominal size range, it is believed that separation based on wall thickness would improve as the influence of another variable, flake surface area, is reduced.

Before testing each material sample had to be prepared, packaged and labelled. The mixed material did not require any screening or washing; it was simply weighed, packaged and labelled accordingly. The $5 - 10\ mm$ sample had to be prepared by sieving mixed material (20 kg sample) using a vibrating screen. Once enough material was screened it was weighed, packaged and labelled.

PP and HDPE (MDS products) material had to be washed and dried before weighing and packaging. A sample of PP was taken from a batch that corresponded to a PP quality of 90%. The material was then washed in cold water and drained to remove all residual magnetic fluid. The material was then dried by spreading it out over a plastic sheet to speed up the drying process. Once dried it was weighed, packaged and labelled. HDPE material was prepared in the same way as PP material.

3.7.2 Nihot® Amsterdam WS-Z zigzag air classifier

The Nihot® WS-Z air classifier is a typical zigzag air classifier (see Figure 3-9). Material is fed into the top of the zigzag channel by a vibrating screen where initial separation occurs. The light material immediately becomes entrained in the airflow and is removed from the top of the chamber whereas the heavy material falls under its weight to the bottom of the channel. The transitional material (the material with a settling velocity that closely resembles the velocity of the air flow through the channel) becomes partly entrained in the air flow and, depending on a number of physical processes within the separation chamber; either falls to the bottom or exits the top of the channel.

The initial investigation focused on determining different thickness cut points by varying the air flow rate through the system. The feed rate for all tests was therefore kept constant. Since most

manufacturers do not directly measure the air flow velocity inside the separation channel, the air flow rate is adjusted mechanically: in this case it is adjusted by changing the aperture of the air flow duct and fine tuning the air flow rate by allowing air to flow in through an adjustable opening at the top of the channel (see Figure 3-10). The operator increases the aperture to increase air velocity and decreases it to reduce air velocity. The air inlet at the top of the separation chamber is used to fine tune the air velocity (opening it reduces air velocity in the chamber and closing it increases air velocity). See appendix 4 for more images.

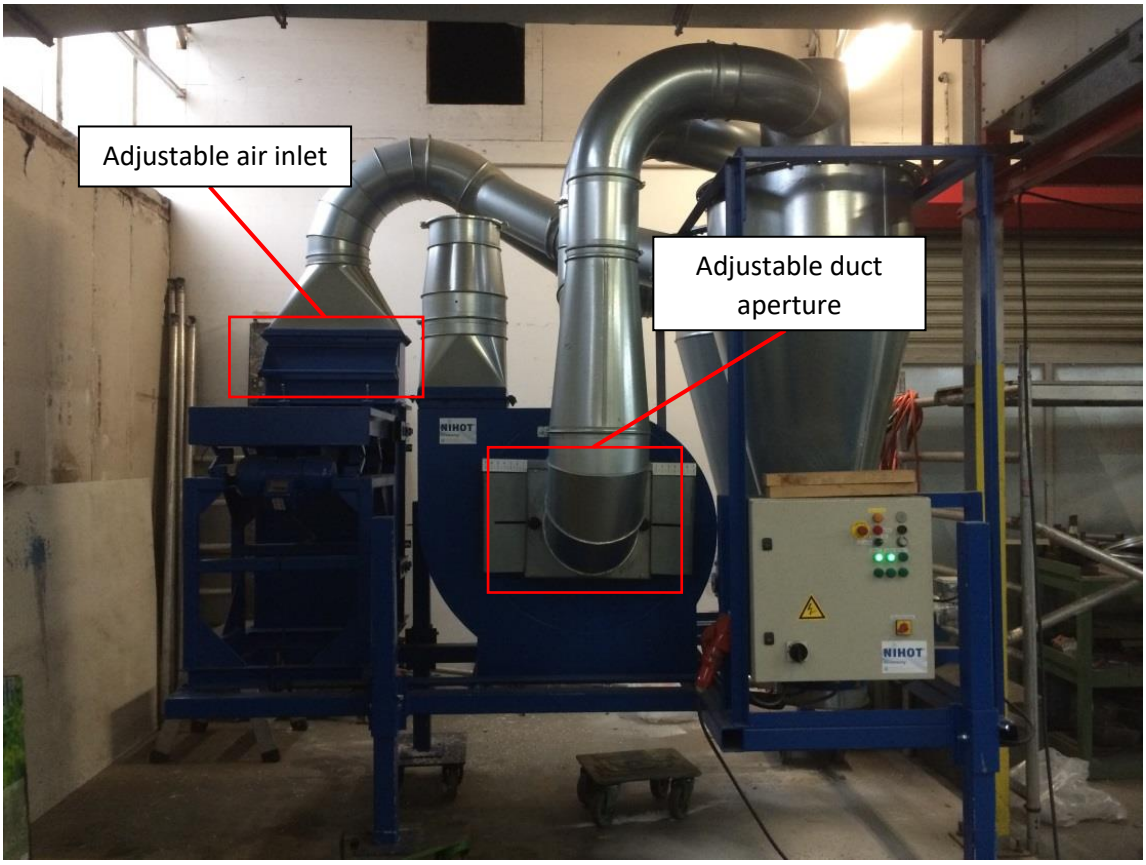


Figure 3-9 Nihot® laboratory setup

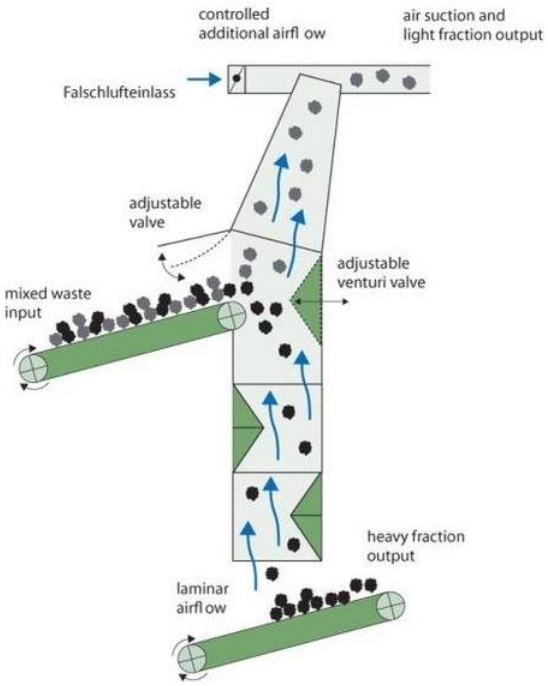


Figure 3-10 Nihot® WS-Z zigzag shifter

3.7.2.1 Method – Nihot® air classification

Firstly, a starting point (in terms of air flow) was established by passing small amounts of material through the classifier and examining the product fractions. Slight adjustments were then made to achieve a cut point at around 0.8mm. 1/3 of the mixed sample (≈6 kg) and 1/3 of the 5 to 11 mm screened sample (≈ 6 kg) was then processed by the air classifier to produce two products for each sample.

By adjusting the air flow duct aperture to increase the air velocity, the test was repeated cutting the material at approximately 1 mm. By adjusting the air flow duct aperture to reduce the air velocity, the test was repeated cutting the material at approximately0.6 mm. Once all tests were completed, each sample bag was weighed to determine the mass ratio of the product fractions.

Using the sample splitter, a small sample from each sample bag was collected and labelled for thickness distribution measurements. Using the Vernier calipers, each flake from thickness sample was measured to determine the thickness distribution corresponding to each fraction. Measuring the thickness distribution of each fraction was important for generating the separation curves.

3.7.3 Herbold® SZS air classifier

The Herbold® air classifier setup was somewhat different to the Nihot® setup (see Figure 3-11); the zigzag separation chamber was much taller than the Nihot® system's chamber. The Herbold® system was also powered by two fans; one fan induced the air flow through the chamber with the other fan being used to feed material into the zigzag chamber. In this case material was fed into a rotary air separator (cyclone) by means of a fan which then fed into the zigzag chamber (see Figure 3-12). See appendix 5 for more images.

Figure 3-11 Herbold® SZS 630/212 Air classifier

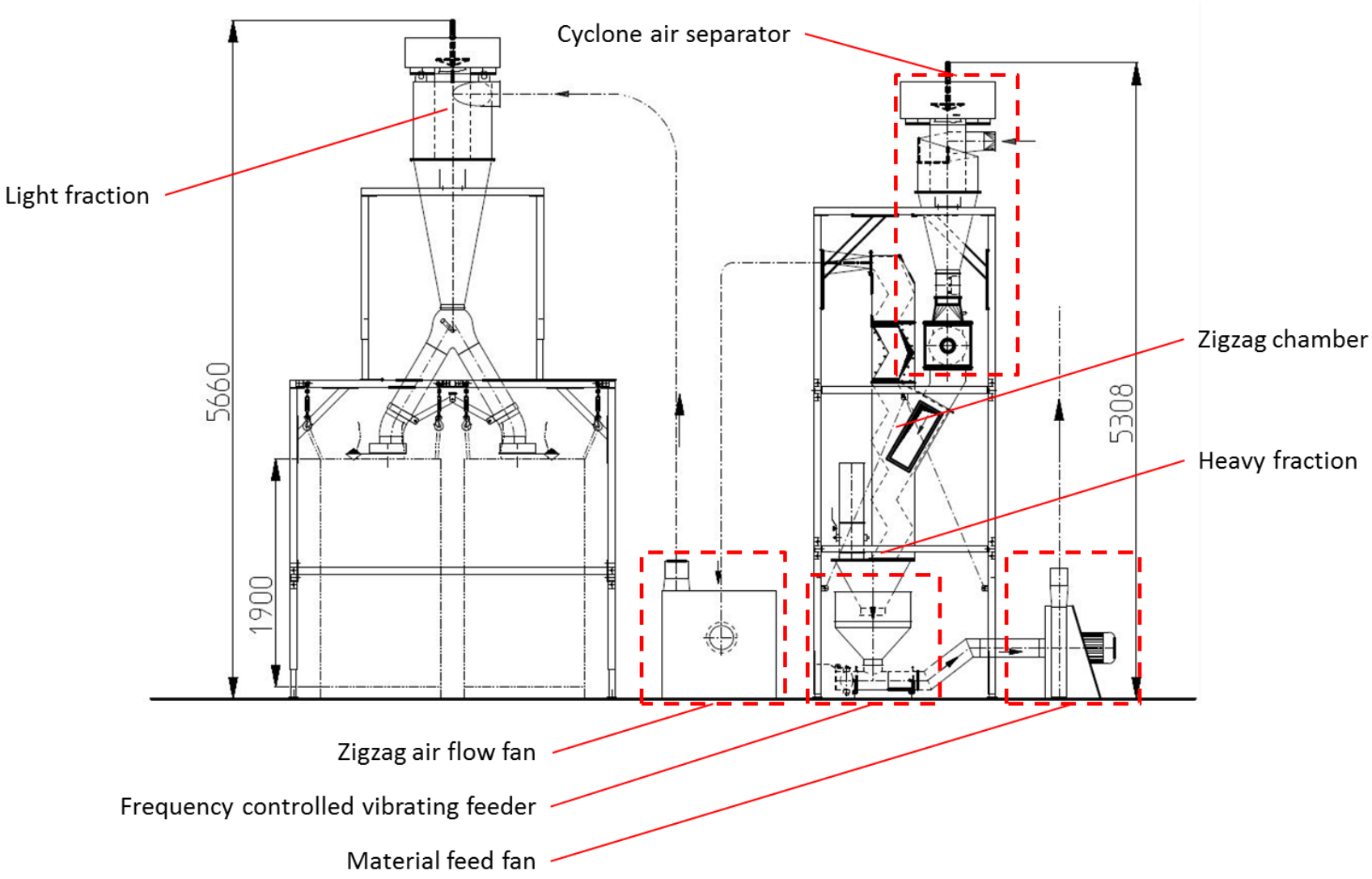


Figure 3-12 Herbold® SZS 630/212 engineering drawing

The focus of testing on the Herbold® system was to determine if a taller zigzag air classifier would result in a better separation of the material. In addition, since it was possible to adjust the material feed rate, the effect of feed rate on separation was also investigated.

3.7.3.1 Method – Herbold® air classification separation efficiency

Before processing each sample, a starting point was estimated. A few handfuls of mixed material were fed into the air classifier at specific valve and aperture settings. Each fraction was then measured to determine if the settings corresponded to an acceptable cut point (wall thickness range). This was repeated several times; each time adjusting the fan frequency settings, until the desired cut point was achieved (between 0.8-1mm).

Each sample (20 kg[16]) was then processed with the same settings rendering a light and heavy fraction for each sample. Once all tests were completed, each sample bag was weighed to determine the mass ratio of the product fractions for each test.

Using the sample splitter, a small sample from each sample bag was collected and labelled for thickness distribution measurements. Using the vernier calipers, each flake from each thickness sample was measured to determine the thickness distribution corresponding to each fraction. The material from the testing phase at Herbold® was then saved for further laboratory analysis.

3.7.4 Herbold® feed rate assessment

3.7.4.1 Method – Feed rate study

To determine the effect of feed rate on separation efficiency the fan frequency settings were kept constant. A fraction of the test material was then fed into the system at a feed rate of100 kg/h. This was then repeated at a feed rate of 900 kg/h with the fan frequency settings as they were in for the first test.

Once all tests were completed, each sample bag was weighed to determine the mass ratio of the product fractions for each test. Using the sample splitter, a small sample from each sample bag was collected and labelled for thickness distribution measurements. Using the Vernier calipers, each flake from each thickness sample was measured to determine the thickness distribution corresponding to each fraction.

3.8 Alternative separation method - Ballistic separation

An alternative to air separation with zigzag type air classifiers is ballistic separation. Ballistic separation is not a conventional separation method used for plastic flake material, but has shown potential in terms of separation based on mass and geometric profile. For the purposes of this study a simple, laboratory scale ballistic separation setup was used to determine the effectiveness and efficiency of separating plastic flake material in comparison with traditional zigzag classifier systems (see Figure 3-13).

The principle of separation is the exploitation of each particle's ballistic trajectory as defined by its mass and geometric profile (see section 2.7.5 for mathematical explanation). Material is fed onto the vibrating screen[17] and gains momentum as it moves down the ramp under the force of gravity. The

[16] 20 kg had to be processed to ensure that there was enough material from each fraction for further laboratory testing

[17] The vibrating screen ensures the feed rate is kept constant and also to ensure that material is spread evenly over the Aluminium ramp.

ramp is fixed at an angle with the bottom edge curved to impart velocities in the vertical and horizontal directions. As the particles leave the ramp they are acted upon by the forces of gravity and air resistance meaning that the heavier (thick-walled) particles tend to travel further than the lighter (thin-walled) particles.

Included in the study is the use of a fan as an air knife to improve the sharpness of separation. The fan is placed close to the trajectory of the particle's leaving the ramp and it set at a given air velocity to impart an impulse force vector on each particle as it passes the fan (Figure 3-14). Both configurations were investigated; with and without the air knife.

