ARCADA

Effect of Recycling in Post-Consumer Polystyrene Cups

Mehnaz Rumana Ahmed

Degree Thesis

Plastics Technology

2016

DEGREE THESIS	
Arcada	
Degree Programme:	Plastics Technology
Identification number:	12851
Author:	Mehnaz Ahmed
Title:	Effect of Recycling in Post-Consumer Polystyrene Cups
Supervisor (Arcada):	Mirja Andersson
Commissioned by:	

Abstract:

The aim of the thesis was to recycle post-consumer polystyrene cups and to analyze the changes in mechanical and rheological properties of the recycled polystyrene. The mechanical properties were tensile strength, Young's modulus and the rheological properties was melt flow index. In order to analyze the changes in properties, material testing results of pristine polystyrene were compared with the recycled polystyrene. The same polystyrene material was recycled and tested twice in order to see the effects of recycling on the polystyrene. Different recycling machines such as plastic shredder, extruder and injection molding were used to recycle the material. The properties have been tested with tensile testing machine and melt flow index machine. In order to find the tensile strength and Young's modulus, dog bones were made with the injection molding machine and tested with tensile testing machine. The melt flow rate was tested by using recycled polystyrene pellets in the melt flow index machine. The obtained results of pristine polystyrene and recycled polystyrene were compared in order to find out the changes in mechanical and rheological properties due to the recycling process. According to the results, there was no significant changes in the tensile strength and Young`s modulus after the recycling process whereas the melt flow index rate decreased 56.4% after the second recycling process. All the recycling and material testing process has been done in Arcada Plastics Laboratory.

Keywords:	Recycling, Plastics, Polystyrene, Mechanical properties
Number of pages:	63
Language:	English
Date of acceptance:	

Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

The world produces and consumes thousands of tons of polystyrene every day. The enormous variety of application of polystyrene turned it into one of the most common plastic in everyday life. As a result, a big amount of polystyrene products ended up in the landfill as waste. Since polystyrene is a non-biodegradable material, the products made from polystyrene does not break down and takes up a lot of space in landfill. Recycling of polystyrene is the best option in order to reduce the massive amount of PS waste. Although the technology for recycling polystyrene is available, the market for recycling is relatively small and shrinking. But the collection and recycling rate of polystyrene is rather smaller than the production and the consumption rate of polystyrene around the world.

The topic has been chosen as polystyrene recycling is a quite potential and challenging topic itself. Since polystyrene is a brittle material, it is relatively difficult to recycle polystyrene compared to other plastic material which makes the topic an interesting and challenging one. Another inspiring feature of the topic is, there are a lot of opportunities to learn and acquire skills as it involved good amount of practical laboratory work that required knowledge and uses of different material recycling and testing machines and instruments. Having knowledge on this particular topic is a valuable experience for the future studies, research and work field.

1.1 Aim and Objectives

The aim of the thesis is to recycle post-consumer polystyrene cups and to analyze the changes in properties of the recycled polystyrene. The idea was to see how the recycling process affects the mechanical properties of polystyrene, to compare the mechanical values of pure polystyrene and the recycled polystyrene. In short, to determine if polystyrene worth recycling or not.

1.2 Background

The theoretical background of the thesis contains detail information about the following topics. The overview of plastic and its recycling process has been discussed. An overall background study of polystyrene which includes the mechanical properties, manufacturing process, market and pros and cons of polystyrene has been discussed. All the machines that has been used during the thesis work which is located in Arcada Plastics Laboratory has been discussed, explaining how the machines works, what are the possible outcomes from the machines. The mechanical values which has been obtained from the tests in order to get the expected outcome of the thesis has been explained along with their formulas.

1.3 Method

The thesis has been divided into two major sections which are literature review and laboratory experiments. All the data for the literature review has been collected from books, online sources, email correspondence and so on. Some of the technical information and knowledge has been gathered from Arcada Plastic laboratory as well. All the laboratory experiments have been done in Arcada Plastic Laboratory using different machines following the laboratory regulations properly. Prior to the laboratory experiment, post-consumer or used cups has been collected and washed properly in order to recycle. The laboratory experiments can be divided into two sections: processing the materials and then testing the materials. After every experiment, the results have been recorded for further calculation or evaluation.

2 THEORETICAL BACKGROUND

The aim of this chapter is to briefly explain the literature review that has been done during the thesis. In order to do that, this chapter has been divided into five sections.

In the first section, the overview of plastics and different types of plastics has been discussed.

In the second section, plastic recycling and the process has been explained.

The third section contains the polystyrene background which includes properties, applications, manufacturing process, market and consumptions of polystyrene.

The fourth section briefly explained all the machines used and their process.

And finally in the last section, the mechanical properties and formulas has been discussed.

2.1 Plastics

Plastic is a wide-ranging term of any synthetic or semi-synthetic organic polymer consist of long chains of carbon and other chemicals and substances. (PlasticsEurope) Plastic is almost everywhere. Such as clothes, boxes, houses and household materials, toys, electronics, aircrafts, construction industry, food containers, cars, hospital equipment, industrial areas etc. There are various types of plastics with their own characteristics and specific uses or applications. While making new plastic products and recycling plastics, it is necessary to consider the characteristics of plastics. The common characteristics of plastics are thermal conductivity, impact strength, tensile strength, coefficient of thermal expansion, chemical resistance, stiffness, hardness, heat deflection, flammability, shrinkage, electrical insulation etc. Generally, selection of plastic for different applications are based on these characteristics. (Productive Plastics, Inc,2016)

There are different molding and manufacturing process for plastics material. Such as blow molding, Injection molding, filament winding, thermoforming, vacuum forming, CNC machining, centrifugal casting, continuous strip molding, compression molding, profile extrusion, continuous lamination, pressure bag molding, pressure forming, pulshaping, twin sheet forming, pultrusion, liquid resin molding, reaction injection molding (RIM), rotational molding, resin transfer molding (RTM). (Ramsdale, 2004)

Plastic has both advantages and also some disadvantages. Plastic makes human life much easier and cost effective. They are lightweight, easy to handle, recyclable, versatile, impermeable, electrical and good thermal insulating capacity, corrosion resistant, easy and cheap to manufacture. One of the biggest disadvantages of plastic is, it is non-biodegradable. It can literally stay in the landfill for hundred years without degrading. Which cause pollution in water, landfills, ocean, forests etc.

There are different kinds of plastic with different properties, characteristics and different applications. Plastics are basically of three types. Such as-Thermoplastics, Thermoset, Elastomers.

2.1.1 Thermoplastics

Thermoplastics are made of polymers linked by the intermolecular interaction by creating linear structures. Thermoplastics can be reheated or reshaped. The polymer can take two different types of structures depending on the intermolecular interaction that occurs between the polymer chains, such as amorphous structure and crystal structure. It is possible that both structures can be present in the same thermoplastic material.

In amorphous structure the polymer chains obtain structure like a ball of yarn and the amorphous structure is directly accountable for the elastic properties of thermoplastics. In crystal structure the polymer chains obtain ordered structure and the crystal structure is directly accountable for the mechanical properties of stress resistance and temperature resistance of thermoplastic material. Thermoplastics are soluble in certain solvents, high impact resistant, allow plastic deformation when heated, may rise in the presence of certain solvents, may melt before passing to a gaseous state, thermoplastics can be recycled and can be remolded or reshaped.

Thermoplastic example:

- Acrylonitrile butadiene styrene – ABS
- Polycarbonate – PC
- Polyethylene – PE
- Polyethylene terephthalate – PET
- Poly (vinyl chloride) – PVC
- Poly (methyl methacrylate) – PMMA
- Polypropylene – PP
- Polystyrene – PS
- Expanded Polystyrene – EPS (adhesiveandglue.com)

2.1.2 Thermosets

Thermosets are made of polymers linked together by chemical bonds, obtaining a vastly crosslinked polymer structure. once a thermoset composite is molded, it cannot be remolded or reshaped. This makes thermosets unrecyclable. The highly crosslinked structure is directly accountable not only for the high mechanical and physical strength but the poor elasticity of the materials. Thermosets are insoluble, high impact resistant.

Thermosets example:

- Epoxide (EP)
- Phenol-formaldehyde (PF)
- Polyurethane (PUR)
- Polytetrafluoroethylene – PTFE
- Unsaturated polyester resins (UP) (adhesiveandglue.com)

2.1.3 Elastomers

Elastomers are made of polymers linked by chemical bonds obtaining a slightly cross-linked structure. High elongation and flexibility is the main characteristics of elastomers. Elastomers also has low permeability to air, gases and water, good thermal insulation, good mechanical properties, generally insoluble and ability to adhere. Elastomer can be stretched when a force is applied and once the force is released it can return to its original dimension. Elastomers which can be melted by using heat are called thermoplastic elastomers and elastomers which cannot be melted by heat are called thermoset elastomers.

Elastomers example:

- Silicon
- Natural Rubber
- Synthetic rubber
- Polybutadiene (adhesiveandglue.com)

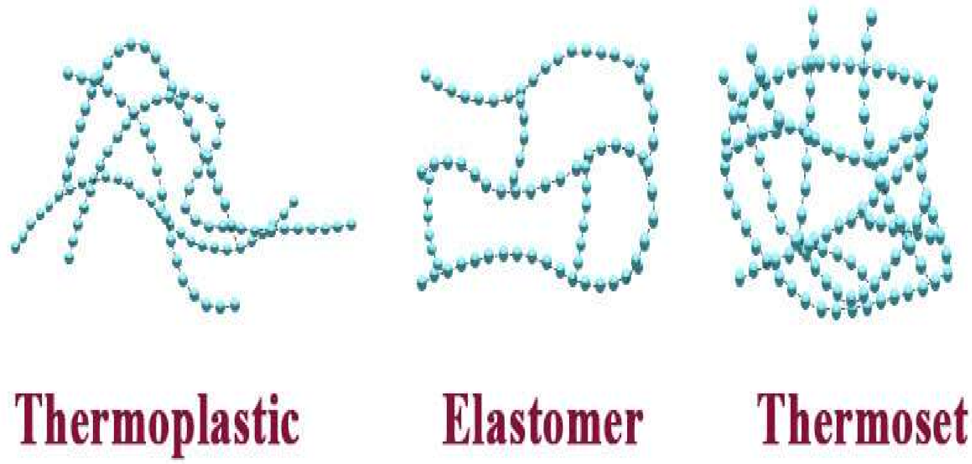


Figure 1: Thermoplastics, thermosets and elastomers (Adhesivesandglue.com)

2.2 Plastic recycling

Plastic recycling is the process of recovering plastic waste and reprocessing this material into useful products. A vast amount of plastic products is being used every day throughout the whole world. Since plastic is not bio-degradable, plastic waste takes a vast amount of space in landfills and as well as the oceans. So in order to reduce the plastic waste from landfills and reduce plastic pollution, plastic recycling is a very important actions. Plastic recycling signifies one of the most dynamic sector of plastic industries nowadays. During the recycling process, the recycled plastic is most of the time totally different from their original or former state. Plastic recycling can be divided into four sections:

- Primary - mechanical reprocessing into a product with equivalent properties
- Secondary- mechanical reprocessing into products requiring lower properties
- Tertiary- recovery of chemical constituents and
- Quaternary- recovery of energy (Hopewell et al., 2009)

Plastic recycling is step by step process. The first step is collecting the plastic waste from landfills and oceans. The second step is sorting, which means sorting out the recyclable plastic from the waste and separating similar types of plastics. It is very important to separate them by resin type and color. It can be automatically or manually. After that the plastics are shredded, then melted and finally by extrusion process the plastics can be given new useful forms. Recycled plastics are then used to manufacture useful everyday items as garbage bags, hangers, sign panels, footwear, switch boxes, road signs, pipes, flooring tiles, urban furniture, etc.

Plastic recycling is very important issue in order to save the planet earth as it does not break down easily and takes hundreds of years to degrade. Plastic recycling saves energy and reduces the amount greenhouse gas emission. Plastic recycling is relatively cheaper than recycling other material as it is lightweight and takes less fuel to ship or less effort during collecting, separating or sorting.

In order to be able to recycle plastics, it is very important to know different kinds of plastics, their labelling and their applications. The table below shows various types pf plastics, their numbers and application for their recyclable resins.

Table 1: Summary of plastic recycling codes and applications (Wansbrough and Yuen)

Code	Name	Description	Examples
1 PET	Polyethylene terephthalate	Usually clear or green, sinks in water, rigid, glossy	soft drink bottles biscuit trays
2 HDPE	High density polyethylene	Slightly opaque, low gloss, crackly film	milk bottles supermarket bags
3 PVC	Polyvinyl chloride	Semi-rigid, glossy, sinks in water	detergent bottles pipes raincoats
4 LDPE	Low density polyethylene	Flexible, not crinkly	bread bags six-pack rings shrink wrap
5 PP	Polypropylene	Semi-rigid, low gloss	straws screw-on lids
6 PS	Polystyrene	Often brittle, glossy	polystyrene foam yoghurt containers
7 Other	This includes a variety of copolymers such as ABS acrylonitrile butadiene polystyrene, and multi-layer plastics	—	margarine containers squeezable sauce bottles

2.3 Polystyrene

Polystyrene is a synthetic aromatic polymer made from the monomer styrene with the help of a process called polymerization. Polymerization is a process where monomers are joined with each other in order to make long molecular chains called polymer, is called polymerization. (Crawford, Page. 2, 1998)

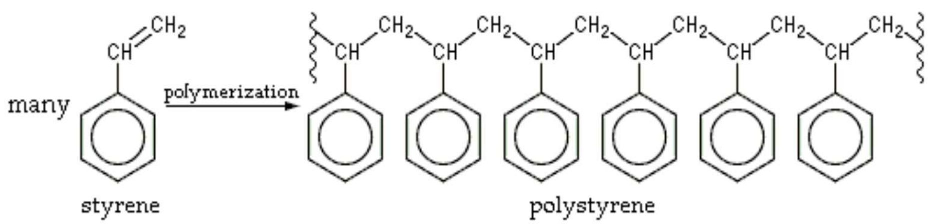


Figure 2: Styrene polymerization process (Derrick, 2010)

Polystyrene was discovered in 1839 by Eduard Simon, he distilled an oily substance named styrol. After few days, Eduard noticed that the styrol had thickened into a jelly called styrol oxide from oxidation. In 1845 English chemist John Blyth and German chemist August Wilhelm von Hofmann showed that the same transformation of styrol took place in the absence of oxygen. They called their substance metastyrol. Analysis later showed that metastyrol was chemically identical to Styrol oxide. In 1866 Marcelin Berthelot identified the formation of metastyrol or Styrol oxide from styrol as a polymerization process. About 80 years later it was realized that heating of styrol starts a chain reaction that produces macromolecules, following the thesis of German organic chemist Hermann Staudinger (1881–1965). This eventually led to the substance receiving its present name, polystyrene. (PlasticsEurope)

Styrene is the monomer of polystyrene which is obtained from crude oil. Distillation, steam-cracking and dehydrogenation are required to convert the crude oil into styrene.

Crude oil refining produces naphtha which contains a mixture of low molecular weight saturated hydrocarbons of various compositions. By the cracking process, it is converted into a smaller group of unsaturated hydrocarbons. Cracking is a process where naphtha is heated in the absence of air to a high temperature. By the distillation process, the mixture is separated into its fundamental components producing mainly ethylene, propylene, styrene and such. These products can be used in petrochemical plant either as feedstocks or fuels. By the cracking process, natural gas can also be converted into ethylene and other products. Ethylene and benzene are reacted to form ethylbenzene which is dehydrogenated into styrene. At the end polystyrene is produced by polymerizing styrene. This is an exothermal reaction that can be started with organic peroxide or by heat. GPPS is manufactured by polymerization of styrene alone. HIPS is manufactured by adding polybutadiene rubber at the styrene polymerization stage. The final produce is obtained in the form of pellets. After that the polystyrene pellets are ready to be extruded, thermoformed or injection molded as required. (Plastic Europe)

The figure below shows the process of polystyrene production from crude oil and natural gas

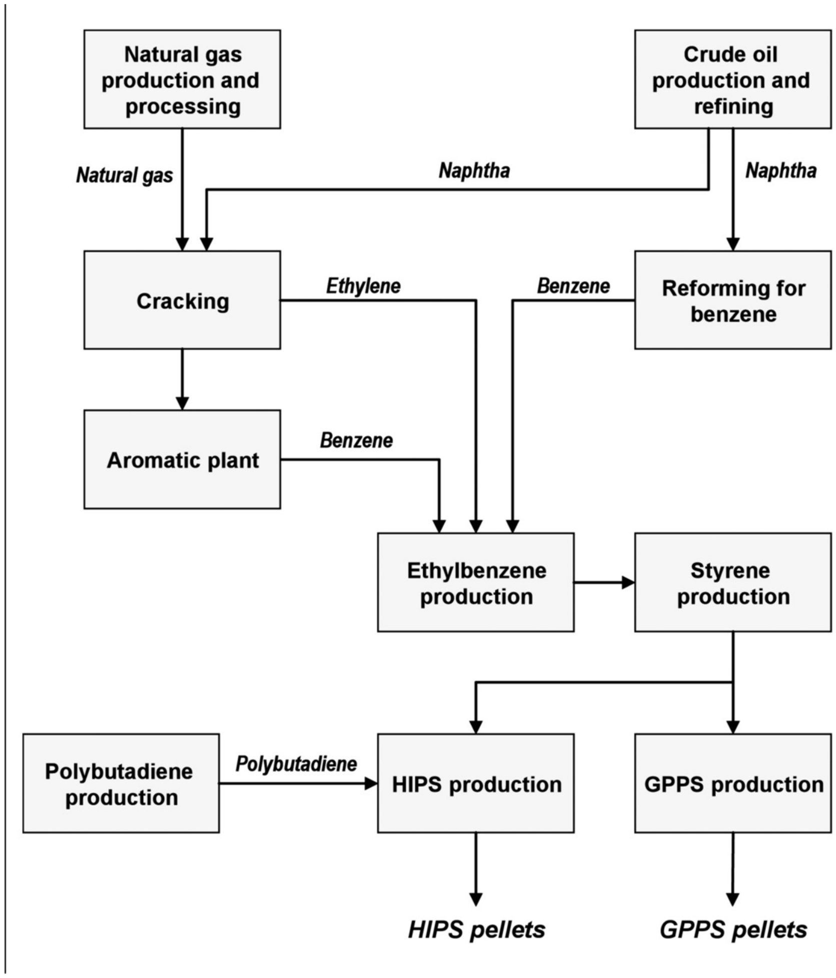


Figure 3: Polystyrene production from crude oil and natural gas (Plastic Europe 2008)

Polystyrene can be rigid or foamed. It has low melting point, hard, brittle, and naturally transparent but can be colored by adding colorants. Unfilled polystyrene is amorphous and has a glassy, sparkling appearance. It is also known as crystal polystyrene or general purpose PS. High impact polystyrenes (HIPS) are made by adding rubber or polybutadiene with the GPPS in order to increase the toughness and strength during the polymerization process. Polystyrene has good water resistance, high dielectric strength, balanced properties of impact strength and heat resistance, can be easily machined. Polystyrene is widely used in home appliances, toys, electronics and food industry because of its good impact strength at low temperatures. (Polystyrene Specifications, 2016).

Polystyrenes are generally processed by injection molding. But because of its excellent process ability, other methods such as blow and vacuum molding, thermoforming, extrusion or compression molding, and machining work equally well. PS grades are resistant to a wide variety of chemicals: alkalis, salts, lower alcohols, and weak acids. Polystyrenes also comply with FDA regulations. (Polystyrene Specifications, 2016)

The physical properties of polystyrene are due to the presence of weak van der Waals forces between the chains of polymer. The forces weaken when heated and the chains glide past one another. Because of that, polystyrene is highly elastic and softens when heated beyond its glass transition temperature. The mechanical properties of polystyrene include tensile strength, elongation, young`s modulus, impact strength, and toughness. Because of photo oxidation, polystyrene degrades when exposed to sunlight, which affects its mechanical properties. Thermal properties of polystyrene such as thermal conductivity, glass transition temperature, heat distortion temperature are exhibited when it is subjected to heat. Polystyrene is solid in normal temperature, but it turns into liquid form when heated above glass transition temperature. This liquid form can be used easily for molding or extrusion. (Deshpande, 2013)

Properties of polystyrene are listed below in table 2.

Table 2: Properties of polystyrene (Polystyrene Specifications, 2016)

Physical	
Density	1.05 (g/cm^3)
Water Absorption, 24 hrs.	0.06 %
Mechanical	
Tensile Strength	7,500 (psi)
Tensile Modulus	450,000 (psi)
Tensile Elongation at Break	47 %
Flexural Strength	61,000 (psi)
Flexural Modulus	475,000 (psi)
Compressive Strength	14,500 (psi)
Hardness	75M (Rockwell scale)
Thermal	
Coefficient of Linear Thermal Expansion	4.0 (x 10-5 in./in./°F)
Heat Deflection Temperature	95 °C
Max Operating Temperature	65 °C
Thermal Conductivity	0.14 W/m-K
Glass transition temperature	95 °C
Vicat Softening Temperature	107 °C
Electrical	
Dielectric Strength	60 (V/mil)
Dielectric Constant at 1MHz	2.5
Arc Resistance	70 sec
Volume Resistivity	(ohm-cm) at 50% RH
Rheological	
Melt flow index	11g/10min

Polystyrenes have excellent mechanical and physical properties. It is lightweight, relatively inexpensive, hard, generally transparent, but available in various colors, has excellent insulation properties, good processability. Drawbacks of polystyrene are flammability, Poor solvent resistance, brittle, Subject to stress and environmental cracking, poor thermal stability. The advantages and disadvantages of polystyrene are shown below in table 3.