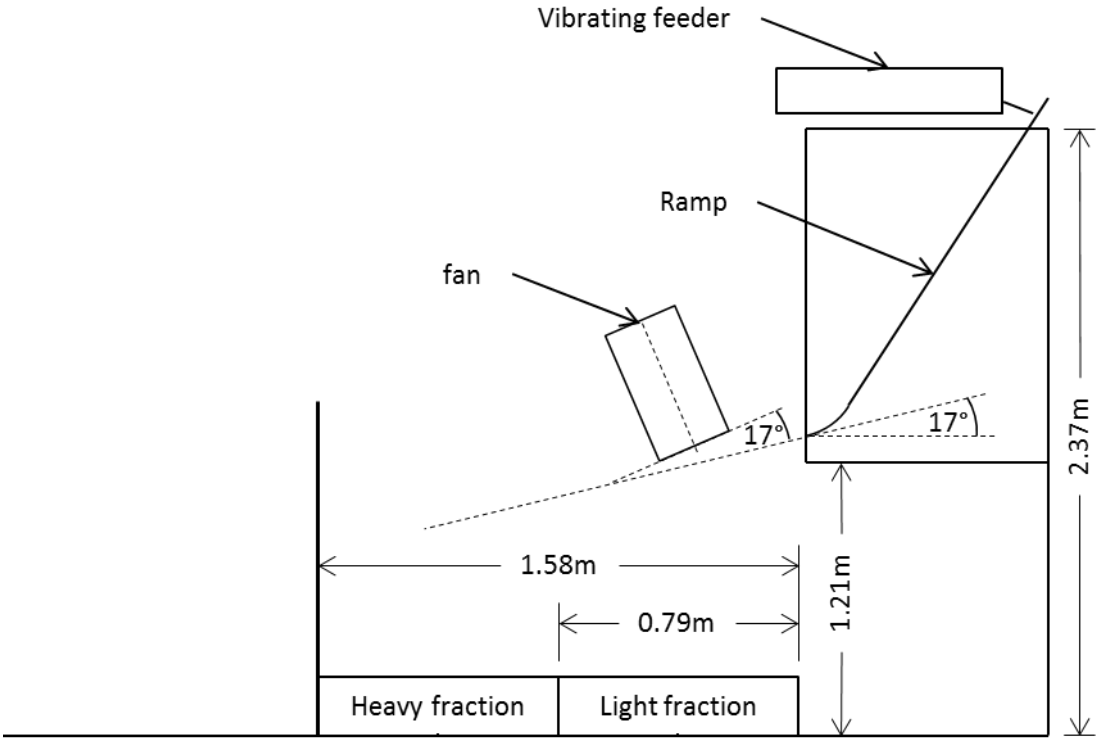
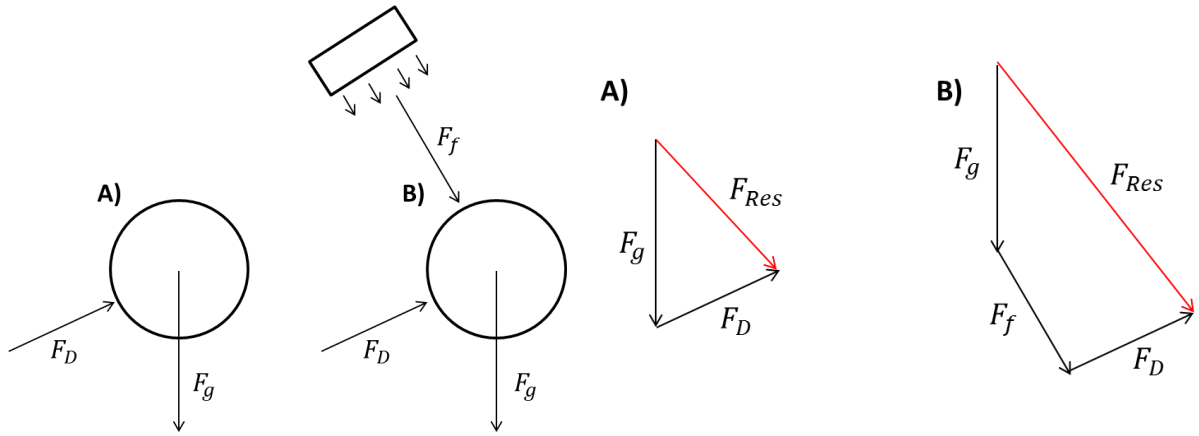


Figure 3-13 Ballistic separator setup



Free body diagrams A) no fan B) with fan **Balance of forces A) no fan B) with fan**

Figure 3-14 force diagrams

3.8.1.1 Method – Ballistic separation

Firstly, the ballistic setup was arranged to represent the dimensions as shown in Figure 3-13. The plastic trays were positioned accordingly with foam boards placed along each edge to ensure no material falls outside of the trays (see Figure 3-15).

Ballistic separator with air knife in place **Foam board barriers**

Figure 3-15 Ballistic setup

Approximately 2 kg of material was then placed onto the vibrating screen. The vibrating screen was set at a frequency that fed material slowly and evenly over time to minimize the effect of particle interactions on separation (as stated in the literature review – Section 2.8.3.2). Once all the material had been fed through the system each fraction (light and heavy) was collected and weighed. Using the sample splitter each fraction was then split down to a manageable size ready for thickness distribution measurements. This was then repeated with the air knife turned on.

3.9 Material property measurements

Part of the investigation involves measuring the mechanical and melt flow properties before and after air classification to determine whether or not the melt flow and mechanical properties of each material improved or worsened.

The measurement of the various material properties was conducted on material samples from the two proposed processing scenarios: air classification before MDS processing (Figure 1-6), and air classification after MDS processing (Figure 1-7).

In total, seven samples were tested for its mechanical and rheological properties (Highlighted in grey in the above figures)

- Mixed material (control sample)
- Mixed, air separated material (pre-MDS material separated into two fractions)
- PP, air separated material (post-MDS material separated into two fractions)
- HDPE, air separated material (post-MFD material separated into two fractions)

The mixed material represents the control sample. It provides information about the composition, mechanical and rheological properties of the recyclate before any processing and upgrading has taken place. By comparing the results from the measurements of all other samples it makes it possible to determine by what degree the recyclate has been upgraded or downgraded in terms of composition and rheological properties for each of the two scenarios outlined in Figure 1-6 and Figure 1-7. Complimentary to determining how the main research question is answered (is it possible to improve the melt flow properties of a recyclate by separating it into two fractions: a thin-walled fraction and a thick-walled fraction), results will also shed some light on the optimum process configuration.

3.9.1 Test sample preparation – Injection moulding

In order to understand each sample's mechanical and melt flow properties the flake material from each sample had to be processed into standardized, homogeneous test bars suitable for further analysis. Injection moulding involves melting and homogenizing the polymer mix in the heated chamber of the injection moulding machine before it is injection moulded into test bars. A representative sample of more than 2 kg is needed in order to produce test bars that are homogeneous and without voids or other defects.

3.9.1.1 Materials and equipment

The test bars were injection moulded using the Arburg Allrounder® 320 S 500-150 injection moulding machine (see Figure 3-16) fitted with a die machined with the profile of the desired test samples (one tensile and one impact specimen). The relevant technical specifications of the machine include:

Figure 3-16 Arburg Allrounder® 320 S 500-150 injection moulder

In order to produce 25 homogeneous test samples, 2 kg of each sample had to be prepared for injection moulding to ensure that the material was properly homogenized inside the barrel of the machine.

3.9.1.2 Method

Injection moulding each sample into test bars is a straightforward process. Material is simply fed into the hopper where it then feeds into the heated barrel. A combination of heat, friction and pressure ensures that the polymer melt mixes effectively creating a homogeneous melt (see Figure 3-17). Each discrete cycle produces a single tensile specimen and a single impact specimen (see Figure 3-18).

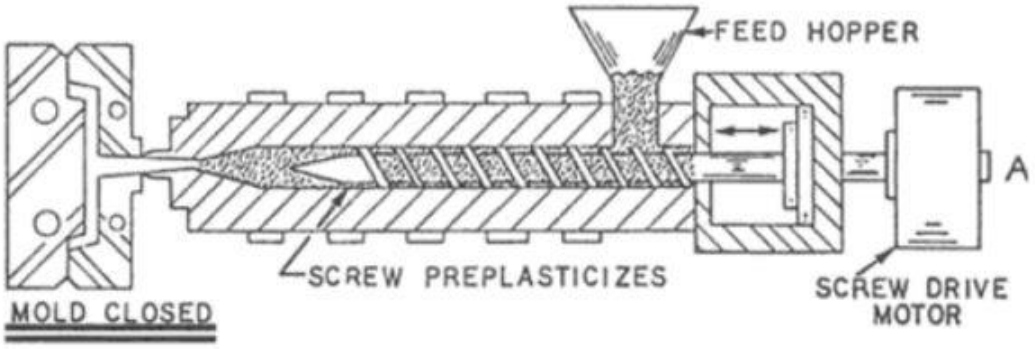


Figure 3-17 Typical injection moulder configuration (source: (Rosato and Rosato, 2000)

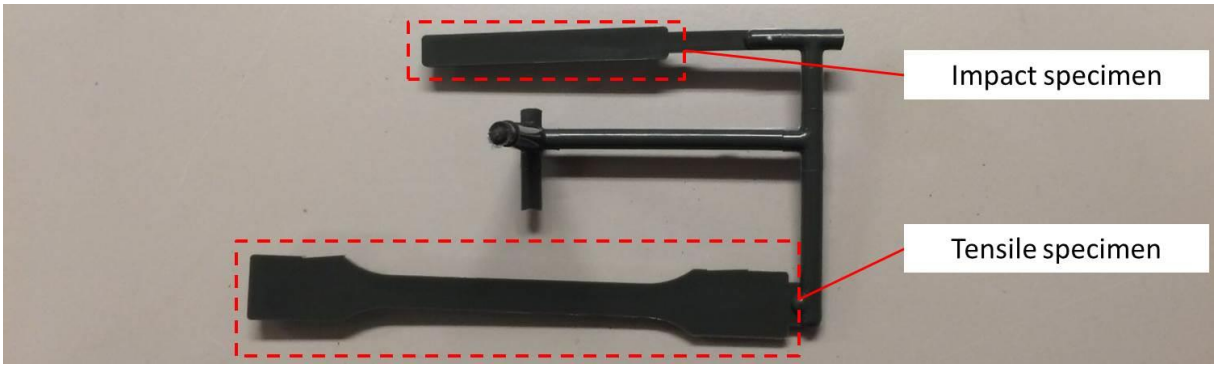


Figure 3-18 Injection moulded tensile and impact specimen

Once all the parts have been moulded they need to be stored in a temperature controlled environment, where the temperature was kept constant at 21°C, for a period of three days. This is done to ensure that morphology of the polymer has stabilized (it continues to crystalize even after it has cooled to room temperature). Once it has rested the specimens may be used for testing.

3.9.2 Tensile properties

Tensile testing was conducted on each sample to determine the mechanical properties of the material. The test determines the:

- Elastic modulus
- Yield strength
- Ultimate tensile strength
- Maximum tensile strain
- Strain at yield

These material properties are important for manufactures for the purposes of product design and manufacturing.

3.9.2.1 Materials and equipment

Tensile tests were conducted in compliance with ISO 527-2 Type 1a. The tensile tests were done using an Instron® 5565 electromechanical testing system (see Figure 3-19) using an extensometer to carefully measure the strain during elastic deformation. Three uniform, defect free tensile samples were chosen from each batch for tensile testing. The extensometer used was an Instron® axial clip-on extensometer. The tests were conducted at 23 °C.

Figure 3-19 Instron® 5565 Electromechanical tensile tester

3.9.2.2 Method

To carry out the tensile tests a test bar is first placed in the hydraulic grips of the system. The extensometer is then clipped onto the specimen. The process is then activated; the hydraulic grips then begin to pull the specimen apart at a testing speed of 50 mm per minute.

When the strain reaches 2.5% of the 100 mm gauge length the process stops to allow the operator to remove the extensometer. The extensometer must be removed to prevent damaging it at strain rates higher than its maximum strain of 2.5%. The operator then reactivates the system to continue the test. The sensors coupled to each hydraulic grip continue to measure the strain and tensile force until the specimen fractures or reaches a maximum predefined strain (most polymer samples do not fracture). The information is recorded and stored in PDF and .csv format.

3.9.3 Impact testing

Impact testing was carried out in compliance with ISO 179-1. The preferred impact test in Europe is the Charpy impact test. The Charpy impact test is undertaken by breaking a test specimen using a weighted pendulum. The energy taken to break the specimen is measured by taking the height difference between the height of the pendulum after an impact before and after impact (taking friction losses into account – see Figure 3-20). The specimen has a notch machined into it that acts as a stress concentrator allowing a crack to propagate in the transverse direction (see Figure 3-21).

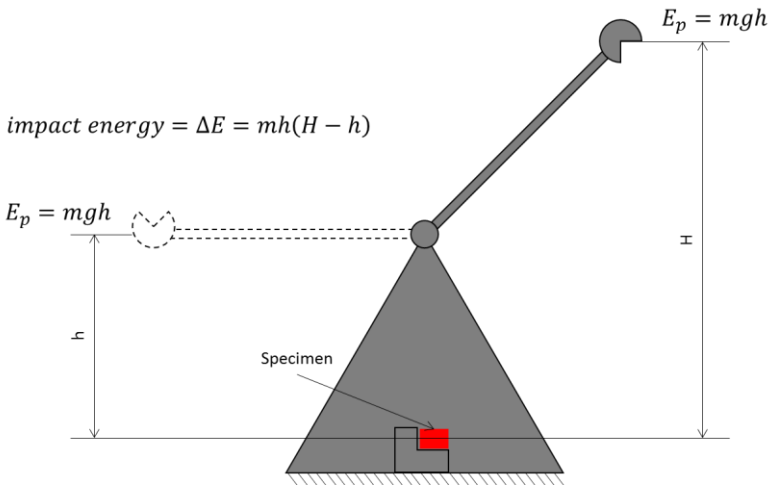


Figure 3-20 Charpy impact energy calculation

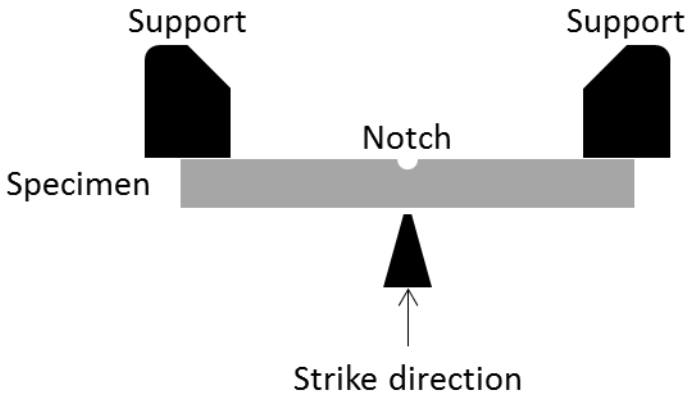


Figure 3-21 Charpy impact specimen

3.9.3.1 Materials and equipment

To carry out the impact tests an Instron® CEAST 9050 impact pendulum was used (see Figure 3-22). Test bars that were injection moulded along with the tensile specimen are then prepared (machining the notch) according to ISO 179-1 (International Organisation for Standardization).

3.9.3.2 Method

The first step is to set up the Instron® pendulum in its primed position. The test specimen is then placed on top of the supports, ensuring that the notch is aligned equidistant from each support (see Figure 3-23). Once the specimen is in place the pendulum can be dropped. The impact energy can then be read off directly from the machine.