Table 3: Characteristics of polystyrene (Polystyrene Plastic, 2016)

Advantages	Disadvantages
• Hard and stiff	• Brittle
• Excellent insulation properties	• Poor thermal resistant
• Inexpensive	• poor solvent resistant
• food contact acceptable	• Flammable
• Good processability	• Subject to stress and environmental cracking
• Lightweight	
• Water resistant	

2.3.1 Applications of polystyrene

Polystyrene is designed for applications demanding excellent mechanical and electrical properties. Because of that polystyrene has an enormous variety of applications. It is widely used in home appliances, protective packaging, toys, food industry, construction industry, medical equipment, electronics and automobile industry etc. The following table shows varieties applications of polystyrene in everyday life.

Table 4: common uses of polystyrene (PlasticEurope)

Packaging industry	• Packaging containers for fragile or protective items such as glass, foods etc. • Electronics • Other appliances due to its excellent cushioning properties and strength
Food industry	• Disposable food containers • food containers to prevent food spoilage because of its excellent insulation properties
Electronics	• Computers • televisions • all types of IT equipment • cassette tape housing • clear jewel boxes to protect CD's and DVD's
Medical industry	• disposable petri dishes • pipettes • tissue culture bottles • Medical cups, medical keyboards, plastic boxes and other types of laboratory ware due to its inert nature, water impermeability and durability
Construction site	• Building floating docks • pipes • window profiles • to insulate ceilings, walls, floors, etc., from external temperature variations and humidity
Household appliances	• Kitchen and bathroom accessories • garden equipment, lawn accessories • smoke detector, Refrigerator, oven, blender, toys etc.

2.3.2 Polystyrene market and consumption

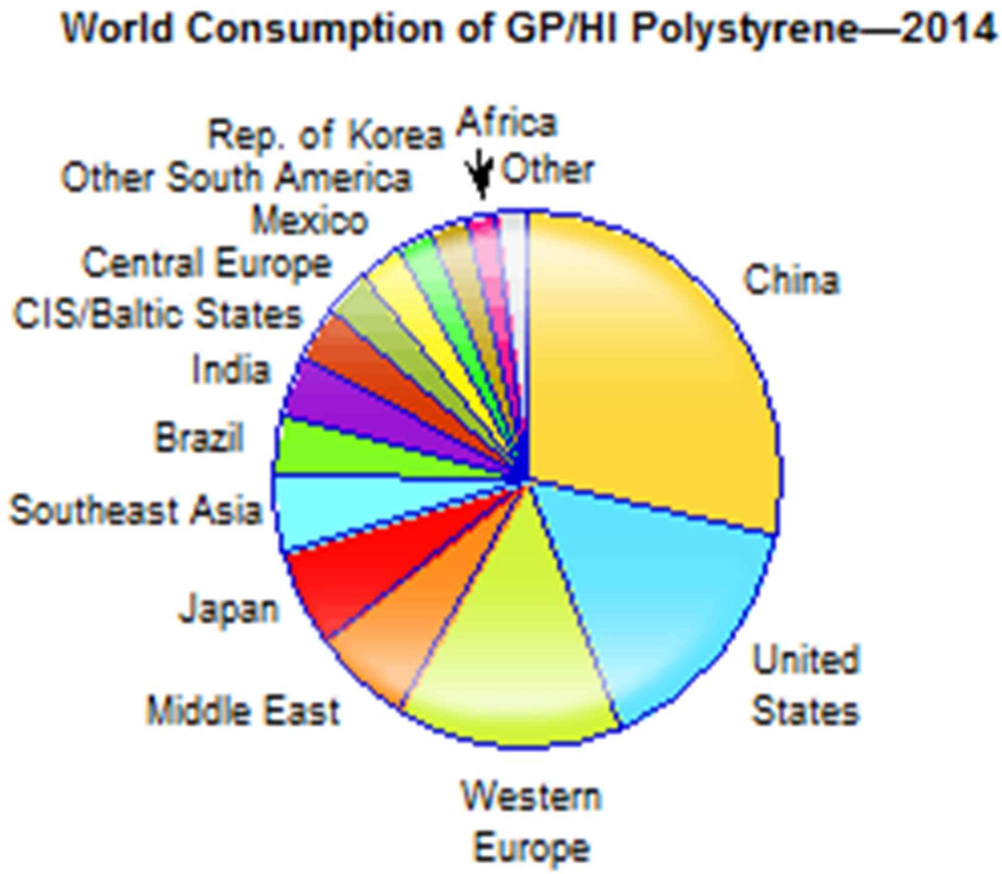


Figure 4: World consumption of PS (Chemical Economics Handbook Polystyrene, 2014)

The pie chart shows the world consumption of polystyrene in 2014. According to the chart, the production and consumption of polystyrene was highest in Asia with 50% of total world production and 46% of total consumption. China is the leading segment in the Asia-Pacific market, owing to the availability of cheaper raw materials and low labor costs. North America and Western Europe follow distantly at about 15–20% of total production and consumption. The important evolving economies such as Brazil and India also plays major role in the global polystyrene market. The largest market for polystyrene is in packaging applications. accounting for 37% of world consumption in 2014. Applications include a variety of products ranging from food containers and trays, to one-time use disposable cutlery, as well as nonfood packaging, such as clear bottles, plastic lids, and jewel cases used to protect CDs. Electronics and appliances represent the second-largest market for polystyrene. Overall growth for polystyrene in 2014–2019 is expected to be only about 1–2% per year, led by 2–3% growth in China and India. Consumption in Western Europe and North America is expected to decline and further alliance in the industry is likely. (Chemical Economics Handbook Polystyrene, 2014)

2.4 Laboratory Tools and Instruments

All the machines and instruments that has been used has been located in the Arcada plastic laboratory. The idea of this section is to introduce the machines that has been used and to briefly explain their operating process and outcomes. The plastic shredder, extruder, injection molding machine has been used in order to process the material. The melt flow index machine and the testometric tensile testing machines has been used in order to test the mechanical properties of the material.

2.4.1 Plastic Shredder

The principle of this machine is quite simple. Basically the plastic material is which is desired to be recycled are inserted into the machine through a hopper. Then the materials are transported to the cutting blade or shredding blade which shred the material into quite small pieces or plastic flakes which can be used as plastic resin. Those shredded materials are then collected into a collector. Between the shredding blade and the collector there is a filter which filters the uneven or the bigger particles. These uneven or big plastic pieces can damage the extruder or injection molding machine screw. So the expected outcome from this machine is to get even shaped plastic flakes in order to run the next recycling process properly.

Figure 5: Plastic shredder (Author, Arcada Plastic Laboratory 2016)

2.4.2 Extruder

Extrusion is one of the common plastic processing method. In this process, the raw material in which can be either granules or pellets, are inserted into the barrel through a hopper. The raw material or the resin is usually gravity-fed through the feed throat where the material comes in contact with the screw. This long rotating screw forces the material forward in the barrel towards the die. As soon as the resin moves along within the barrel, it is exposed to desired high temperatures depending on the resin until it starts to melt. Most extruder's have a barrel that gradually escalate the heat from the filling end to the feed pipe to allow steady melting and minimize the risk of overheating which can result to plastic degradation. At the end of the barrel, the molten plastic is forced through a filter plate which removes any contaminants from the material. After passing the filter plate, the material enters into the die where it cools down and hardens, generally with the help of water bath. Once the material has cooled, it can be cut into small pellets by using pelletizer. During the extrusion process, it is important to maintain the correct temperature level. (Crawford, page 246, 1998) The figures below show the schematic view of the extruder and the water bath.

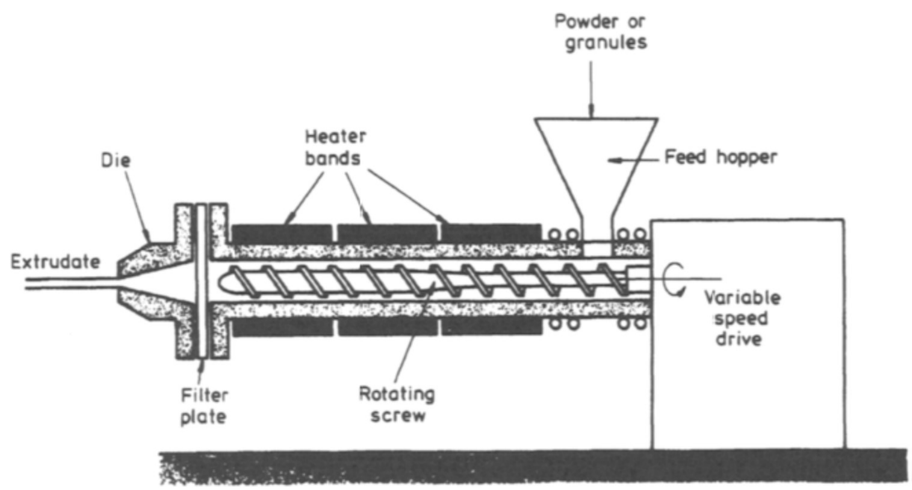


Figure 6: Schematic view of screw extruder (Crawford, page 246, 1998)

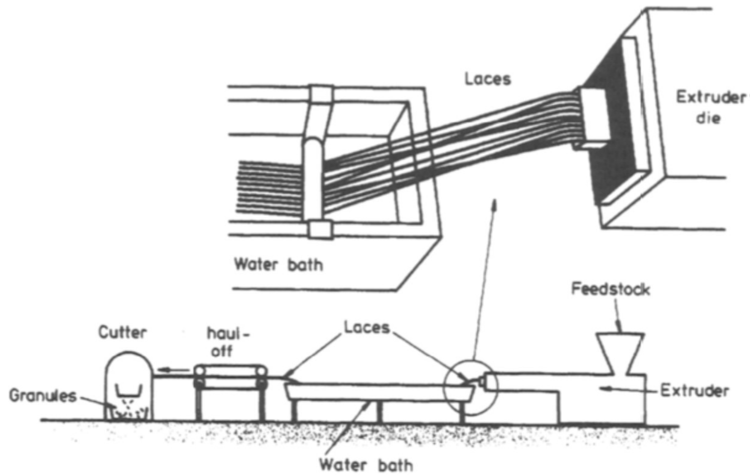


Figure 7: Water bath (Crawford, page 265, 1998)

An extruder screw principally has three different zones. They are -

Feed Zone: The function of this zone is to warm up the plastic and transfer it to the following zones. The design of this section is important since the constant screw depth must supply sufficient material to the metering zone so as not to starve it, but on the other hand not supply so much material that the metering zone is overfilled. The ideal design is related to the nature and form of the feedstock, the geometry of the screw and the frictional properties of the screw and barrel in relation to the plastic. The frictional properties of the feed-stock material have a significant impact on the melting rate which can be accomplished. (Crawford, page 246-247, 1998)