Instron® CEAST 9050 Impact pendulum

Figure 3-22 Impact test equipment

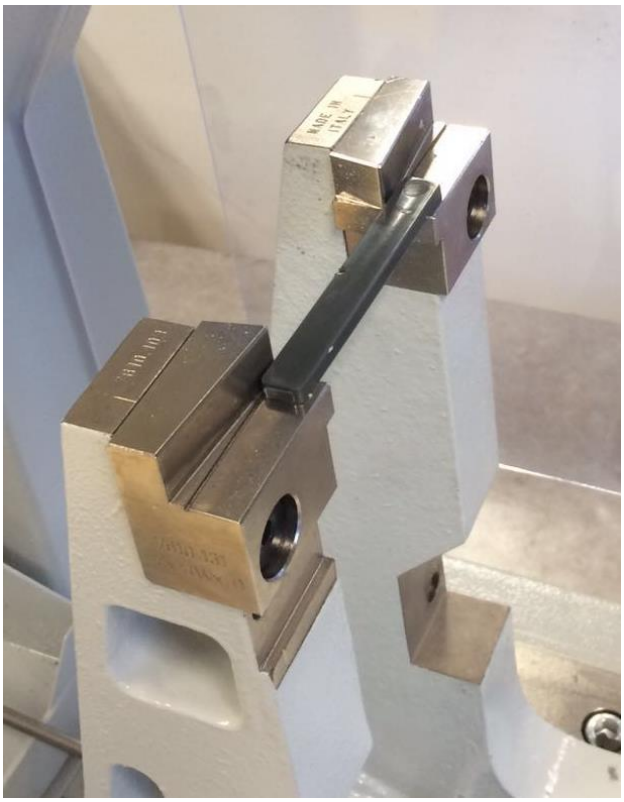


Figure 3-23 Impact specimen in place

3.9.4 Melt Flow Rate test

Melt Flow Rate (MFR) testing was undertaken in compliance with ISO 1133. The test involves heating the sample (190 °C for polyethylene and 230 °C for polypropylene) and forcing it through a standard sized orifice under a weight (usually 2.16 kg, depending on the type of plastic). The rate at which the polymer is forced through the orifice is termed the Melt Flow Index (MFI) with units, g/10 min.

3.9.4.1 Materials and equipment

The system used to measure the MFR properties of each sample was the Göttfert® Modell MP-D (see Figure 3-24). It is an automated MFR measuring device that complies to ISO 1133 testing standards (Shenoy and Saini, 1986). The samples used are either tensile or impact test bars that have been cut into pieces in order for them to fit into the system.

Figure 3-24 Göttfert® Modell MP-D MFR test machine

3.9.4.2 Method

Firstly, the system needs to be set up according to what sample is being tested. For polypropylene the temperature is set to 230 °C and for polyethylene the temperature is set to 190 °C (according to ISO 1133). The mass of the weight is 2.16 kg. Once the system has been configured correctly the test material is place in the system. It should be given enough time to melt completely. Once the material is completely melted the weight can be dropped (the machine is automated and does this automatically). The material then flows through the orifice; the machine then takes samples at a given time interval (see Figure 3-25). The average of the results is then taken as the MFR of the sample. The mixed and the air separated material was tested at both temperatures as it is a mixture of polyethylene and polypropylene.

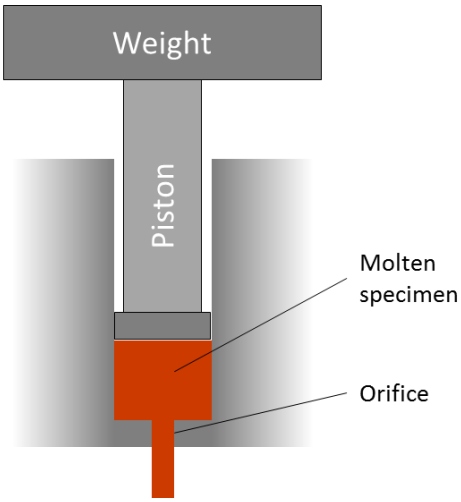


Figure 3-25 MFR test system

3.9.5 Differential Scanning Calorimetry test

DSC (differential Scanning Calorimetry) is a thermal analysis technique that looks at how a samples heat capacity changes with a change in temperature; keeping the temperature constant (over different temperature ranges between 20°C and 200°C) allows the heat flux through the sample to be accurately measured. This, coupled with the understanding of the enthalpies of different materials allows the user to determine the purity of different material fractions in the sample. DSC in this case is used to measure the amounts of polypropylene and polyethylene in each sample. The heat rate chosen was 10°C/min and the sample size was 10 mg.

3.9.5.1 Materials and equipment

To conduct the DSC analysis a Mettler Toledo® DSC822 machine was used (see Figure 3-26). Small amounts of each sample were tested to determine its composition according to ISO11357.

3.9.5.2 Method

The first step was to prepare a small amount of material from each sample to be analyzed by the DSC machine. This was done by cutting a small piece of material from one of the spare tensile or impact samples and placing it in a metal crucible. The crucible is then placed in the DSC machine. The machine then heats up the crucible and measures the amount of energy passing through the sample.

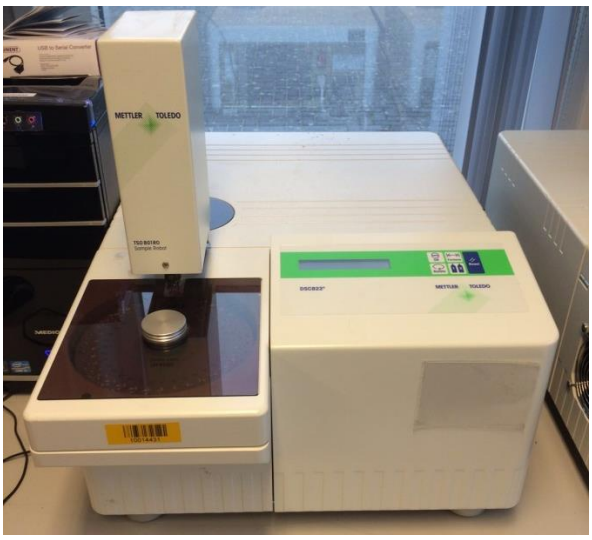


Figure 3-26 Mettler Toledo® DSC822

CHAPTER 4

4 Results and discussion

The results and discussion section presents the results from all the tests described in Chapter 3. Sections 4.1 to 4.4 describe and discuss the physical characteristics of the different material samples; the measurements are unique to this report and are not compared with any literature. Sections 4.5 to 4.7 present and discuss the results from the air classification and ballistic separation tests. The performance results for each setup are compared with findings from other studies (described in the literature review). Section 4.8 presents and discusses the results from the mechanical property and melt flow measurement tests. The results are compared with the properties of related polymers discussed in the literature. The final section (4.9) presents and discusses the current and future process configurations based on the findings from the research.

4.1 Size measurements

This section presents and discusses the results of the size measurement tests. Table 4-1 describes the mass of each size range as a percentage of the total mass for each sample discussed in section 3.4.2.

Table 4-1 Size measurement results

	Mixed sample	**Mixed sample (<10 mm)**	**HDPE BM grade**	**PP IM grade**	**HDPE BM + IM grade**
$\mathbf{0-5\ mm}$	11%	29%	10%	14%	6%
$\mathbf{5-11\ mm}$	50%	70%	54%	60%	76%
$\mathbf{>11\ mm}$	39%	1%	36%	26%	18%

The table shows that the mixed sample contained a large fraction of material above a nominal size of $11\ mm$. This was an important finding as both density separation and air classification are impacted by the flake size of the material. The MDS system requires flakes to be below $12\ mm$ in order to prevent blockages throughout the system. This result was anticipated; the $20\ tonne$ mixed sample was subsequently screened (using a rotary screen with a 10 mm round mesh) to remove the large material fraction. The oversized material was then re-shredded and mixed back into the sample to avoid changing the composition of the sample (mixed sample, 10 mm).

Table 4-1 shows that that the majority of the material is in the size range between 5 mm and 11 mm. Re-shredding the material increased the 0-5 mm fraction by almost 20 %; A possible reason for this is the fact that PP is usually a more brittle polymer than HDPE and tends to fracture into small pieces when shredded (Ghosh, 2001). The material was also passed a few times through the shredder and the rotary screen to ensure that all the material was correctly sized. Each time the material was shredded small pieces of brittle material broke away from the larger flakes.

The results also show that if the material were to be screened for air classification purposes, the ratio would be as follows (see Figure 4-1):

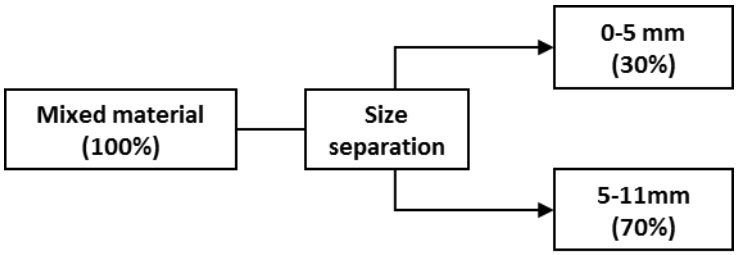


Figure 4-1 Size separation mass ratio

Screening the material into more than one fraction means that each fraction would have to then be processed in batches. This has implications for the process as a whole as provisions would need to be made for the storage of each fraction before it is processed.

The table also shows the particle size distribution of each of the individual components of the mixed material (HDPE BM grade, PP IM grade and HDPE BM + IM grade).

4.2 Thickness measurements

The thickness measurement results for each sample are shown on individual histograms in the subsections that follow (see section 3.4 for a description of each sample).

4.2.1 Mixed sample thickness distribution

Figure 4-2 provides a clear description of the wall thickness distribution of the mixed sample. The distribution is positively skewed as less and less material is measured as wall thickness increases. As a result, the majority of particles from the sample have a wall thickness somewhere between 0.5 and 1.2 mm. This accounts for 64% of the material which is a mixture of blow and injection mould grade material (see Figure 2-16 for more information). With reference to all four charts, if separation is carried out at a wall thickness of approximately 0.9 to 1.0 mm the result would be a mixed fraction of blow mould (BM) and injection mould (IM) material (0.0 to 0.9 mm) and an IM rich fraction (> 0.9 mm).

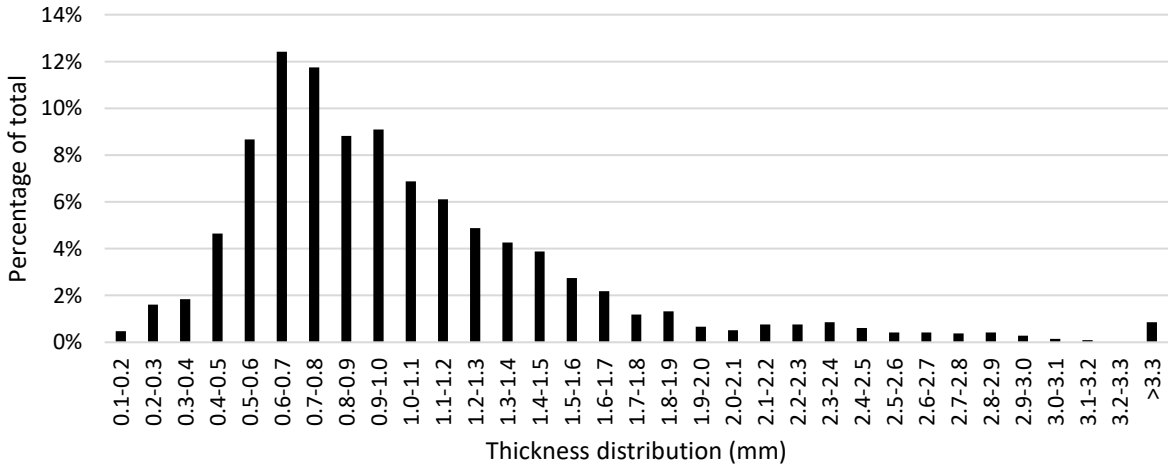


Figure 4-2 Mixed sample wall thickness distribution

4.2.2 HDPE blow mould grade sample thickness distribution

Figure 4-3 shows the results from the measurement conducted on the HDPE BM grade material. What is interesting is that the material wall thickness distribution is narrower and symmetrical compared to the mixed sample thickness distribution. It is a useful result because it reinforces the statement that the BM materials are generally thin-walled. The fraction above 1.1 mm is most likely material from the bottle caps; the bottle caps are injection moulded and tend to have a thicker wall thickness than the bottle itself. The fraction > 1.1 mm makes up approximately 13% of the total sample.

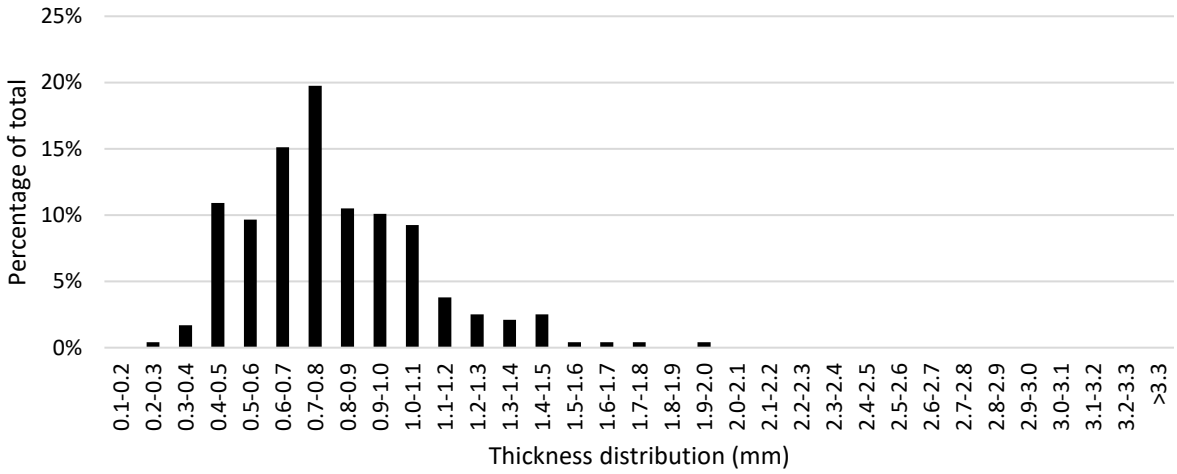


Figure 4-3 HDPE BM grade sample wall thickness distribution

4.2.3 PP injection mould grade sample thickness distribution

Figure 4-4 shows the results from the measurement conducted on the PP IM grade material. The wall thickness distribution for this sample is spread over the entire thickness range and has a flatter profile compared to the mixed sample thickness distribution. In this case, the majority of the material lies somewhere between 0.6 and 1.6 mm and accounts for 72% of the total sample. This result is also useful because it shows injection mould grade material is spread over a wider thickness range. Using the information found in the previous subsection it is clear that it will not be possible to create a very good quality blow mould material; the thickness distributions of BM and IM grade material between 0.0 and 1.0 mm overlap significantly.

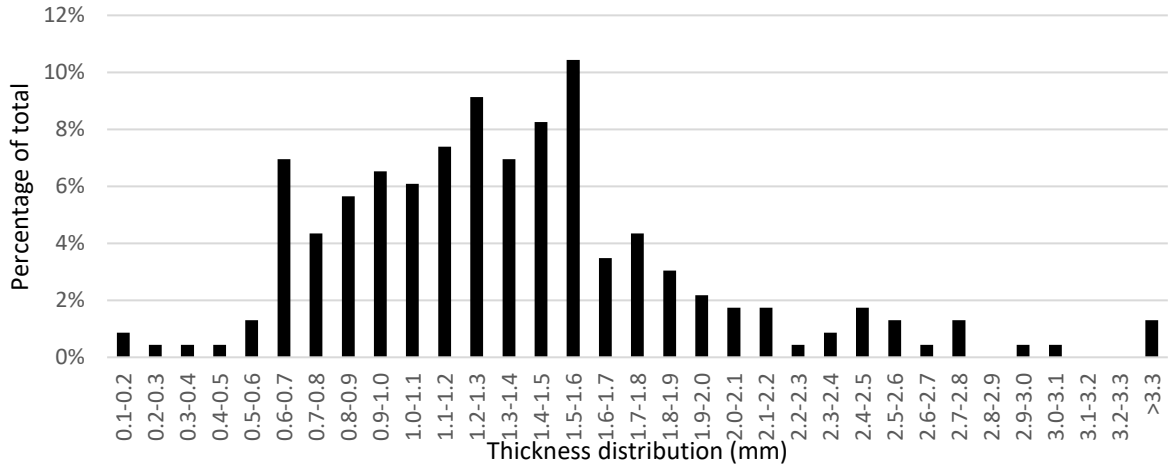


Figure 4-4 PP IM grade sample wall thickness distribution

4.2.4 HDPE blow mould and injection mould grade sample thickness distribution

Figure 4-5 shows the results from the measurement conducted on the HDPE BM and IM grade material. Again, the wall thickness distribution is spread over the entire thickness range with the majority (72%) of the material having a wall thickness > 1.2 mm. Unfortunately, it is difficult to draw any substantial conclusions from this chart because the ratio between IM and BM grade material in this sample is unknown.

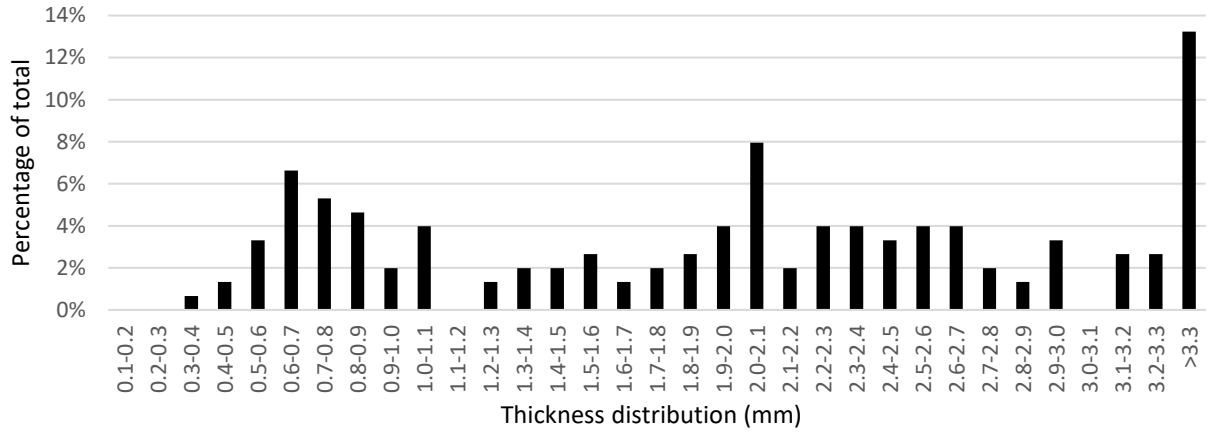


Figure 4-5 HDPE BM & IM grade sample wall thickness distribution

4.2.5 Correlation between wall thickness and polymer type

Figure 4-6 shows the composition of the material corresponding to wall thickness. The chart shows that the material, up to a wall thickness of approximately 2.4 mm, is a fairly even mixture of PP and HDPE. There is also a small amount of polystyrene (PS) in the thin walled fractions of the sample. The material above a wall thickness of 2.4 mm is predominantly HDPE and is probably material from the HDPE IM and BM fraction of the mixed sample. Because there is material in this fraction that is mostly likely BM grade material, it could make sense to remove it from the mix to increase the purity of the IM fraction.

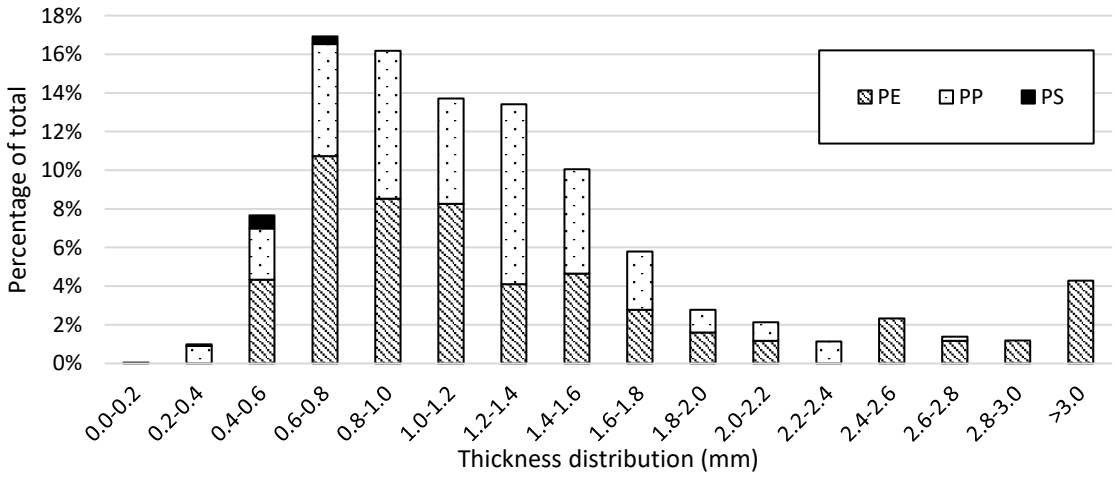


Figure 4-6 Correlation between wall thickness and polymer type

4.3 Density measurements

The density range measurements for each sample are shown in Table 4-2 (refer to section 3.5.3 for an explanation of the different density ranges). The results are given as a percentage of the total mass of each sample. Looking at the HDPE BM grade sample measurement, the results indicate that there is a small amount of PP material (8%) in the mix. This is most likely the PP injection moulded bottle caps that are not removed by the hand sorters. If this material was to be sorted separately using an air classifier (as discussed in section 4.2.2) it could be possible to remove the PP IM grade material creating a very good quality BM product.

Another interesting result is the HDPE content in the PP IM grade product. It seems that food containers are mostly manufactured from PP but a small number of products (14%) are manufactured from HDPE. Unfortunately, this would be difficult to remove from the PP IM grade product because the wall thicknesses of the PP and HDPE containers are the same (see Figure 4-6).

Table 4-2 Density range measurements

Density (kg/m^3)	Mixed sample	HDPE BM grade	PP IM grade	HDPE BM + IM grade
$\rho < 920$	37%	8%	83%	3%
$920 < \rho < 920$	2%	1%	3%	1%
$\rho > 930$	61%	91%	14%	96%

4.4 Settling velocity measurements

The results from the settling velocity experiment are shown in Figure 4-7 below. The chart shows the settling velocity increases as the thickness of the material increases. The results also suggest that the size and shape of the particle does not have, in this case, too much influence on the settling velocity of each particle. Furthermore, Figure 4-7 points out that the settling velocity is fairly sensitive to the wall thickness of the material. It is an important finding with regards to air classification because it suggests that a sharp separation is possible.

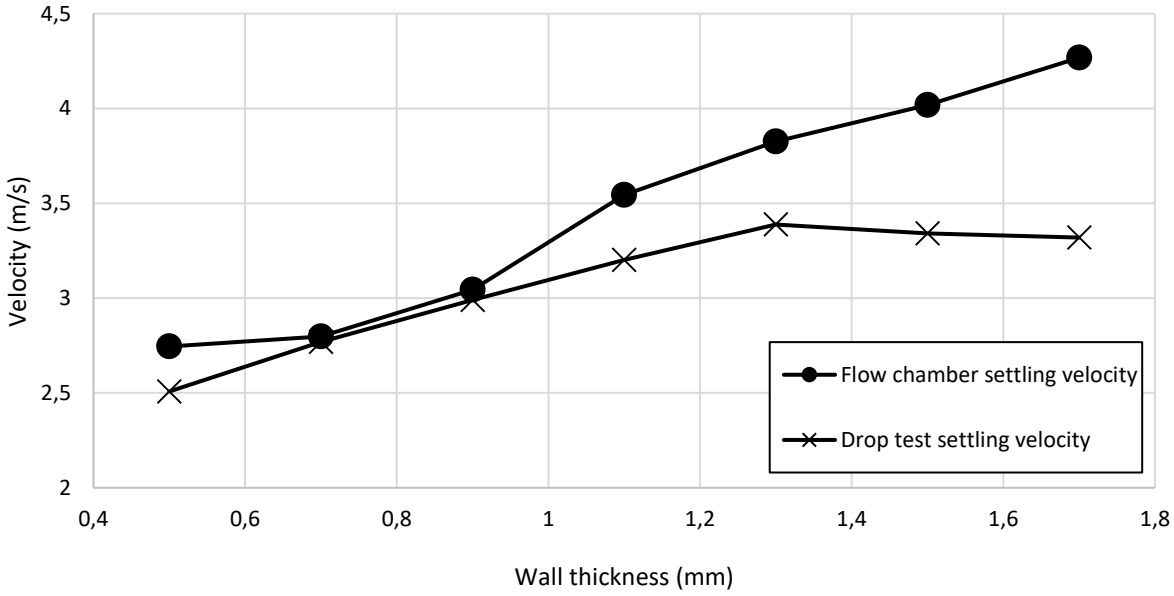


Figure 4-7 Settling velocity experiment

4.5 Air classification

4.5.1 Nihot® air classification

The results from testing the material on the Nihot® system are discussed below.

The mass measurements of each fraction from the air classification test describe the ratio between heavy (thick-walled) and light (thin-walled) fractions.

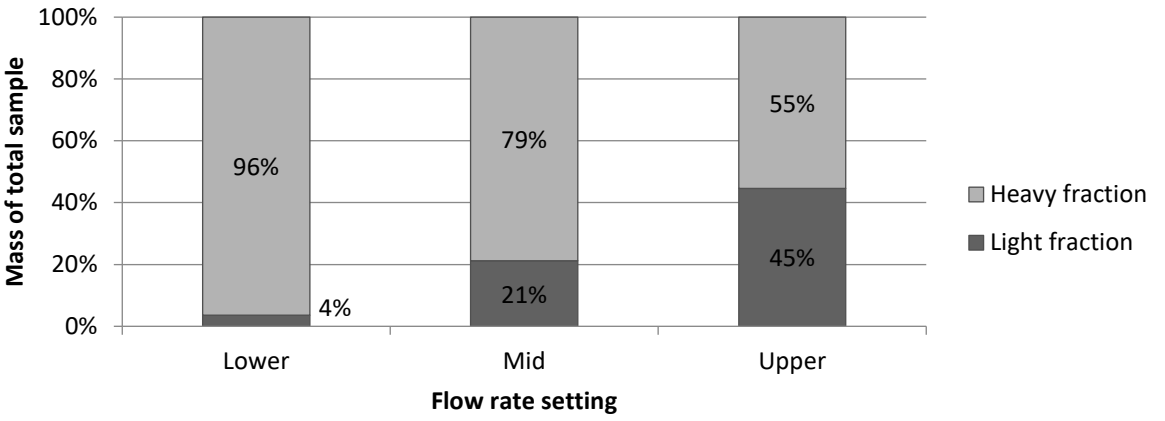


Figure 4-8 Mass fractions (mixed material)

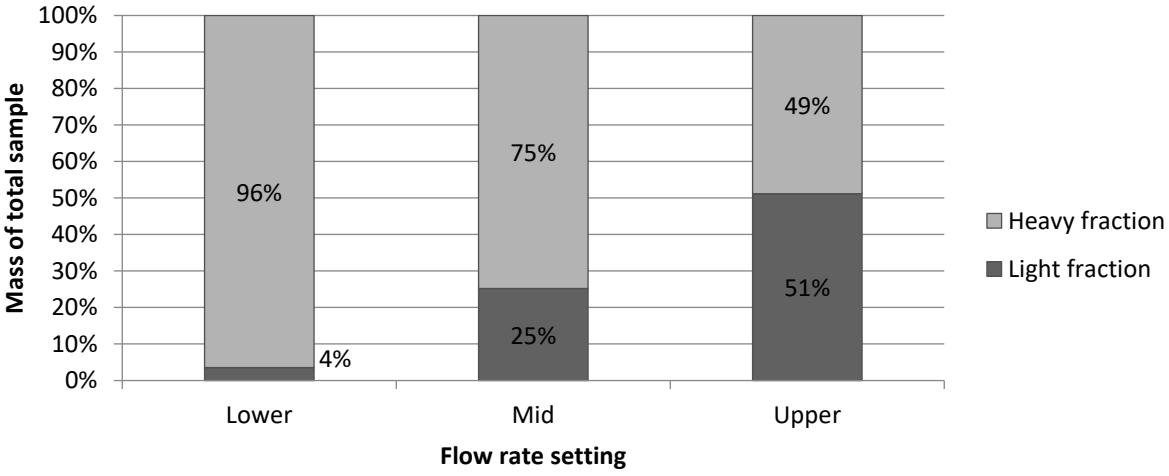


Figure 4-9 Mass fractions (mixed material – 5 – 11 mm)

The recovery curves in Figure 4-10 illustrate the relative performance of the classifier at the three different air flow velocities.

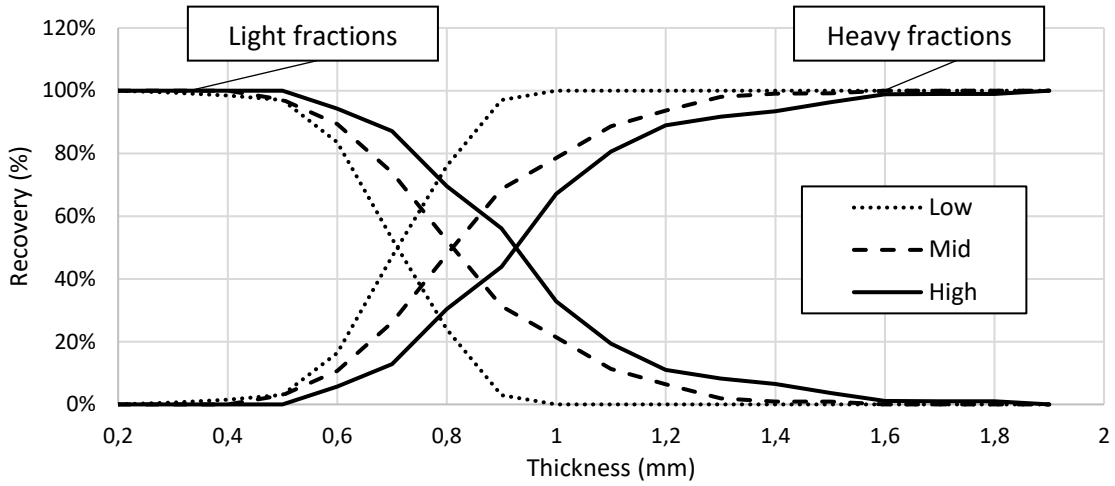


Figure 4-10 Recovery curves (Mixed material)

In addition to the measurement of the air classifiers performance, the charts point out the d(50%) cut points (shown in Table 4-3). Please see section 2.8.3.3 for information regarding the calculation of the sharpness index. Section 2.8.3.3 provides information regarding the calculation of the sharpness index.

Table 4-3 Mixed material cut points and sharpness indices

Test	Cut point (mm)	Sharpness index, *S*
Low	0.71	0.79
Mid	0.81	0.72
High	0.93	0.70

Figure 4-11 shows the recovery curves for the separation tests conducted on the mixed material that was screened (5-11 mm).