Compression Zone: In this zone the depth of the screw gradually decreases so as to compressed the plastic. This compression has the double role of pressing any trapped air pockets back into the feed zone and improving the heat transfer through the reduced thickness of material. (Crawford, page 246-247, 1998)

Metering Zone: In this zone the screw depth is again constant but considerably less than the feed zone. The melt is regulated in this zone in order to supply at a constant proportion, material of constant temperature and pressure to the die. This zone is the simplest one to analyze as it includes a viscous melt flowing along a uniform channel. (Crawford, page 246-247, 1998)

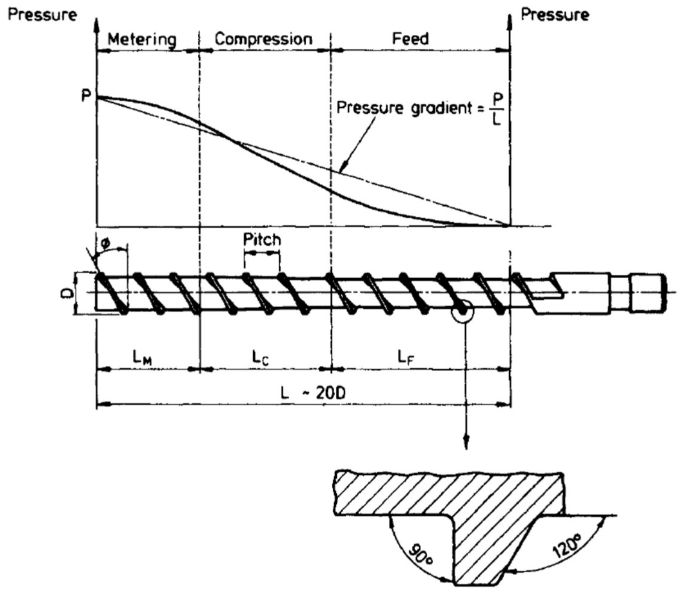


Figure 8: Different zones of an extruder screw (Crawford, page 247, 1998)

Figure 9: Extruder (Author, Arcada Plastic Laboratory 2016)

2.4.3 Pelletizer

The function of this machine is to make pellets from extrudate coming through the extrusion machine. The extruder and the pelletizer has been used almost at the same time. As soon as the extrudate started to coming through the mold as a form of wire, it has been cooled by using the water bath system. After that the extrudate were directly inserted into the pelletizer in order to make to pellets. Inside the pelletizer, there is a cutting blade which cuts the extrudate by required size. While extruding, it is very important to make sure that the extrudate are in proper size as the pelletizer is unable to cut too big or too small sized extrudate. And even if it does in some cases, the result will be poor quality pellets.

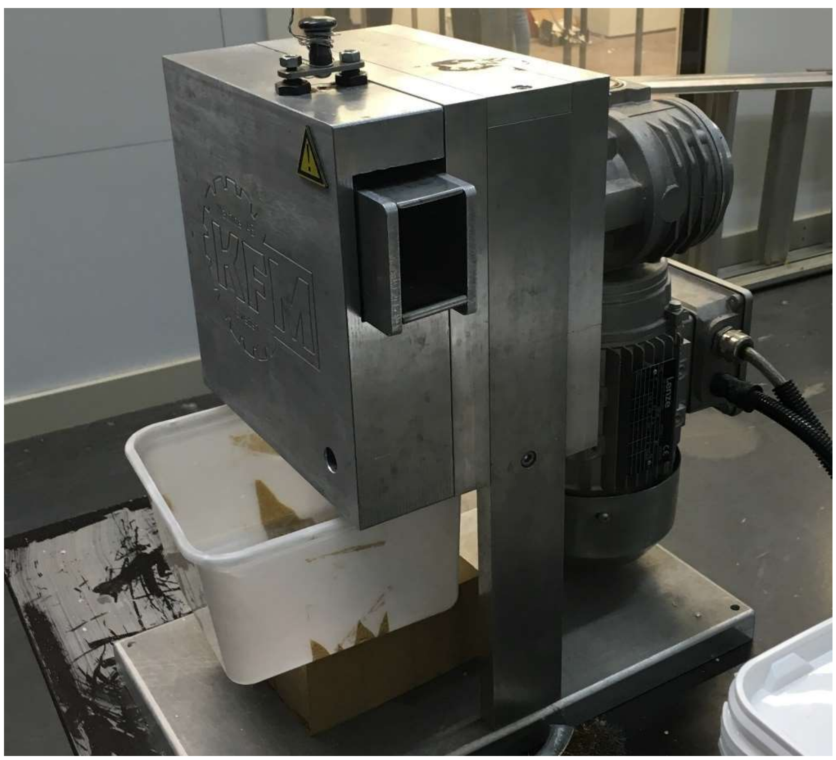


Figure 10: Pelletizer (Author, Arcada Plastic laboratory 2016)

2.4.4 Injection Molding Machine

The injection molding machine is one of the most commonly used machine nowadays. The biggest advantage of this machine is it can produce wide variety of materials in any sizes. The mold and the parameters can vary depending on the required products. Different plastic materials have different parameters.

The figure below shows the illustration of the different parts of an injection molding machine.

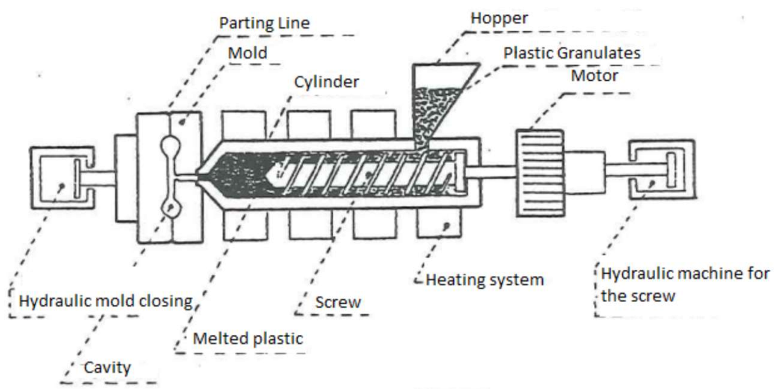


Figure 11: An injection molding machine (Terselius, Page. 155, 1998)

An injection molding machine basically consists of screws, cavity, cylinder, heaters, hopper, mold, motor, parting line. Hydraulic machine for the screw. Hopper is used to transport the materials towards the cylinder or the barrel. The cylinder is heated up with the heater in order to heat up the plastic material. The screw moves along the cylinder which helps the material to pass along the cylinder. The heating system is located in different points of the cylinder. The motor provides the power input in order for the screw to rotate within the cylinder. The purpose of the cavity is to produce and contain the shape of the injection molded part. The surface which separates the cavity from the mold is called parting line. The hydraulic machine for the screw pushes the cylinder forward during the injection stage. (Weckström, 2012)

The injection molding process quite simple. Basically the materials, which is in the form of pellets or granules, are inserted into the cylinder through a hopper. The material is heated inside the cylinder with the heating system and turns into molten plastic. The screw inside the cylinder forces the molten plastic towards the mold and then it is clamped together with force. Once the process reached required cooling time, the mold opens and the final product is removed automatically or manually. (Crawford, page 279, 1998)

The figure below demonstrates the injection molding cycle after the molten plastic is injected into the mold.

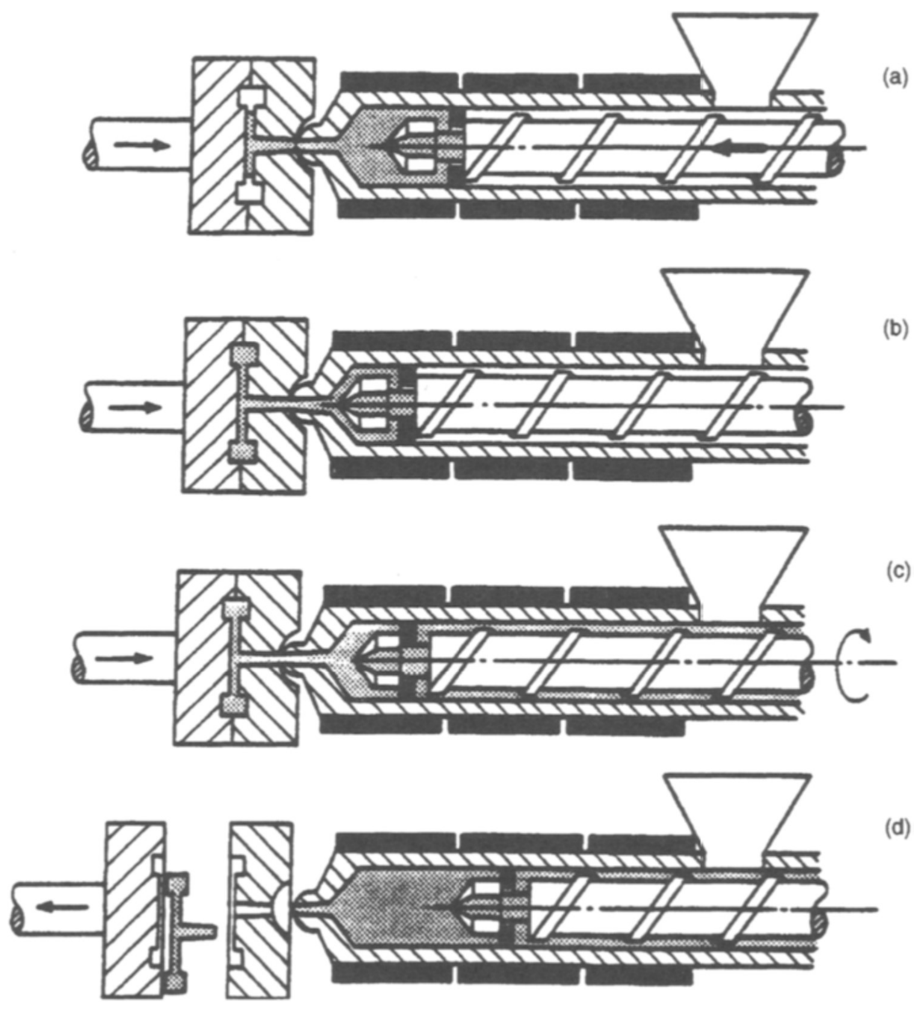


Figure 12: injection molding machine steps (Crawford, page 281,1998)

The process starts with the injection unit. Once the mold is closed, the screw pushes the melt into the mold. The air inside the mould is pushed out through small vents at the edges of the melt flow path. When the cavity is filled, the screw continues to push forward in order to apply a holding pressure which squeezes the extra melt into the cavity to reduce the shrinkage of the plastic as it cools. This holding pressure is only effective as long as the gates remain open.