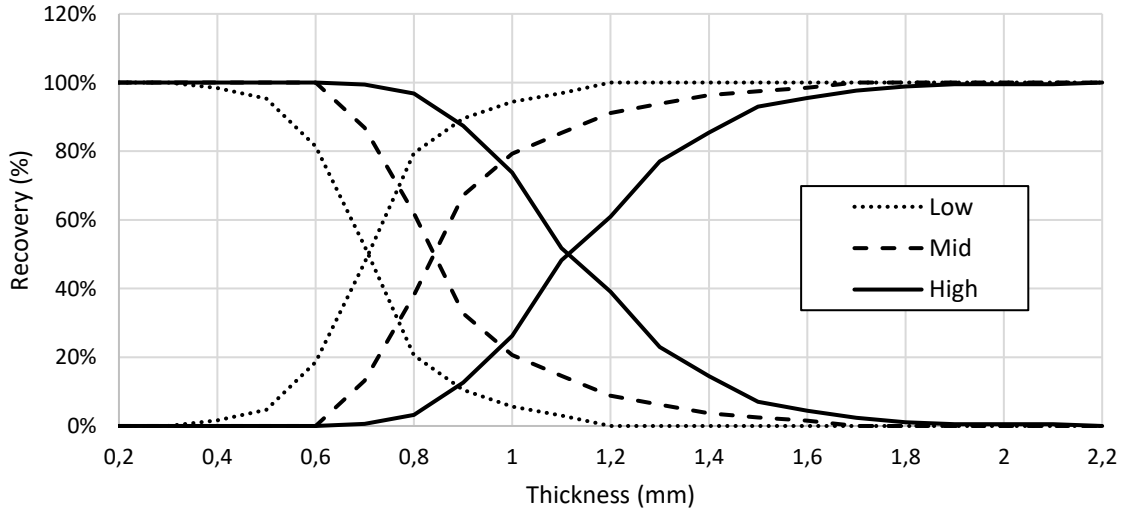


Figure 4-11 Recovery curves (mixed, 5-11 mm)

Table 4-4 provides the cut point and sharpness index information relating to the air classification experiment conducted on the mixed, screened (5-11 mm), material sample.

Table 4-4 Mixed (5-11 mm) material cut points and sharpness indices

Test	Cut point (mm)	Sharpness index, *S*
Low	0.71	0.79
Mid	0.84	0.77
High	1.11	0.76

The air classification tests conducted on the Nihot® system yielded good performance results. It is quite clear that separation of the rigid plastic material based on wall thickness is possible. The sharpness indices indicate that good separation was achieved (take note that a sharpness index of 1 represents perfect separation – practically not achievable). The results also suggest that the system has the ability to achieve satisfactory separation efficiencies; the sharpness indices from the tests lie between 0.79 and 0.70. Classifiers in general tend to have sharpness indices anywhere between 0.5 and 0.8.

In terms of the mass ratios between the two fractions (see Figure 4-8 and Figure 4-9) the results show that the mass ratio shifts as the air flow rate increases. Focusing on the separation curve sharpness indices the results suggest that sharpness efficiency decreases slightly as air flow rate increases; an increase in turbulence possibly has an influence on the efficiency of an air classifier. The more turbulent the air flow the lower the separation efficiency of an air classifier.

Comparing the tests conducted on each material, the results show that sieved material does not translate into improved separation efficiencies, however, screening the material does shift the separation cut point when comparing the high air flow rate tests.

4.5.2 Herbold® air classification

The results from testing the material on the Herbold® system are discussed below.

The mass measurements describe the ratio between heavy (thick-walled) and light (thin-walled) fractions for each test and can be seen in Figure 4-12 and Figure 4-13. The chart shows the fraction of total material that ended up in the thick and thin walled fractions.

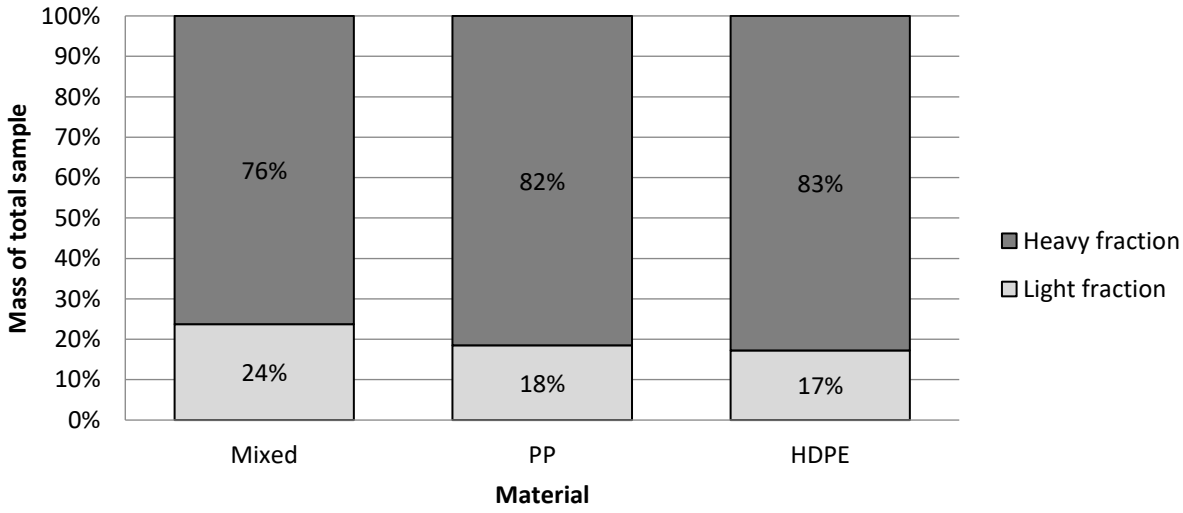


Figure 4-12 Herbold® testing mass measurements

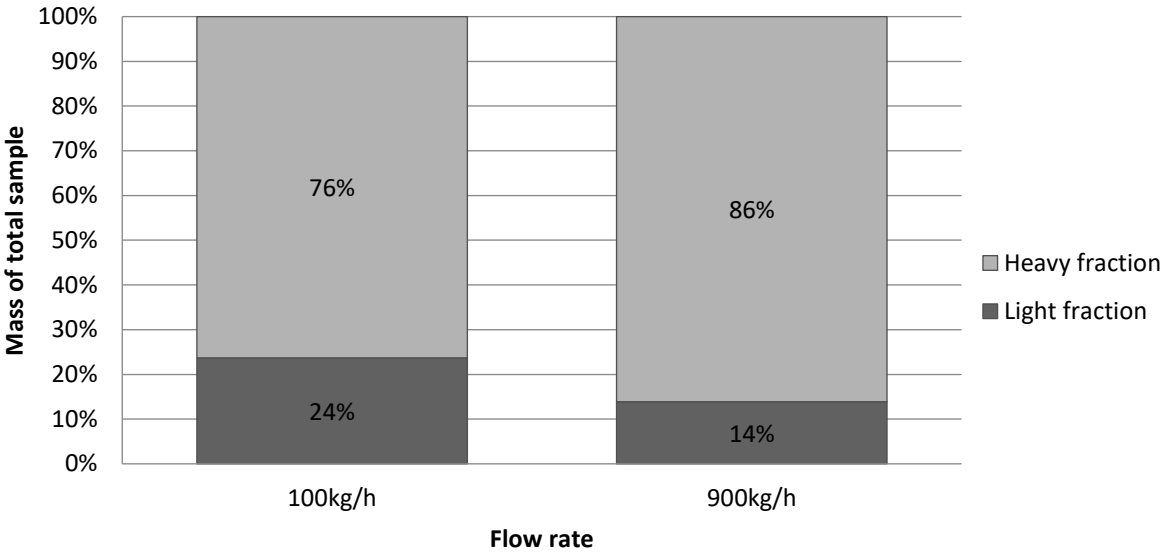


Figure 4-13 Mass measurement – feed rate comparison

Figure 4-13 describes how feed rate affects the separation performance of an air classifier. The chart shows that at a high feed rate (900 kg/h) more material ends up in the heavy fraction compared to the same test done at a lower feed rate (100 kg/h). This is a result of a higher number of particle interactions within the air separation chamber which makes it more difficult to liberate the light from the heavy material (Hagemeier et al., 2014).

The recovery curves illustrate the relative performance of the classifier for each of the samples at 100 kg/h (see Figure 4-14). The recovery curves relating to the feed rate test are shown in Figure 4-15.

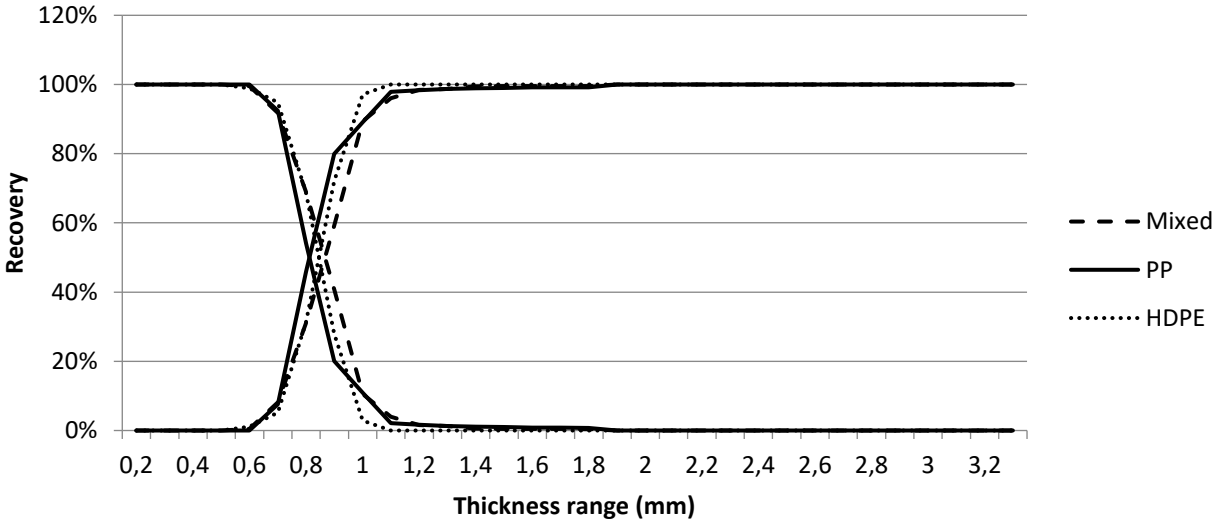


Figure 4-14 Recovery curves (Mixed, PP and HDPE material)

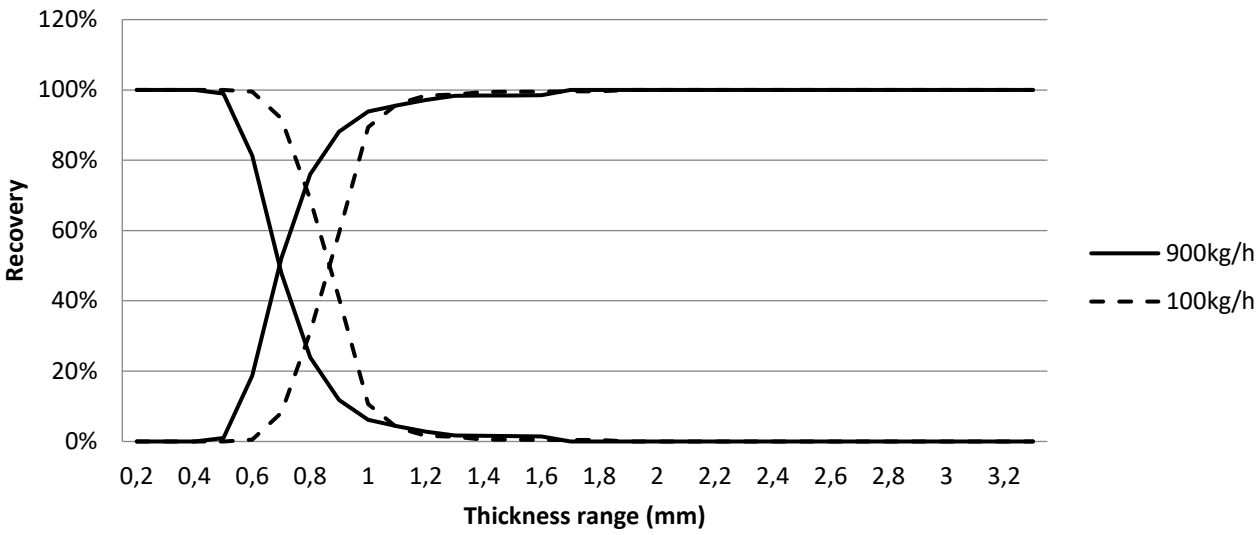


Figure 4-15 Recovery curves – Mixed sample (feed rate assessment)

The cut points and sharpness index results for the tests conducted on the Herbold® system are shown in Table 4-5. Please see section 2.8.3.3 for information regarding the calculation of the sharpness index.

Table 4-5 Original, P1 and P2 material cut points and sharpness indices

Test	Cut point (mm)	Sharpness index, *S*
Mixed sample (100kg/h)	0.87	0.82
Mixed sample (900kg/h)	0.69	0.78
PP sample	0.81	0.84
HDPE sample	0.85	0.85

Mixed material, PP and HDPE samples were tested on the Herbold® setup at a single air flow rate. The mass measurement results highlight that at a cut point of approximately 0.85 mm the mass ratio between light (thin-walled) and heavy (thick-walled) material is about 1:5. These figures differ by almost a factor of two when comparing them with the results in section 4.2. Again it is explained by the fact that perfect separation efficiencies are not possible meaning that material at the d(50%) point is found in equal ratios in both the heavy and light fractions. This diffusion of each fraction contaminating the other is the reason between the difference in theoretical and practical ratio.

With regards to separation efficiency, the Herbold® system conducted better than the Nihot® system (see Table 4-5). It therefore confirms the hypothesis that taller air classifiers tend to yield better separation efficiencies than shorter systems even on material that is very similar in terms of size, thickness and density as stated in the literature.

Focusing on material mass flow rates through the Herbold® system it was discovered that material flow rate did indeed have a significant impact on separation efficiency. This is clearly shown in Figure 4-15; as the mass flow of the material through the classifier increases so the separation efficiency decreases.

In general, the results suggest that the material is well suited for these type of air classifiers. Very good separation efficiencies were achievable at a number of different cut points on both air classifiers.

4.5.3 Bulk density measurements

The bulk density measurement results are shown in Figure 4-16 below.

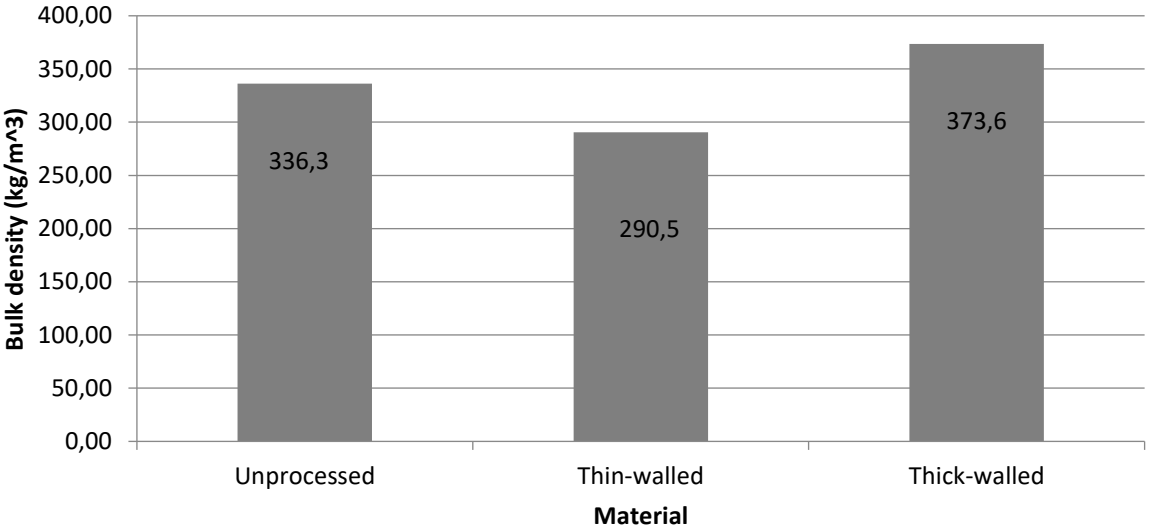


Figure 4-16 Mixed sample bulk densities

The bulk density result indicates that when the material is separated into a thin-walled and a thick-walled fraction, by means of air classification, the bulk density changes slightly. This is an important result from the perspective of process volume calculations.

4.6 Alternative separation method – Ballistic separation

As discussed in section 3.8 two scenarios regarding ballistic separation were considered; with and without the use of an air fan. The mass ratio and separation efficiency results from each test are discussed in this section. The mass ratios from each test are shown in Figure 4-17.

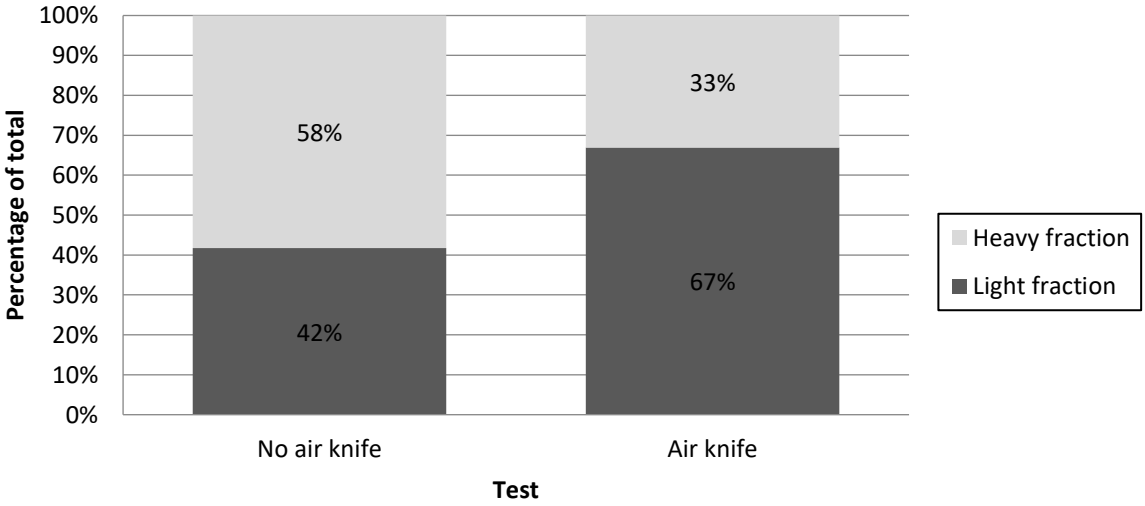


Figure 4-17 Ballistic testing mass measurement results

The separation curves for each test are shown in Figure 4-18.

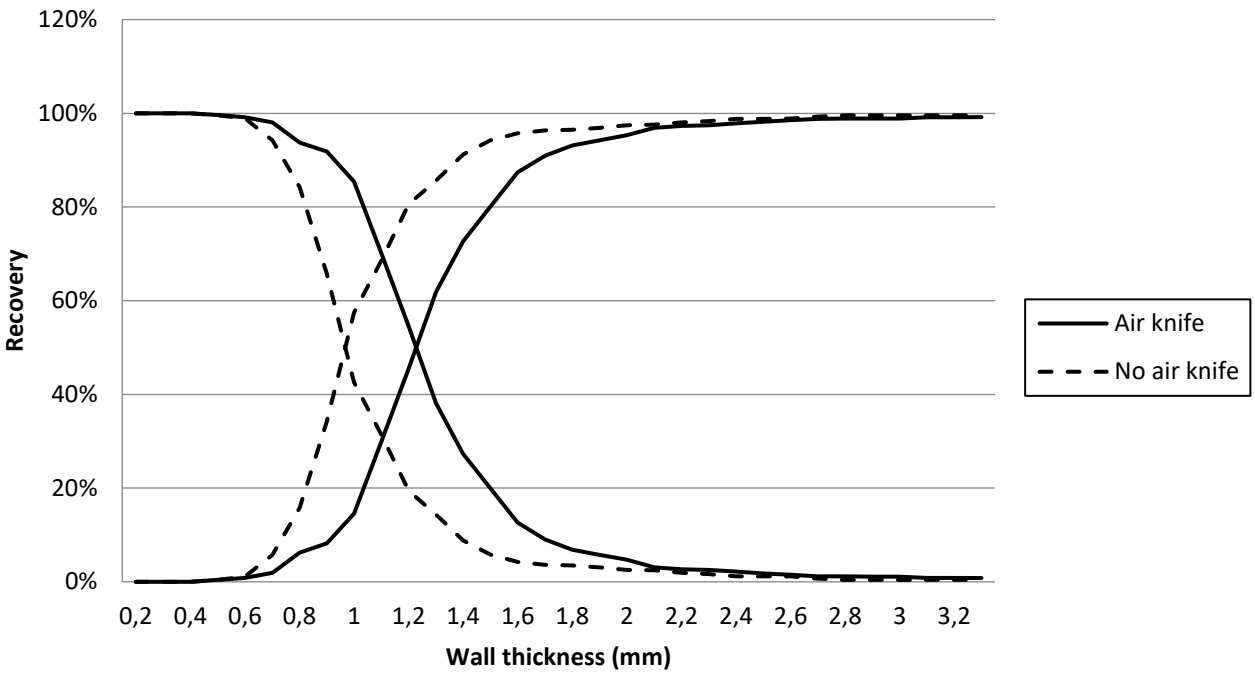


Figure 4-18 Separation curves

The cut points and separation indices are shown in Table 4-6.

Table 4-6 Cut points and separation indices

Test	Cut point (mm)	Sharpness index, *S*
Air knife	1.23	0.75
No air knife	0.97	0.74

Separation by means of ballistic trajectory was conducted for the two scenarios described in section 3.8. The results from the experiment suggest that separation using a simple ballistic setup yields results that are comparable to that of the Nihot® air classifier setup (see sharpness index results). In terms of the mass ratio between the heavy and light fractions, the results from the ballistic separation experiment are comparable with the results from the Hihot® high air flow rate test.

With regards to the air knife addition, as expected it shifted the cut point towards the thicker material as it redirected more of the thin walled material into the light fraction bunker. The air knife can therefore be used to shift the cut point but it seems that it had little impact in terms of separation efficiencies.

4.7 Results comparison – Nihot®, Herbold®, and Ballistic separation

This final section briefly compares the results of the three air classification investigations.

Table 4-7: Air classification results comparison

System	Sample	Cut point (mm)	Sharpness index, *S*
Nihot®	Mixed material	0.81	0.72
Herbold®	Mixed material	0.87	0.82
Ballistic	Mixed material	0.97	0.74

In summary all three systems performed fairly well on the material as all three systems were able to separate based on wall thickness differences and all yielded reasonably good separation efficiencies. Comparing the results shown in Table 4-7 it is clear to see that the Herbold® setup performed the best (sharpness index of 0.82). In terms of the overall process model, however, the separation efficiencies achieved by the Herbold® system may be more than what is required. In terms of capital investment costs, it may be appropriate to make use of a ballistic separator as the technology is far simpler and cheaper than a zigzag air classifier system.

4.8 Material property measurements

The analytical test results of the various polymer samples are shown and discussed in the following section.

4.8.1 Tensile test results

The results from the tensile tests are shown in the figures in the following subsections. It is important to read this section in conjunction with section 2.3.2.7 because it discusses the mechanical properties of various packaging thermoplastics. Also note that the samples in each figure have been numbered to make each discussion easier to read.

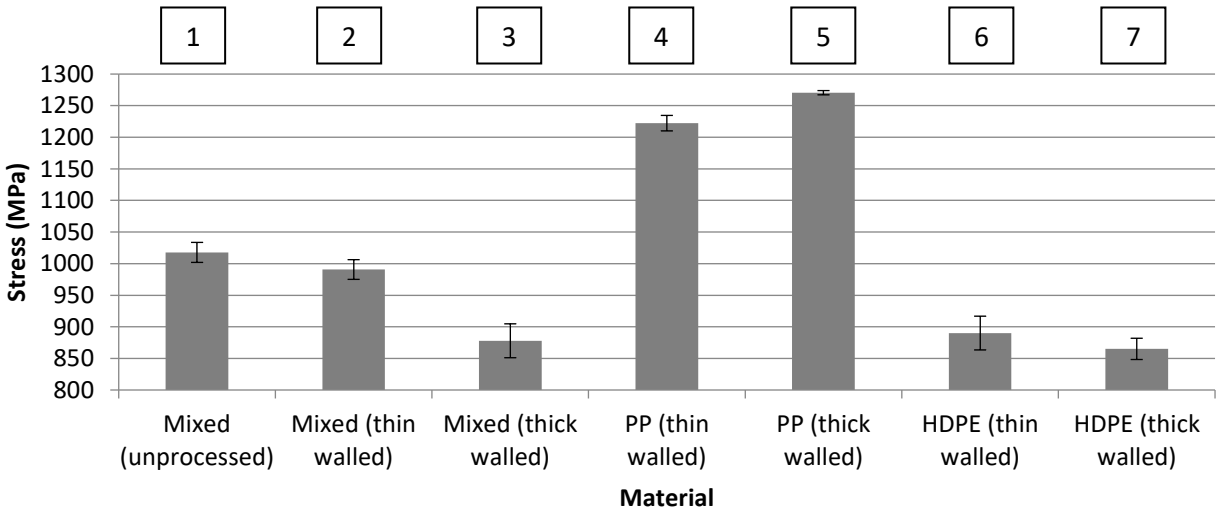


Figure 4-19 Modulus

The elastic modulus test results are shown in Figure 4-19. The modulus properties of samples 1 and 2 are comparable to virgin HDPE materials (see Table 2-2). The modulus of sample 3 is, however, approximately 12% lower and is more comparable with the modulus figures of the HDPE samples (samples 7 and 8). Looking at the composition of this sample (see Figure 4-27), the mixed, sample 3 contains more HDPE than sample 2. In this case, it is possibly the high HDPE content that reduces the modulus of sample 3.

Looking at the PP samples (sample 4 and 5), the results show that the modulus for both samples increased significantly; the results are comparable with modulus properties of virgin PP materials (see Table 2-2). The literature suggests that PP is a stiffer, brittle material compared to HDPE. These results suggest that this is true, even for recycled materials.

Looking at the HDPE samples (6 and 7) the modulus for both is significantly lower than samples 1, 2, 4 and 5. It suggests that the higher the HDPE content, the lower the modulus; this relates to the fact that HDPE tends to be a tougher, more ductile material.

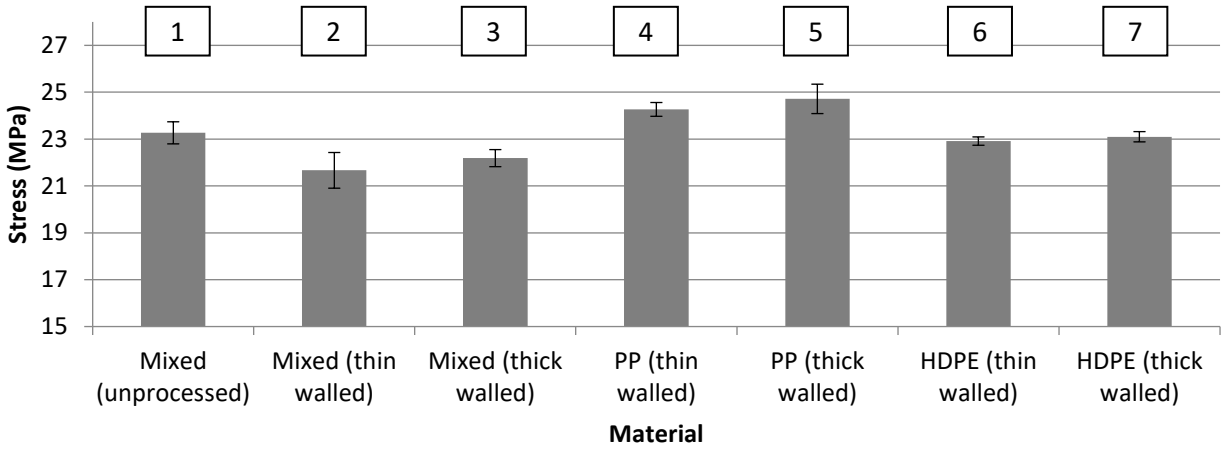


Figure 4-20: Yield stress

The yield stress results show that the unprocessed sample (sample 1) and the two HDPE samples (sample 6 and 7) has a yield strength comparable to virgin HDPE. Air classification had little impact on either of the HDPE samples, but it did increase the yield stress properties of sample 5. The yield stress properties of both PP samples (4 and 5) are comparable to virgin PP materials.

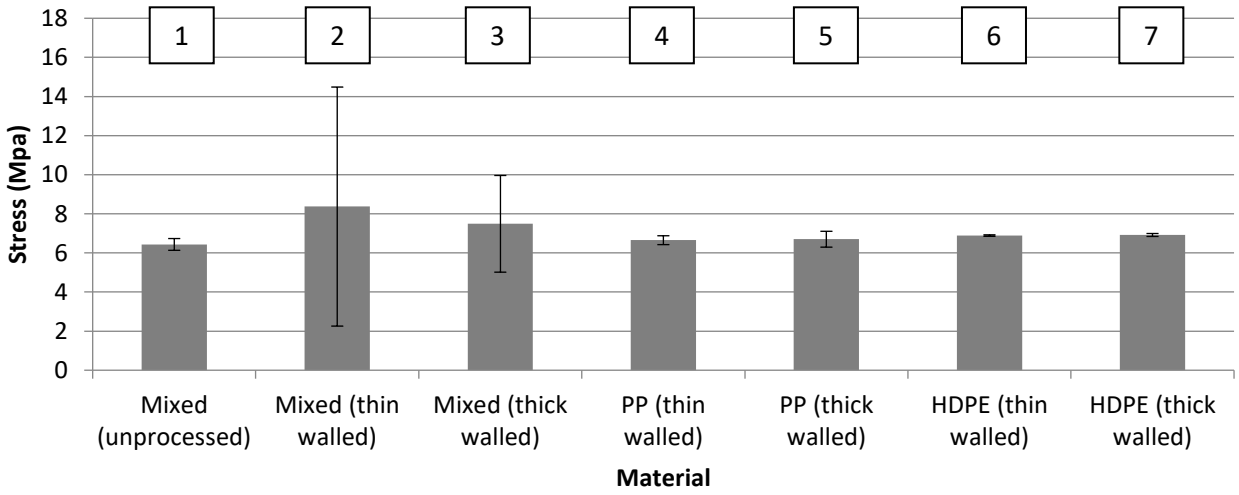


Figure 4-21 Tensile stress

The tensile stress results do not show any significant improvement with any of the processed samples (samples, 4, 5, 6, 7). The two mixed, processed samples (sample 2 and 3) do show a high standard deviation meaning that the quality of this material is highly variable compared to the PP and HDPE samples; It remains unclear why these results are so varied.