Once the gate solidifies, the plastic can no more enter the mould and the screw starts moving backward and draw in new plastic from the hopper. The materials are then transported to the front of the screw but as the mould cavity is filled with plastic, the effect is to push the screw backwards. This prepares the next shot by adding the desired amount of plastic in front of the screw. Once the preset shot size amount is reached, the screw stops rotating and the machine waits for the moulding and runner system to be completed. The last cycle starts once the molding has cooled down to a certain temperature in order to maintain its shape. After that the molded part or the final product is ejected automatically or manually. Once the final product is ejected, the mold closes and its ready to start a new cycle. (Crawford, page 282,1998)

The figure below shows different stages during injection molding process in a pie chart.

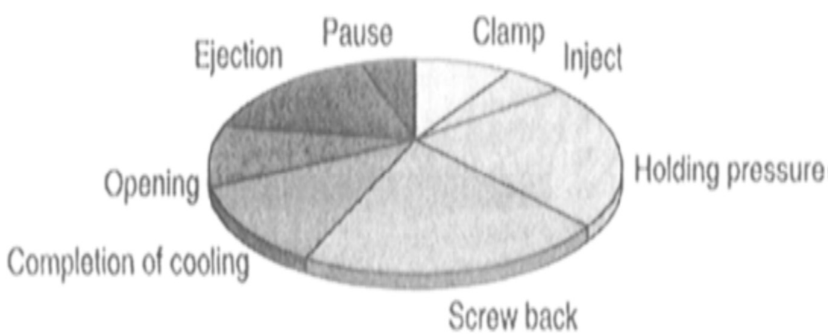


Figure 13: Stages during injection molding (Crawford, page 282,1998)

Figure 14: Injection molding machine (Author, Arcada plastic Laboratory, 2016)

2.4.5 Testometric Tensile Testing Instrument

Testometric tensile testing instrument is used for evaluating the mechanical properties such as strength and deformation of a material. Tensile test is one of the most common testing method for any material and is much faster and reliable than any other methods. In this method, a specimen or sample is subjected to a controlled tension until failure. The instrument is connected to a software called win-test analysis, which provides the value of tensile strength and young`s modulus as a form of datasheet. The procedure of the instrument is as following. At first, the right dimension of the sample, which are length, width and thickness, is inserted. The length is distance between the two grips in the machine that hold the piece in place. The thickness and width are measured at the middle of the piece. Then the sample is inserted between the grips and are closed properly. After that by pressing the start button on the software, the testing starts. The instrument applies an increasing load to the test sample up to the point of failure. The process creates a stress-strain curve which illustrates how the material reacts throughout the tensile test. The test can be done as many time as required. After finishing the test, the data are saved as PDF format for later calculation and evaluation.

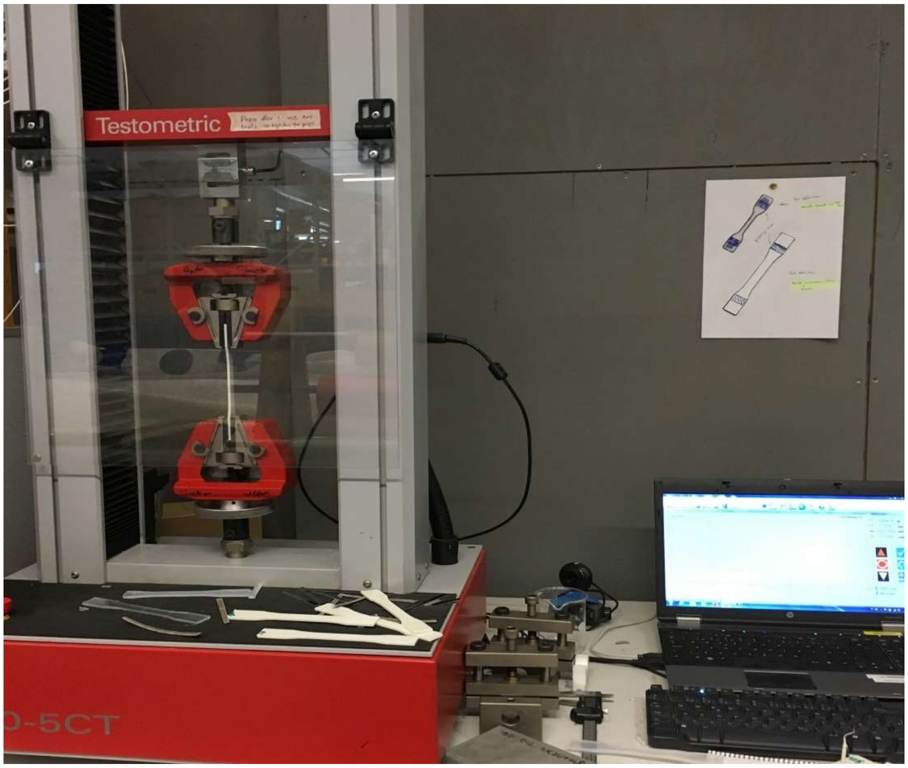


Figure 15: Testometric tensile testing instrument (Author, Arcada plastic Laboratory, 2016)

2.4.6 Melt Flow index Instrument

The melt flow index instrument determines the melt flow properties of a material at a specific temperature and load. In other words, the test determines how nicely a polymer is able to flow. The melt flow index instrument consists of cylinder, barrel, piston, piston head die, die retaining plate, insulation, insulating plate, removable weight. There are two different procedures of this measurement method. One is mass measurement method and the other one is displacement measurement method. The melt flow index can be determined by either ASTM D1238 standard or ISO1133 standard. The melt flow index is usually calculated in g/10min. Melt flow rate is an indirect measurement of the molecular weight of a plastic. High melt flow rate corresponds in low molecular weight and vice versa.

The MFI test is done by extruding molten material from the barrel of a plastometer under preset conditions of temperature and load. Around 5 to 6 grams of the sample is taken in the barrel where the sample is preheated for a specified amount of time. A die with an opening of typically around 2 mm diameter is inserted into the barrel. The material is packed properly inside the barrel to avoid any air pockets. A piston is introduced which acts as the medium that causes extrusion of the molten polymer. Once the preheating is done, a specified weight is introduced onto the piston. The weight applies a force on the material and it immediately starts flowing through the die. A sample of the cut melt is taken after the desired period of time and is weighed accurately. For melt mass flow rate, time segments of the extrudate rate is calculated in g/10min. For the melt volume flow rate, the distance that the piston moves in a specific time for the piston to move a specific distance is measured in cm^3/10min. Melt volume flow rate may be converted to melt mass flow rate, or vice-versa, if the density of the material is known. (Wikipedia,2016)

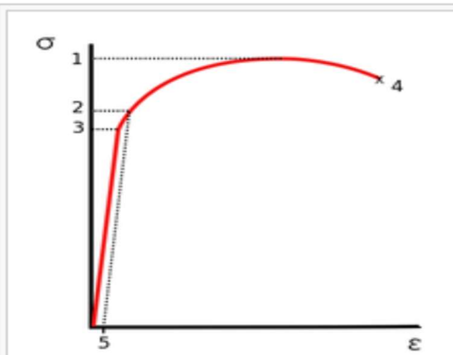
Figure 16: Melt Flow Index Instrument (Author, Arcada plastic Laboratory, 2016)

2.5 Mechanical Properties

The mechanical properties help to determine the characteristics and usefulness of any material. The mechanical values can be obtained from the tensile strength, young`s modulus and melt flow index tests. These values are easily comparable with other materials. In this section the mechanical properties and their formula has been discussed.

2.5.1 Tensile strength

Tensile strength is a measurement of the maximum amount force a material can withstand before failure or breaking. The tensile strength can be determined by the tensile testing method. The tensile test gives the data as a stress vs strain graph. The highest point of this stress versus strain curve is the tensile strength of the material being tested. Tensile strength unit is N/mm² or MPa. (Wikipedia,2016)



Stress vs. Strain curve typical of aluminum
1. Ultimate strength
2. Yield strength
3. Proportional limit stress
4. Fracture
5. Offset strain (typically 0.2%)

Figure 17: stress-strain curve (Wikipedia,2016)

The formula for calculating tensile strength is given below.

σ = F / A

where,

σ= tensile strength [N/mm² or (MPa)]

F= Force [N]

A= The cross-sectional area of the sample [mm^2] (Wikipedia,2016)

2.5.2 The Young`s modulus

Young`s modulus is the measurement of the stiffness of a material. It is defined as the ratio of uniaxial stress over uniaxial strain. The value determines how much a material will extend under tensile load or shorten under compressive load. Young`s modulus is calculated by dividing the tensile stress or strength with the tensile strain in the elastic portion of the stress-strain curve. The formula of young`s modulus is given below.

$$E = \frac{tensile\ stress}{tensile\ strain} = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta\,\mathrm{L}/\mathrm{L}}$$

Where,

E = Young`s modulus or modulus of elasticity (MPa)

F = Force exerted on an object under tension (N)

A =Original cross sectional area of the piece tested (mm²)

ΔL = changes in length pulled (mm)

L = Original length of the piece being tested (mm) (Wikipedia 2016)

2.5.3 Melt flow index

The melt flow index test is done in order to determine the fluid mechanical properties for molten polymer at a specific temperature and load. The melt flow index can be obtained by the melt flow index testing method. The value obtained from the machine is the amount of materials in grams, that has flown through the die in 10 minutes. (Arcada Plastic Laboratory,2016)

The formula for melt flow index is given below.

Mass Flow rate = (600*m) /t [g/10 min]

Where,

t = time of extrudate in seconds
m= weight of extrudate
600=the factor used to convert grams per second into grams per 10minutes.
(Arcada Plastic Laboratory,2016)

3 METHOD

In this section, the recycling process of the post-consumer polystyrene cups has been discussed in details. The whole experimental part can be divided into three steps.

1. Collecting and preparing the PS cups
2. Recycling the material
3. Testing the material

The information about the PS cups used for this thesis project, dog bones and used parameters for different machines can also be found in this section.

3.1 Collecting and preparing material

For this experiment, post-consumer polystyrene cups have been collected. In order to get the exact information about the raw material of these cups, such as, what kind of polystyrene they are made of, the manufacturer (Huhtamaki.com) and the distributor company (Pirkka) of these product has been contacted through email. According to their information, the collected PS cups are made by mixing GPPS and HIPS, which contains 75-85% of GPPS. Collected PS cups were transparent, only a small amount of cups were white in color and they were in different shapes.

After collecting, the PS cups have been washed and dried properly in order to recycle them. The cups have been washed with water and dishwashing soap. Later, they were wiped with clean cloth and set to dry properly. After that they were ready for the recycling process. Before starting the recycling process, the cups has been weighted. The total weight of collected polystyrene cups was 1.5kg.

Figure 18: Post-consumer Polystyrene cups (Author)

3.2 Material Recycling

The idea of material processing part was to recycle the materials and produce dog bones in order to be able to test the sample using material testing machine. The recycling process has been done by the following steps.

1. Shredding
2. Extruding and pelletizing
3. Injection molding

The safety instructions, such as using safety goggles, safety gloves etc. has been strictly followed throughout the recycling process. The whole recycling process has been done twice. And all the parameters, procedures, safety precautions were the same in both recycling process.