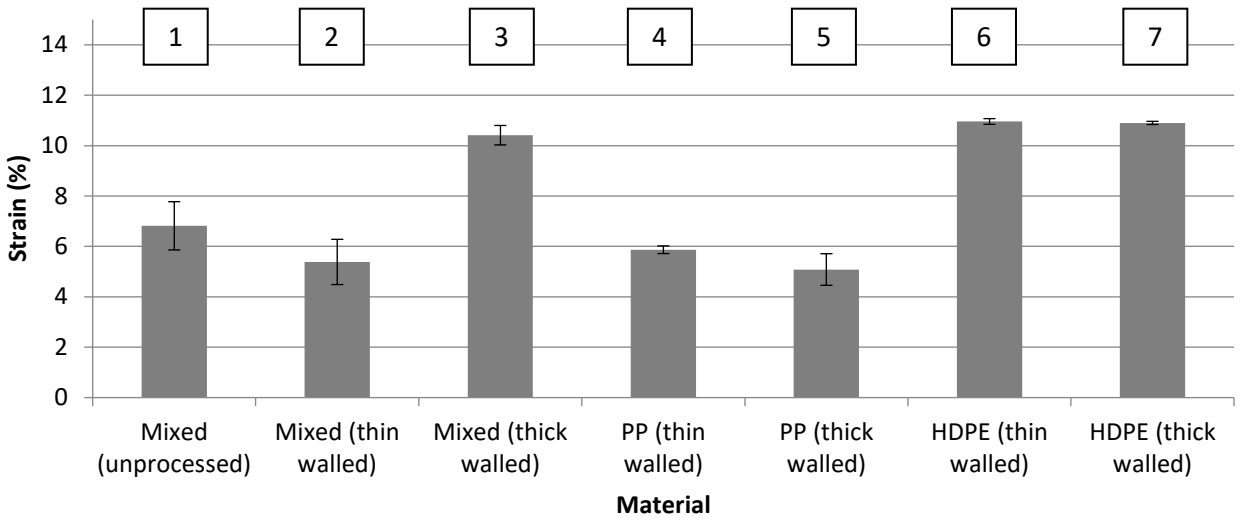


Figure 4-22 Tensile strain at yield

The tensile strain at yield results indicate, and reinforce the modulus test results; the PP samples (sample 4 and 5) are stiffer and yield less than the HDPE samples (sample 6 and 7). With regards to separating the material according to thickness. It did little to influence the stiffness properties of either material.

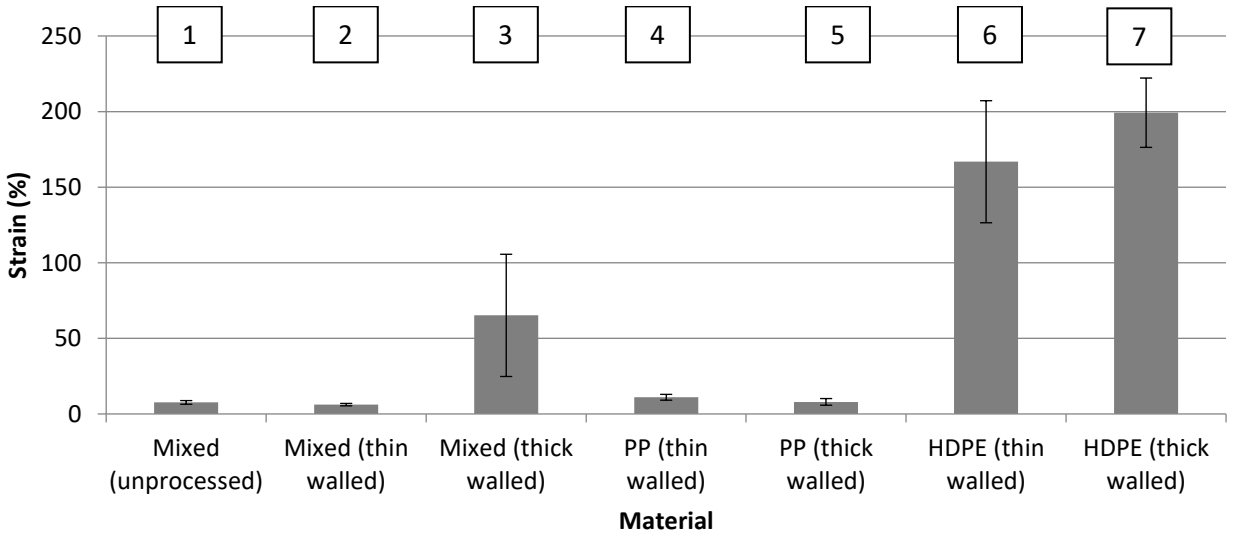


Figure 4-23 Maximum tensile strain

The maximum tensile strain results again show that the PP fractions are stiff and brittle whereas the HDPE samples are more tough and ductile. Sample three shows much higher tensile strain results compared to samples 1 and 2 and this could be as a result of it having a higher HDPE content than the other two samples. Again, sorting the material into a thin walled and a thick walled fraction did not significantly influence the properties of PP or HDPE.

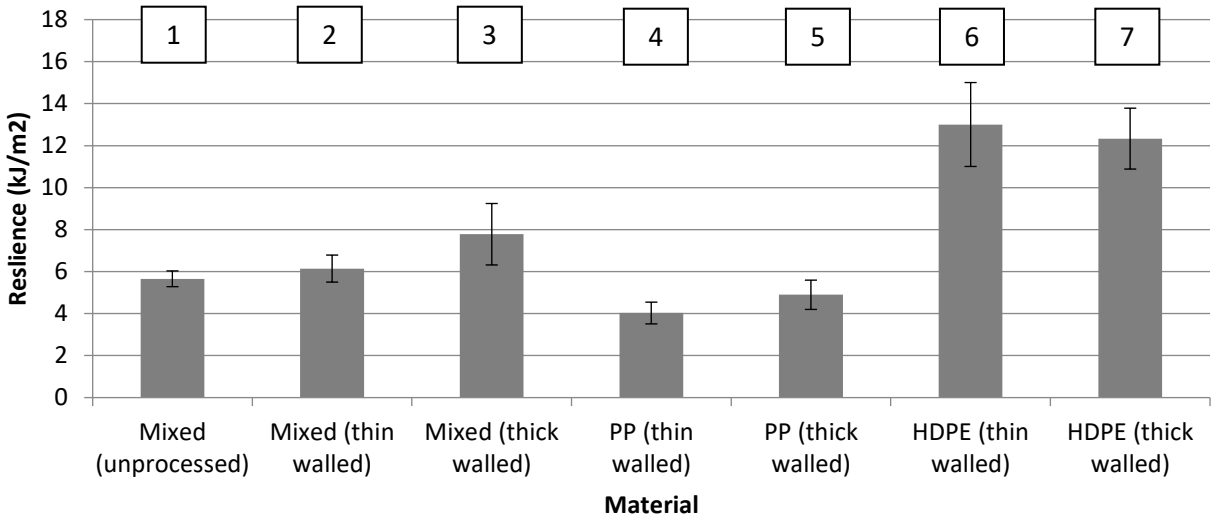


Figure 4-24 Impact resilience

Again, the argument that PE is a tougher material than PP is supported by the impact test results. The chart shows that both HDPE samples have a higher impact resilience compared to the PP samples. The results from the mixed fractions shed little light on the effect of separating the mixed fraction into light and heavy fractions.

4.8.2 Melt Flow Rate test results

The Melt Flow Index (MFI) results are discussed in this section.

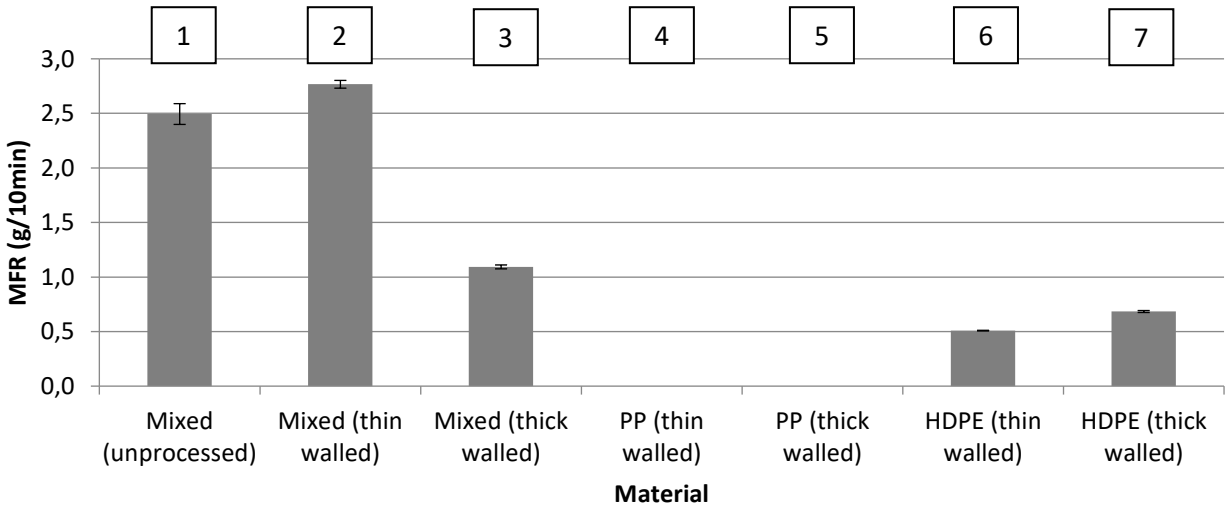


Figure 4-25 Melt Flow Index (ISO 1133 @ 190°C)[18]

[18] Testing at 190°C is the standard for PE samples

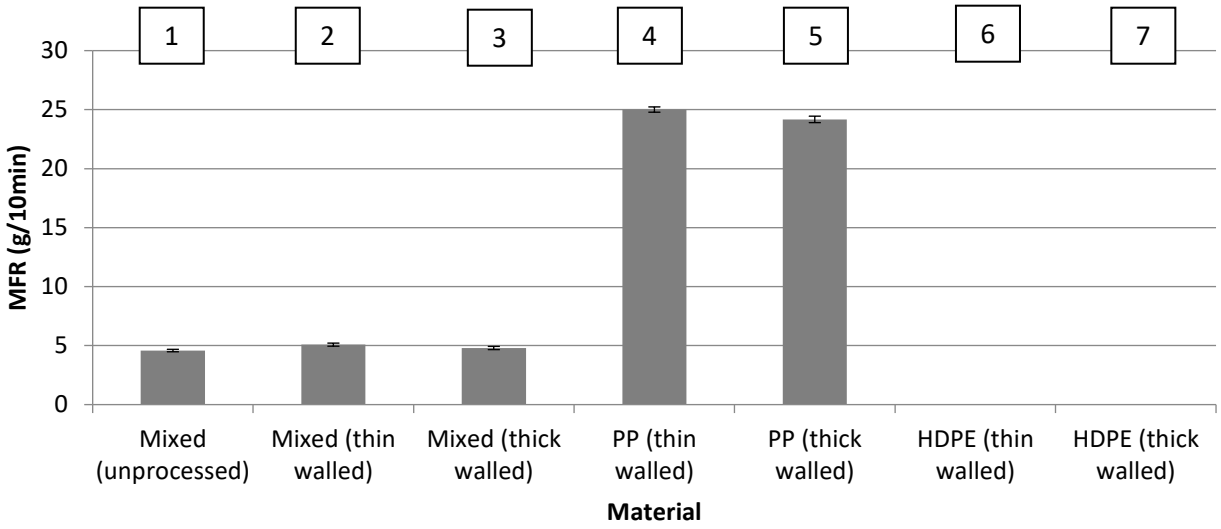


Figure 4-26 Melt Flow Index (ISO 1133 @ 230°C)[19]

The results from the melt flow tests are interesting and confirm some of the earlier assumptions about the characteristics of the product samples; PP and HDPE. Looking at Figure 4-25, it shows that the mixed material (sample 1) has an MFI of approximately 2.5 g/10min. in terms of MFI for manufacturing purposes this material has little value as it is difficult to blow mould or injection mould.

The light and heavy fractions of the original material show results that are in contradiction with the assumption that light (thin walled) material has a lower MFI than heavy (thick walled) material (see Figure 2-16). The light fraction (sample 2) shows that it's MFI is slightly higher than samples 1 and 3. A possible explanation is that the MFI (specifically related to this material), is somewhat independent of wall thickness but rather corresponds to material type (PP or HDPE). From the DSC analysis results (see Figure 4-27) the mixed light fraction mass measurement shows that the PP content is slightly higher than the PP content of the unprocessed sample. Referring back to Figure 4-26, PP sorted out at the recycling facility is also mostly injection mould grade with a high MFI value compared to the HDPE material products that is mostly blow mould grade material with a low MFI value. Furthermore, Figure 4-25 also shows that both HDPE fractions have a low MFI, corresponding to blow mould grade material. What is clear is that processing the material through the MDS improves both the quality and the grade of the PP and HDPE products. It also confirms some of the previous literature that HDPE is mostly used for injection mould applications and PP is mostly used for injection mould applications (see Figure 2-15).

4.8.3 DCS test results

The DCS test results are shown in Figure 4-27 on the following page.

[19] Testing at 230°C is the standard for PP samples

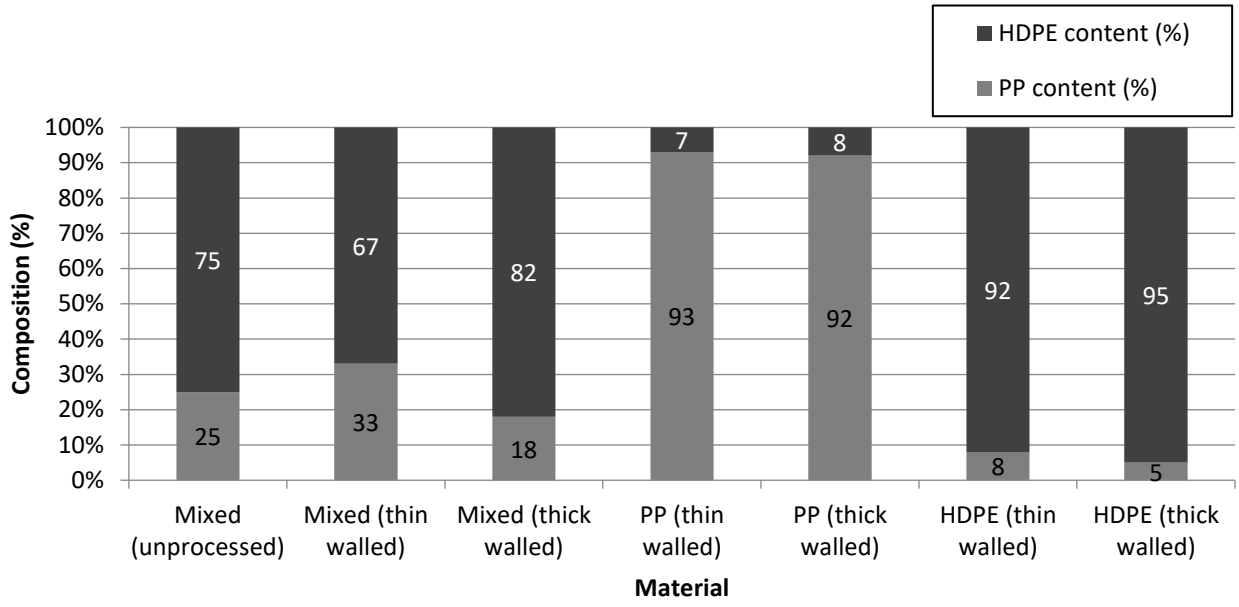


Figure 4-27 DSC analysis

DSC analysis conducted on each of the samples show that both PP and HDPE products from the MDS system are fairly good quality. In terms of the mixed light and heavy samples it suggests that there is more PP in the thin walled fraction whereas more HDPE ends up in the thick walled fraction. Again, this is in contradiction to previous research that suggest that thin walled material is predominantly HDPE, blow moulded material (see Figure 2-16).

4.9 Process configuration

4.9.1 Current processing scenario

It is clear from the results highlighted in the previous section that separating the material based on wall thickness has little influence on the melt flow properties of the PP and HDPE products. To potentially understand why this may be it is worth discussing the current process configuration at the recycling facility.

The current process configuration is shown in Figure 4-28. The current processing line makes use of a number of hand sorters to sort the material into the notable products. To achieve this at economic volumes, hand sorters are trained to sort clearly and easily identifiable objects;

- **Group 1** – trained to sort out PET bottles (different colours)
- **Group 2** – trained to sort out black items (mostly PP)
- **Group 3** – trained to sort out PP IM grade plastics
- **Group 4** – trained to sort out HDPE BM grade plastics (less than 5 litres in volume)
- **Group 5** – trained to sort out HDPE BM & IM grade plastics (typically beer crates and objects greater than 5 litres in volume)

The current process is able to produce economically viable volumes but because it is heavily dependent on hand sorting the quality of the product can vary significantly. Additionally, since hand sorters are trained to pick out material quickly, there remains a large fraction in the residue stream that still contains a significant amount of valuable material.

4.9.2 Proposed processing scenario

With the inclusion of the MDS system into the processing line it makes it possible to reduce the reliance on the hand sorting components of the processing line. MDS's ability to sort polymers by type means that hand sorting the material into PP and HDPE streams is no longer necessary. Additionally, and in line with the results from section 4.8.2, it can be fair to say that air classifying the material into supposed BM and IM grade fractions does not appear to add any significant value.

The process line therefore should still make use of manual hand sorting; however, instead of focusing on sorting the material by polymer type and manufacturing method (IM & BM), hand sorter could focus all of their attention on sorting out all the plastic items that are not black or PET (see Figure 4-29). This could make the hand sorting task easier and may require less manpower to achieve the same throughput volumes.

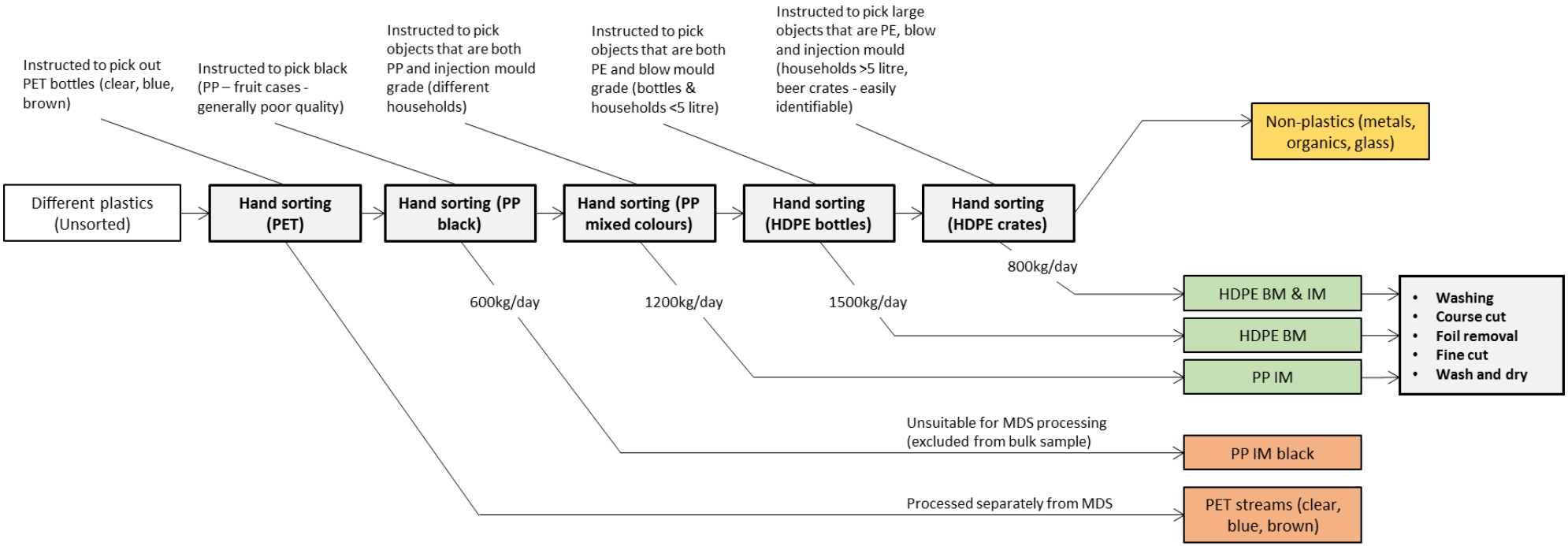


Figure 4-28 Current hand sorting configuration

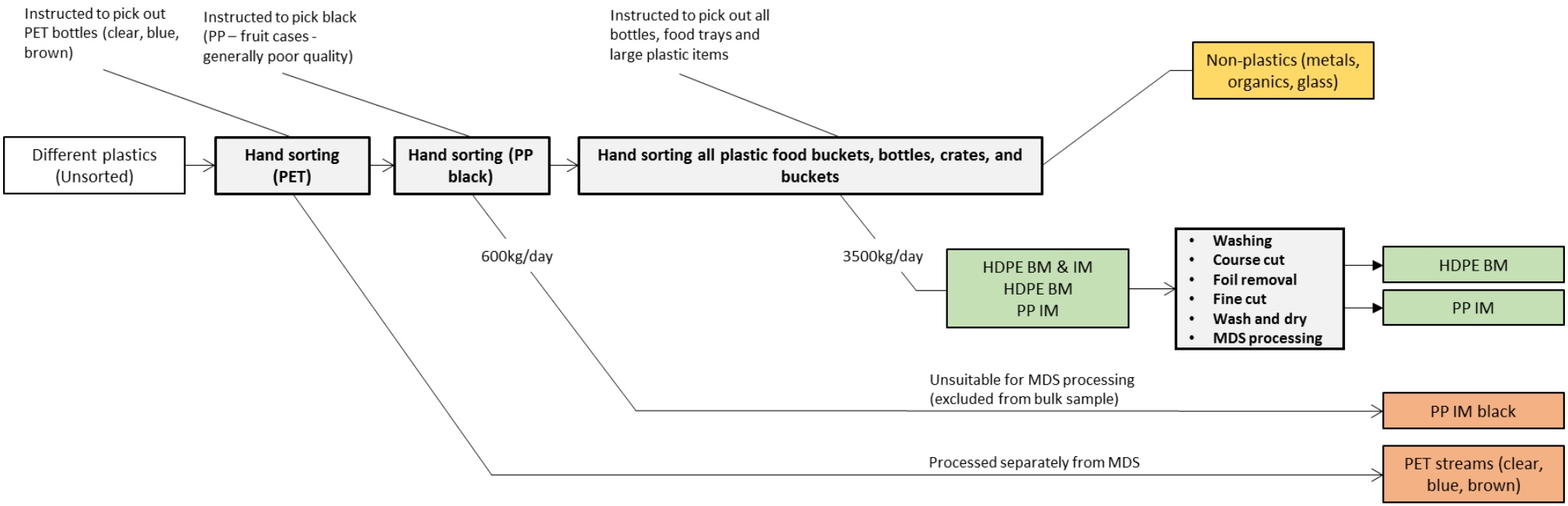


Figure 4-29 proposed process configuration

CHAPTER 5

5 Conclusions and recommendations for future work

5.1 General conclusions

The, study which focused on the material and processing line at the Romanian recycling facility has highlighted a number of important findings. As is, the facility has the ability to produce products of acceptable qualities and volumes as it can take advantage of the relatively low cost related to hand sorting; basic wages in Romania and other eastern European countries make it possible to employ individuals to perform such tasks.

However, the company wants to reduce its reliance on hand sorters in an effort to reduce costs and improve product quality. Fortunately, the MDS system has proven its worth in terms of sorting according to polymer type (Serranti et al., 2015), meaning that hand sorting efforts can be focused on sorting by material grade.

This study which was focused on improving the quality of the classified plastics in terms of fabrication method (BM & IM), has shown that air classification based on material wall thickness is not only possible, but rather effective. It also indicates that air classification has the ability to sort the material over a broad thickness range. In terms of processing it may have implications for other recycling facilities that may need to separate on wall thickness for similar or other reasons.

Although the study suggests that air classification has the potential to sort the material based on wall thickness it did not translate into distinctive IM and BM grade products. However, it does not conclude that there is no correlation between melt flow properties and wall thickness, but rather suggests that the hand sorting strategy at the facility is somewhat effective in sorting the material according to manufacturing characteristics.

Furthermore, it would make sense for the recycler to realign the way in which it performs the hand sorting task with the addition of the MDS system. Hand sorting should focus specifically on manufacturing type (BM and IM plastics); fewer hand sorters would need to be employed whilst maintaining current throughput volumes.

5.2 Recommendations for future work

There is indeed scope for future work regarding the separation of different plastics based on their melt flow (rheological) properties. Additionally, it must be noted that the correlation between BM and IM plastics should not be disregarded; the study should therefore be conducted on a material stream that has not been sorted as comprehensively as the material investigated in this report.

It is also important that research regarding the separation of plastics with differing melt flow properties continues as many developed countries cannot employ people to manually sort economically viable quantities of post-consumer packaging waste. In these cases, mechanized solutions remain invaluable.

Furthermore, a follow-up study could be undertaken where multiple wall thickness range fractions are investigated to more closely examine the correlation between wall thickness and melt flow properties.

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Appendix

Appendix 1 - Size distribution measurement

Step 1:

The vibrating screen setup was arranged by placing the 8mm grid on top of the 4mm grid.

Step 2:

Material was placed on the top of the 8mm grid before the lid was tightened onto the top of the vibrating screen. The machine was then run for 60 seconds at a medium amplitude setting to ensure effective separation.

Step 3:

After each test each fraction was collected, weighed and the mass recorded.

Appendix 2 - Wall thickness distribution measurement

Step 1:

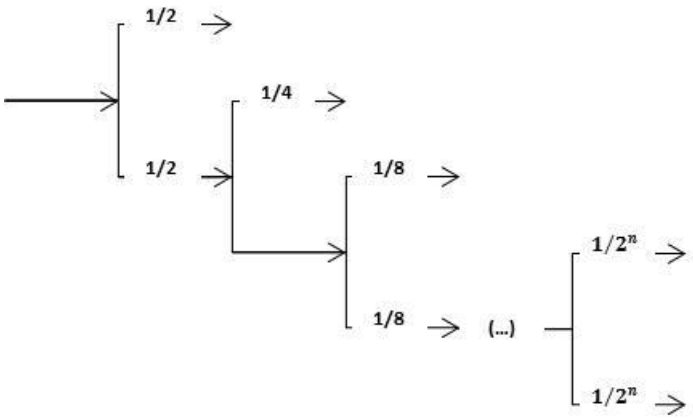
Samples for each material stream were collected (roughly 1 kg). Using a sample splitter each sample was split (divided by two – see the figure below) a number of times until it was a reasonably sized to give a representative fraction of the original sample.

Step 2:

Once the samples had been prepared, each flake's wall thickness was measured and recorded.

Step 3:

Step 2 was repeated for each sample. For the mixed sample (screened), each flake was placed into the cup corresponding to its thickness. Once completed, the contents of each cup were weighed using a precision electronic scale.



Sample splitting

Sample splitter

Vernier caliper

Appendix 3 - Density distribution measurement

Step 1:

Two solutions, 920 kg/m^3 and 930 kg/m^3, were prepared by diluting pure 2-Propanol (ρ≈785 kg/m^3 at 25°C) in a given volume of water (ρ≈1000 kg/m^3 at 25°C) until the density read 920 and 930 (using the hydrometer). Roughly two litres of each was prepared.

Step 2:

The samples were washed in water followed by a wash in a propanol solution to remove the water from the sample. Removing the water prevents dilution of the propanol solution. Diluting the solution changes its specific gravity and can introduce errors into the density measurements.

Step 3:

Thereafter the sample was immersed in the 920 kg/m^3 solution and agitated to ensure that each flake separated effectively according to its specific gravity.

Step 4:

The lighter fraction was then removed from the surface of the solution using a sieve. Once removed, the heavier fraction was collected. The lighter fraction represents the fraction of the material with a density of less than 920 kg/m^3 with the heavy fraction being denser than 920 kg/m^3.

Step 5:

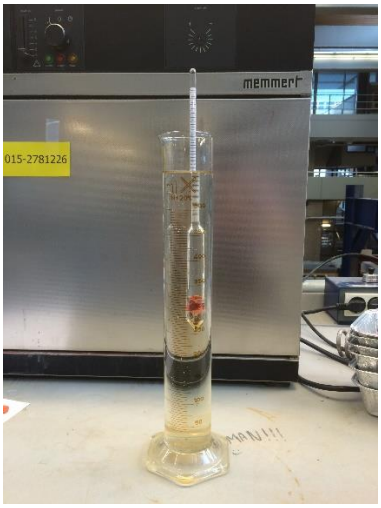
Steps 3 and 4 were then repeated by immersing the heavier than 920 kg/m^3 fraction in the 930 kg/m^3 solution to separate the material between 920-930 kg/m^3 from the material that is denser than 930 kg/m^3.

Step 6:

Once each sample was density separated according to its density, each mass fractions was placed in an oven at 70 °C to evaporate all the liquids from the sample to ensure that the residual liquid had no bearing on the mass of the sample. Once dried each sample was weighed, and its weight documented to give the density distribution of each sample.

Hydrometer

Measuring solution density



Appendix 4 - Nihot® zigzag classifier

Nihot® air classifier

Air valve

Adjustable duct

Vibrating screen

Appendix 5 - Herbold Zigzag air classifier

Zigzag channel

Frequency controlled vibrating feeder

Material in separation chamber

Filter bags

Appendix 6 - Research project consent forms

Letter of Consent

I, Jaap Vandehoek, agree to participate in the MSc research entitled, Pre-treatment Processing of Household Plastic Packaging Waste to be undertaken by Ross Blackstock, under the supervision of Dr Lizelle Van Dyk, and certify that I have received a copy of this letter of consent.

I acknowledge that the research has been explained to me and I understand what it entails, as follows:

1. I agree to allow access to my company and manufacturing facilities for the purpose of this research.
2. The processes of my company will be mapped.
3. I have the right to withdraw my assistance from this project at any time without penalty, even after signing the letter of consent.
4. I have the right to refuse to answer one or more of the questions without penalty and may continue to be a part of the study.
5. I may request a report summary, which will come as a result of this study.
6. I am entirely free to discuss issues and will not be in any way coerced into providing information that is confidential or of a sensitive nature.
7. Pseudonyms will be used to conceal my identity, and that of my company, my employees, my suppliers and my customers. The information disclosed in the interviews will be confidential.
8. Audio-tapes and transcripts will be kept securely stored during the research and after the research has been completed.
9. This project was approved by the Faculty of Engineering and the Built Environment of the University of the Witwatersrand and the School of Mechanical, Industrial and Aeronautical Research Ethics Committee (non-medical) of the University.
10. If I have any questions or concerns about my rights or treatment as a participant, I may contact the Chair of the School of Mechanical, Industrial and Aeronautical Research Ethics Committee (non-medical) at (phone #) or by (email).

Signed: J Vandehoek

Date: 26-05-2015

Questions concerning the study can be directed to:

Ross Blackstock

Tel: +27 82 617 1172 Email: blackstock.ross@gmail.com

Supervisor: Tel +27 11 717 7552 Email: Lizelle.VanDyk@wits.ac.za

Urban Mining Corp

Letter of permission to conduct research at Urban Mining Corp

June 22, 2015

To Whom It May Concern:

This letter serves to inform you that Ross Blackstock (student number 767366) is authorized to conduct technical and commercial research at Urban Mining Corp necessary for him to complete his Master's research project and ultimately his postgraduate studies.

This document is issued upon request of the concerned person.

Yours faithfully,

Jaap Vandehoek

Managing Director
Urban Mining Corp
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