3.2.1 Shredding

The material recycling process started with the shredding process. In this process, the PS cups have been shredded using the shredder machine located in Arcada Plastic Laboratory. Using the shredder was very easy as the procedure of this machine is quite simple. The shredder is the only recycling machine which does not require any parameters. The process of the shredding machine has been discussed in the literature review section.

During the shredding process, some of the collected shredded granules which were comparatively big in size has been shredded for the second time in order to get even shaped granules. Otherwise the uneven or bigger granules may have stuck in the hopper during the extrusion process which can damage the screw inside the barrel. In order to avoid such problems, it has been made sure that all the granules were in same size. Once all the material has been shredded, they were collected and set aside to allow the shredded material to get dry completely.

Table 5: Amount of shredded material and waste

Recycle runs	***Amount of material to be shredded***	***Collected shredded material***	***Total waste during shredding***
1.	1500 g	1146.7 g	353.3 g
2.	848 g	644.4 g	203.6 g

The material has been wasted as a result of not being shredded properly at all and splitting on the floor during the process.

The shredder has been used two times in total. First time it was used to shred the PS cups and the second time it was used to shred dog bones which were made after the first recycling process by the injection molding process and were tested by using the material testing machine. Shredding the dog bones were much easier than shredding the PS cups. The PS cups were getting stuck in the shredding blade quite frequently. As a result, the process needed to be stopped few times in order to fix the problem. Also a lot of uneven shaped granules were collected in the filter which were shredded once again afterwards. On the other hand, there was no such problems while shredding the dog bones for the second recycling runs. It was quite easy and quick.

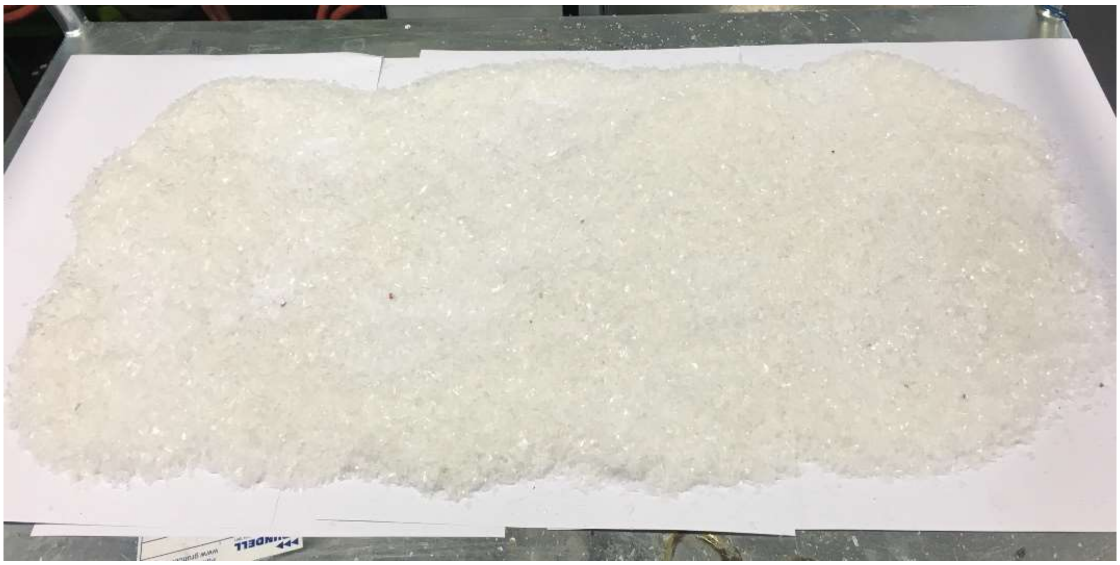


Figure 19: Shredded flakes from PS cups (Author)

3.2.2 Extrusion and Pelletizing

The primary step for using the extruder is to switch on the machine which also includes checking the water system, ventilation, setting the water bath etc. The parameters are the most important things to take into consideration in this process. The set value temperature for all the six zones were 185ºC and the extruder rotation set value was 60rpm. Once the required temperature has been reached, the machine was ready to use. After that, the granules were extruded following the machine procedure carefully. The machine procedure has been discussed in details in the literature review section.

The extruder was also used twice in total. The parameters were same in both cycle. In the first cycle, the PS cups granules has been extruded and the second time the once recycled material has been extruded. Due to lack of experience, extruding the first time was slightly difficult. Some of the extrudate were too thin and some were too thick Which caused much more material waste than the second time during the pelletizing stage.

The pelletizing process starts right after the extrusion. They were pretty much done at the same time. At first, the extrudate flows through the molds, cooled by the water bath system. Right after the water bath cooling system it was then inserted into the pelletizer in order to make pellets from the extrudate. During the first pelletizing process, a good amount of the extrudate were wasted as the pelletizer was unable to pelletize them due to their improper size. But the second time, the process was quite smooth and only a small amount has been wasted. The weight of the pellets has been recorded after pelletizing. Around 10g of pellets were collected and kept aside both times for the melt flow index test.

Table 6: The amount of extrudate and wastage

Recycle runs	***Amount of material to be extruded***	***Collected extrudate as pellets***	***Total wastage***
1.	1146.7 g	848 g	298.7 g
2.	644.4 g	520 g	124.4 g

3.2.3 Injection molding

The last step of material recycling process was the injection molding stage. In this stage, the idea was to produce dog bones in order to test the mechanical properties of the material. Having the right parameters for the injection molding is the most important thing to consider in order to produce a good testing piece. The parameters are different for different materials. The pellets have to be completely dry in order to run the process properly. The injection molding has been done safely and properly following the machine procedure described in the literature review section. During the first injection molding cycle, 54 pieces of dog bones was produced and during the second cycle 32 pieces of dog bones were produced.

Table 7: Injection molding parameters

parameters	value	unit
Temperature		
Nozzle	180	ºC
Cylinder 2	190	ºC
Cylinder 3	190	ºC
Cylinder 4	190	ºC
Hopper	70	ºC
Mold temperature	40	ºC
Mold fastening		
Opening stroke	220	mm
Mold opening		
Cooling time	24	s
Injection		
Injection speed	35-40	m/s
Limitation of injection pressure	62	bar
Injection time	1	s
Holding pressure		
holding pressure	50	bar
Holding time	8	s
Plasticizing stroke	46	mm

3.3 Material Testing

The final step of method is to test the recycled material. Testing the mechanical properties of the material such as tensile strength, young`s modulus and melt flow index was the goal of this section. The result obtained from the material testing can help to determine the effects of recycling process on the recycled PS cups. The material testing method was done in two following steps.

1. Tensile test
2. Melt flow index test

3.3.1 Tensile Testing

The testometric tensile testing machine located in Arcada plastic Laboratory has been used to test the dog bones produced during injection molding processing. The tensile testing was done twice as well. The parameters of tensile testing are force, test speed etc. Same parameters were used in both testing cycle. Tensile testing can provide data of mechanical properties such as, young`s modulus, flexural strength, shear stress etc. The test speed used for the test was 5.1mm/min. In order to get a reliable test result, 15 pieces of dog bones from both the first time recycled and second time recycled polystyrene was tested. The dimension of all the tested dog bones were same. The length was 100mm, width was 13.1mm and the thickness was 3.1mm. The process of the tensile testing has been discussed in the literature review section. In the software, the results are shown as a graph which has been saved as PDF file. Moreover, four pieces of dog bones made out of pristine polystyrene was also tested to be able to compare the result of pristine and recycled material. Once the test was done, all the results were saved carefully for further evaluation and comparison.

3.3.2 Melt Flow Index Test

The melt flow index test determines how well a plastic material is able to flow under preset temperature and pressure. The machine procedure can be found in the literature review section. For this test, around 10g of material were saved from the pellets during both recycle runs. In this test, the parameters have been used according to the ISO 1133 standard. Therefore, the preset temperature for polystyrene was 200ºC and the amount of weight that was used to press down the molten material was 5kg. And a total 6g of the materials has been tested during the test. Once the machine reached the preset temperature which was 200ºC, the materials were inserted into the barrel in order to preheat them for exactly 5minutes. After 5minutes the 5kg weight was in order to press the material. Every after 30 seconds a small piece of the extrudate was cut automatically. The main idea was to calculate the amount of extrudate in every 10minutes. So later, during the calculation the amount of the extrudate in 30 seconds was converted into 10minutes or 600 seconds.

4 RESULT

The obtained results from the material testing process are shown and discussed in this section. The result includes tensile strength, young`s modulus and melt flow index. The results presented as a form of table, chart, graph etc.

The results are divided into three parts where tensile strength, young`s modulus and melt flow index is shown and discussed individually.

In order to compare the mechanical values of the pristine polystyrene and recycled polystyrene, the tensile test have been done in dog bones made out of pristine PS. The test result of pristine PS is also included here in order to see the difference and compare them.

4.1 Tensile strength

Tensile strength is the peak value of nominal stress during the test. The tensile strength results of pristine PS and recycled PS shows remarkable differences. But unpredictably there is not much difference between the 1st time recycled and the 2nd time recycled PS tensile strength values. The results are shown below as table, bar chart and also graph.

Table 8: Tensile strength results

Sample	***Tensile strength***
Pristine	36.975 N/mm^2
1st time recycled	30.007 N/mm^2
2nd time recycled	29.357 N/mm^2

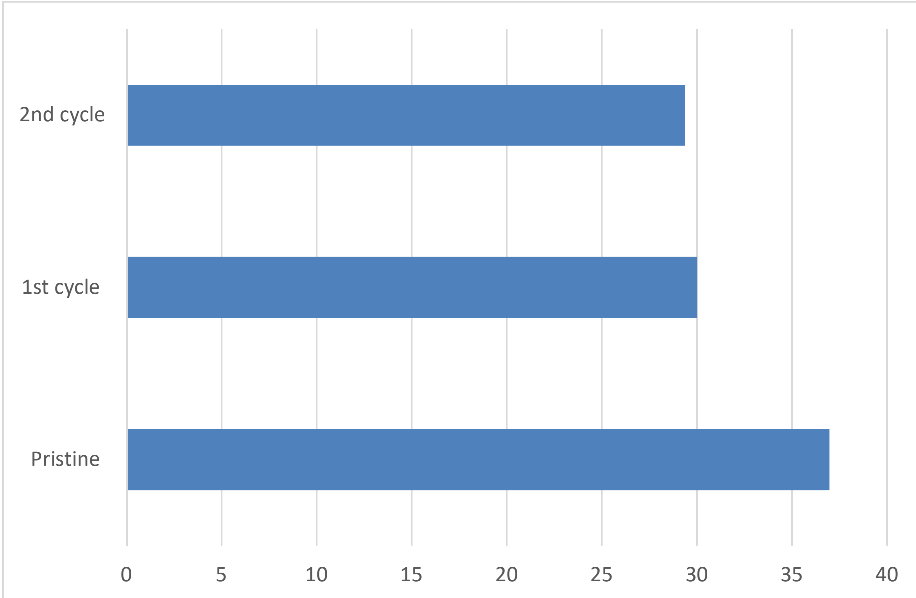


Figure 20: *Tensile strength result bar chart*

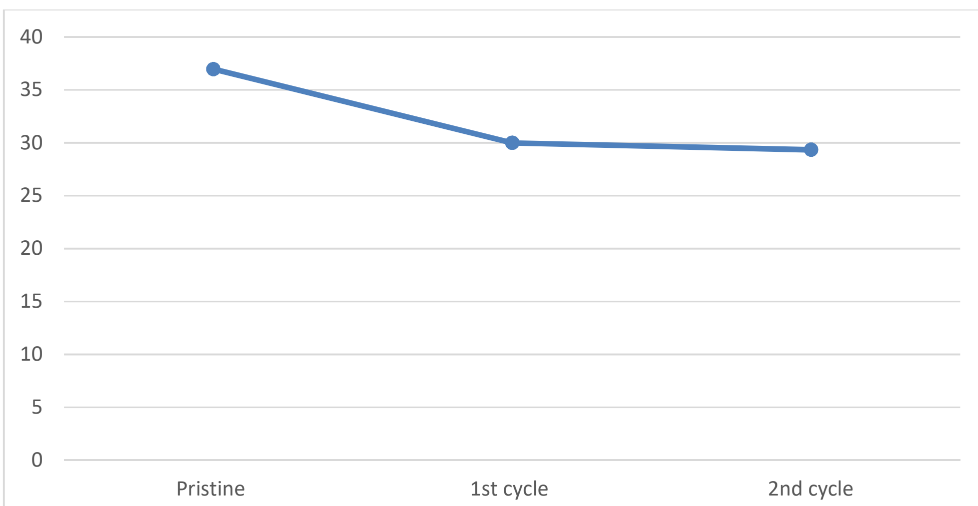


Figure 21: Tensile strength result graph

Some other values from the tensile testing results such as force at peak, force at yield, stress at peak, stress at break, strain at break and strain at yield are shown here as well in forms of table, bar chart and graph.

Table 9: Tensile test data

sample	***Force @ peak (N)***	***Force @ yield (N)***	***Stress @ peak (N/mm2)***	***Stress @ break (N/mm2)***	***Strain @ break (%)***	***Strain @ Yield (%)***
Pristine	1466.100	1466.100	36.975	36.975	2.280	2.280
1st time recycle	1281.100	1281.100	30.007	24.738	7.831	2.440
2nd time recycle	1181.000	1181.000	29.357	23.999	11.270	2.509

The following graphs and charts shows the results of force at peak and yield. In both cases of force and stress, the results showing gradual decrease from pristine PS to recycled PS.

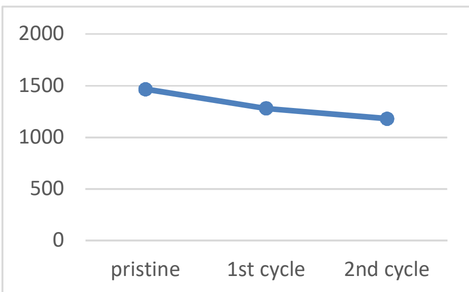


Figure 22: Forces at peak and yield

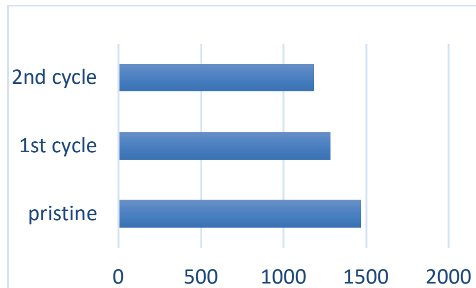


Figure 23: Forces at peak and yield

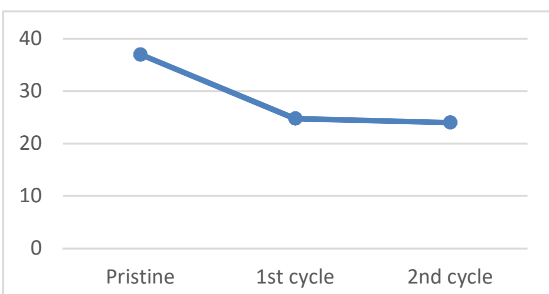


Figure 24: Stress at break

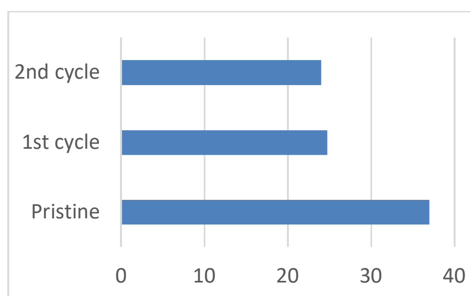


Figure 25: Stress at break

The following graph and bar chart shows drastic increase in the strain at break and yield from pristine PS to 2nd time recycled PS.

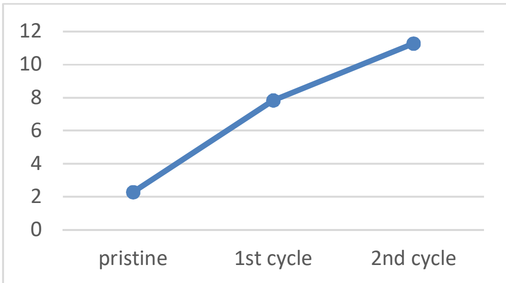


Figure 26: Strain at break

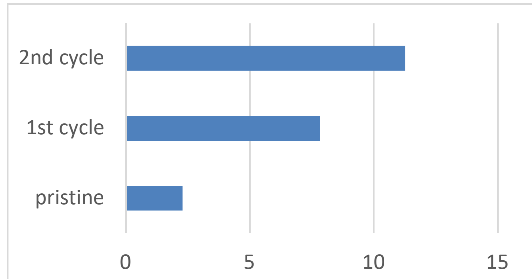


Figure 27: Strain at break

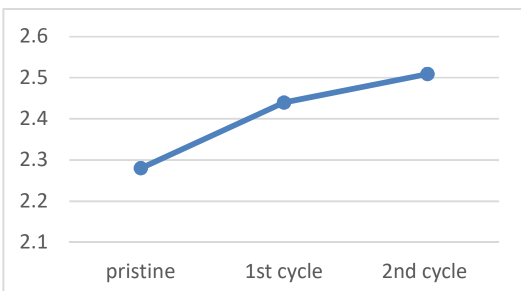


Figure 28: Strain at yield

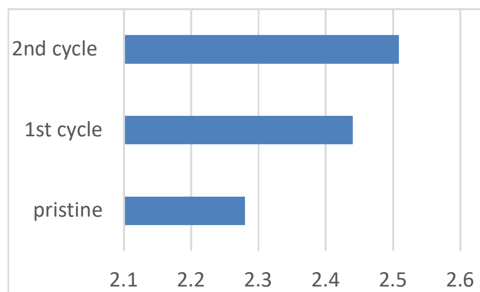


Figure 29: strain at yield

4.2 Young's modulus

The young's modulus results of pristine PS and recycled PS shows gradual decrease. The results are given below.

Table 10: Young's Modulus Result

Sample	***Young's modulus***
Pristine	1673.292 N/mm^2
1^{st} time recycled	1505.295 N/mm^2
2^{nd} time recycled	1365.690 N/mm^2

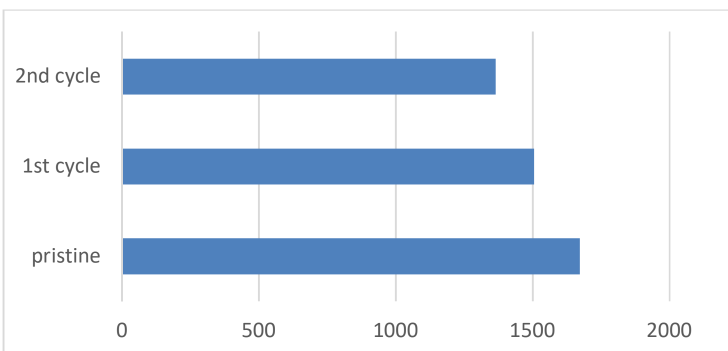


Figure 30: Young's modulus result bar chart

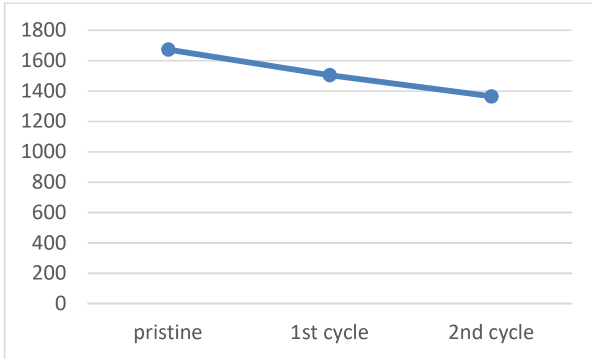


Figure 31: Young's modulus result

4.3 Melt flow index

The melt flow index result shows that the pristine PS and recycled PS value decreased dramatically whereas there is not much difference between the 1st time recycled and 2nd time recycled PS melt flow index values. The test results are shown below in different ways.

Table 11: Melt flow index result

Sample	***Melt flow index***
pristine	11g/10min
1st time recycled	5.36 g/10min
2nd time recycled	4.8 g/10min

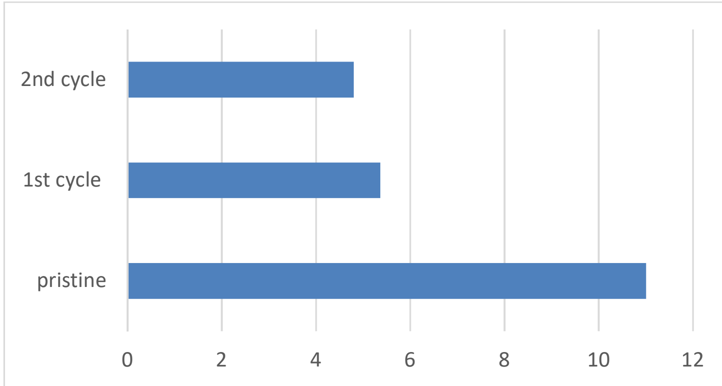


Figure 32: Melt flow index result bar chart

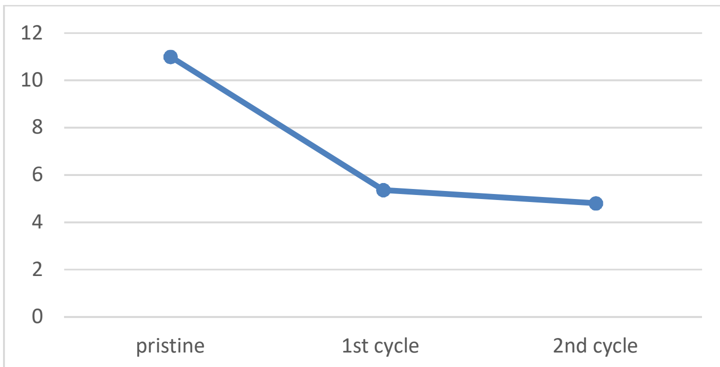


Figure 33: Melt flow index result graph

5 DISCUSSION

In this section, the research methods and the test results will be explained and evaluated. The main idea of this thesis was to compare the results of pristine PS and recycled PS and as well as to see how the results change after each recycling process. The whole recycling process went quite smoothly and without any trouble. Same parameters were used for all the individual recycling and testing machine throughout the process. All the machines were operated following the safety instructions and was cleaned afterwards according to the laboratory regulations. All the obtained results were shown as table, graph and bar chart as well in order to get a very clear idea about the test results.

The tensile strength results in table 8 shows visible difference between the pristine PS sample and recycled sample. The value for the pristine sample was 36.975 N/mm^2 and the 1st time recycled sample was 30.007 N/mm^2, which shows 18.8% decrease in the value. On the other hand, the obtained value was 29.357 N/mm^2 after the 2nd recycling. Which means, after the 2nd recycling process the tensile strength value decreased 20% from the pristine sample value.

In table 9, it is noticeable that, while all the other values such as force at peak, force at yield, stress at peak, stress at break decreased during the tensile testing, the strain values at break and yield increased on the other hand. And also, the force value at peak and the force value at yield were exactly same. The force at peak and yield for pristine sample was 1466.100N and the 1st time recycled sample value was 1281.100N, which represent 12.65% decrease. Meanwhile, the 1st time recycled and the 2nd time recycled sample have 7.8% difference between each other and the difference between the pristine and 2nd time recycled sample value was 19%.

The stress value at break for the pristine sample was 36.975 N/mm^2 and the 1st time recycled sample was 24.738 N/mm^2. The stress value for 2nd time recycled sample was 23.999 N/mm^2 which was quite a small difference. These values represent that, after the first recycling the value decreased 33% and after the second recycling the value decreased 35% from the pristine sample value. The difference between 1st time recycled result and 2nd time recycled result is quite small.

Unlike the other values, the strain values at break and at yield increased after recycling the material. The strain value at break increased dramatically whereas the strain at yield showed a slow increase rate. The strain value at break of the pristine sample was 2.280%, the 1st time recycled sample value was 7.831% and the 2nd time recycled sample value was 11.270%. On the other hand, the strain value at yield increased quite slowly after recycling. The pristine sample strain value was 2.280%. After the first recycling the value was 2.440% and after the 2nd recycling the value was 2.509%.

The young`s modulus also decreased after every recycling process which means the material was losing its stiffness after the recycling process and becoming more elastic. The young`s modulus value of the pristine sample was 1673.292 N/mm^2. After the first recycling, the obtained value was 1505. 295 N/mm^2 and after the second recycling process the value was 1365.690 N/mm^2. The obtained values represent that after the 1st time recycling, the young's modulus decreased almost 10% and after the 2nd recycling the value decreased 18% from the pristine sample`s young's modulus value whereas the difference between recycled sample value was 9.2%.

The melt flow index results changed drastically after the recycling process. The melt flow rate of the pristine sample was 11g/10min. After the 1st recycling process, the melt flow rate calculated was 5.36g/10min. Which means the melt flow rate decreased 51.3% after the first recycling process. After recycling the material for the second time, the calculated melt flow rate was 4.8g/10min, which was decreased 56.4% from the pristine sample value. And the difference between the 1st time recycled and 2nd time recycled sample`s melt flow rate was 10%.

The table below summarize the decreased mechanical properties value of the test results in percentage.

Table 12: Summary of obtained results percentage

Recycle runs	***Tensile strength***	***Young's modulus***	***Melt flow index***
1st time recycling	Decreased 18.8%	Decreased 10%	Decreased 51.3%
2nd time recycling	Decreased 20%	Decreased 18.4%	Decreased 56.4%

6 CONCLUSION

According the obtained test results, it is clear that the focused mechanical properties of polystyrene for this thesis which are tensile strength, young's modulus and melt flow rate decreased after the recycling process. The change in the melt flow index was higher than the tensile strength and young's modulus. As the tensile strength of the material decreased after the recycling process, it is clear that the material was losing its capacity to withstand force. But the change did not seem to be very massive or a sudden drop. The situation was quite similar in case of young's modulus test results. The drop in the young's modulus value was not massive as like as the tensile strength value. As the young's modulus value decreased after the recycling process, it can be concluded that the material was losing its stiffness and was becoming more elastic or flexible in characteristics. The melt flow index result was quite different than the pattern of the tensile strength and young's modulus tests. The melt flow rate value dropped a lot after the recycling process whereas the tensile strength and young's modulus values dropped in a rather small percentage. Basically, when the melt flow rate increase, it means the material has low molecular weight and is low viscosity polymer. On the other hand, when the melt flow rate decrease, it means that the material has higher molecular weight and is highly viscous. According to that theory, it can be concluded that the recycled polystyrene become more viscous than before after the recycling process.

According the overall test results, one can argue that since the mechanical properties did not change drastically even after recycling twice, the recycled polystyrene can still be used to make other daily life products. By recycling polystyrene, plastic industries can reduce the use of new raw material and can reduce material cost through the mechanical recycling process. And the biggest benefit from recycling polystyrene will be reducing the amount of waste from landfills and making useful items from the recycled polystyrene at the same time by producing energy.

7 SUGGESTIONS FOR FUTURE WORK

In this section. the possibilities and suggestions to improve this experiment for the future work has been discussed along with the limitations. First of all, one of the biggest limitation during the experiment was not having good amount of PS cups to recycle as it was quite challenging to collect post-consumer cups. Since PS is a very brittle in characteristics, during the recycling process a fair amount of material has been lost as waste which was realized after starting the process. The number of recycling runs could have increased to at least 4-5times if there was enough material for the test. So in order to do the similar test, it is recommended to start recycling with good enough material considering the wastage fact.

In this thesis, the test result of pristine PS and recycled PS has been analyzed separately. So another possibility of improving the test could be adding raw material or pristine polystyrene with the recycled polystyrene during the recycling process in order to analyze how the mixing can change the properties of the material.

The main focus of this thesis was on the post-consumer PS cups made from GPPS and HIPS. The similar experiments can be done using expanded polystyrene which is also a challenging and interesting topic. In addition to that, recycling other PS products can also be another possibility for the future experiments.

8 REFERENCES

Adhesives, glues and sealants - all about adhesives Available at: http://www.adhesiveandglue.com/ *Adhesiveandglue.com* (Accessed: 9 April 2016).

Chemical Economics Handbook Polystyrene (2014) Available at: https://www.ihs.com/products/polystyrene-chemical-economics-handbook.html (Accessed: 23 April 2016).

Crawford, R.J. (1998) *Plastic Engineering*. 3rd edition edn. Oxford:

Derrick, S. (2010) *Polystyrene Recycling*. Available at: https://wmich.edu/mfe/mrc/greenmanufacturing/pdf/Polystyrene%20Recycling.pdf (Accessed: 9 February 2016).

Deshpande, A. (2013) *Polystyrene properties*. Available at: http://www.buzzle.com/articles/polystyrene-properties.html (Accessed: 22 April 2016).

Grulke, E.A. (1994) *Polymer Process Engineering*. .

Hopewell, J., Dvorak, R., Kosior, E. and edkosior (2009) *Plastics recycling: Challenges and opportunities*. The royal society publishing, Available at: http://rstb.royalsocietypublishing.org/content/364/1526/2115#ref-19 (Accessed: 9 April 2016).

Inc, I.T.W. *Tensile testing*. Instron, Available at: http://www.instron.us/en-us/our-company/library/test-types/tensile-test (Accessed: 16 May 2016).

MEFANET, C. and network, S. medical faculties *Young's modulus*. Wikilectures, Available at: http://www.wikilectures.eu/index.php/Young%E2%80%99s_modulus (Accessed: 17 May 2016).

Melt flow index (2016) in *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Melt_flow_index (Accessed: 27 April 2016).

of, edition, magazine, F., »»…, Culture, L., Control, P., Improvement, done, you've always, »»then…, Presenting, P.P., Conference, S.E.T., Date, new, Plastics, P., P08054•, F4300•, Sensigraphics, also includes, Finishing, P.I., {data_track_clickback, var addthis_config =, {}, var addthis_share =, 4, var wp_blog_version =, {info_status, var addthis_plugin_info = and set Interval, var at_interval = (2016) *Thermoforming plastic material, plastic materials for thermoforming - productive plastics, Inc*. Available at: http://www.productiveplastics.com/plastic-thermoforming-materials/ (Accessed: 11 April 2016).

PlasticsEurope *What is plastic? - PlasticsEurope*. Available at: http://www.plasticseurope.org/what-is-plastic.aspx (Accessed: 9 April 2016).

plc, I.G. *Melt flow rate ASTM D 1238, ISO 1133*. Intertek Group plc, Available at: http://www.intertek.com/polymers/testlopedia/melt-flow-rate-astm-d1238/ (Accessed: 18 May 2016).

POLYSTYRENE FAST FACTS, the way to go, Available at: http://isites.harvard.edu/fs/docs/icb.topic967858.files/PolystyreneFactSheets.pdf (Accessed: 10 April 2016).

Polystyrene (PS) Plastic (2016), Prospector, Available at: http://plastics.ulprospector.com/generics/43/polystyrene-ps (Accessed: 22 April 2016).

Polystyrene Specifications (2016), Boedeker Plastics, Inc. Available at: http://www.boedeker.com/polyst_p.htm (Accessed: 22 April 2016).

Ramsdale, R. (2004) *Manufacturing methods - engineer's handbook*. Available at: http://engineershandbook.com/MfgMethods/ (Accessed: 22 April 2016).

Strong, A.B. (2006) *Plastics: materials and processing*. 3rd edn.

Tensile testing - theory, applications and systems from Mecmesin (2016), AZoM.com Limited, Available at: http://www.azom.com/article.aspx?ArticleID=5551 (Accessed: 16 May 2016).

Terselius, B. (1998) *polymer material*.

TLP library introduction to mechanical testing - theory 1 (2004), University of Cambridge. Available at: http://www.doitpoms.ac.uk/tlplib/mechanical-testing/theory1.php (Accessed: 16 May 2016).

Ultimate tensile strength (2016) in *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Ultimate_tensile_strength (Accessed: 27 April 2016).

Wansbrough, H. and Yuen, D. *PLASTICS RECYCLING*.

WebTechTix (2014) *Tensile test - tensile strength or tension test*. Web Tech Tix. Available at: http://www.aboutcivil.org/tension-test-tensile-strength-test.html (Accessed: 16 May 2016).

Weckström, D. (2012) *Changes in mechanical properties of recycled polypropylene*. Available at: https://www.theseus.fi/handle/10024/41978 (Accessed: 9 April 2016).