# Evaluation of Recycling Polystyrene (PS) from a Microbiology Product

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| | |

Sammandrag:

Detta är ett beställningsarbete av Plastone Oy och i det undersöks möjligheterna vad man kan göra genom återvinning med avfallsmaterialet som uppstår då man tillverkar en mikrobiologisk produkt i deras plastfabrik. Produkten tillverkas genom formsprutning och materialet som används är polystyren (PS). Ur litteraturstudien fann man varierande möjligheter på hur man kan återvinna PS på bästa sätt, men ingen lösning som har varit effektiv i praktiken. Det framgick också att återvunnet PS inte är så vanligt, men det fanns inte tillräckligt med argument varför det inte skulle vara möjligt att återvinna. Därmed blev huvudmålet att undersöka och jämföra hur de mekaniska och visuella egenskaperna påverkas då man återvinner PS. Materialet återvanns totalt tre gånger genom att använda olika mängd av återvunnet material blandat med jungfruligt PS. Materialet återvanns genom användningen av en maskin som sönderdelar plastmaterialet till flis, som sedan gick att återanvända. Test bitarna tillverkades genom formsprutning i form av hundben. Sammanlagt har 8 olika test material tillverkats. Samma bitar har använts i alla försök för att få ett mera jämförbart och noggrant resultat. De mekaniska egenskaperna som undersöktes var slag- dragprov. De optiska egenskaperna transmittans och färg analys undersöktes med UV-Vis spektroskopi. Materialets strukturella egenskaper undersöktes med mikroskop. Till sist gjordes expert intervjuer för att bedöma möjligheterna att återvinna materialet. Enligt resultaten har återvunnet PS mycket liknande egenskaper som jungfruligt PS. De mekaniska egenskaperna skiljde sig en aning då det var högre återvinnings grad men inte nämnvärt eller så pass mycket att det skulle förändra användning syftet. Lika så var det med de visuella egenskaperna. Genom att återvinna PS kan man spara materialkostnader och effektivera avfallsprocessen betydligt.

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Abstract:

This thesis was commissioned by Plastone Oy and it investigates the possibility of what to do with the scrap material that comes from the production of the microbiology product in their plastic factory through recycling. The product is produced using injection moulding and the material used is polystyrene (PS). The literature that was reviewed found several possibilities of how to recycle PS in the best way but none that was efficient practically. It also revealed that recycling PS is not so usual, but there were not enough arguments why it could not be possible. Therefore the main aims were to investigate and compare how the mechanical and visual properties affect when PS is recycled. The material was recycled three times with different amount of grades of recycled material and raw virgin PS material. In total 8 different materials were produced. The material was recycled with the use of a plastic shredder were the outcome were in form of PS flakes. The test pieces were produced trough injection moulding. All the same test pieces have been used during the testing in order to gain a more comparable and accurate test result. The mechanical properties have been investigated by impact test and tensile test. The optical transmittance and colour analyse have been investigated by UV-Vis spectroscopy. The structural property has been investigated by microscopy test. Finally expert interviews have been made for evaluation of the recycling possibilities of the material. According to the results recycled PS has very similar results as raw virgin PS. The mechanical properties differ slightly when the grade and cycle of amount of recycled material were higher but not significant or that much that it would change the end use purpose. The visual properties were even more similar. By recycling PS material it can save material costs and improve the efficiency of waste process considerably.

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# FOREWORD

For this thesis I want to thank Mariann Holmberg for the support, guidance and faith in me, John Ekholm for providing an interesting project, the lab staff for supervising and set up of the different machines, especially Björn Wiberg for the help with the UV-Vis spectroscopy and the microscope. I would also like to thank all my friends in school for the interesting discussions and great company, especially Pontus Salminen for all the help and support. And last but not least, a big thank you to Anna Tarkianinen and my brother Stefan Eklöf for supporting and believing in me.

# 1 INTRODUCTION

Like all factories that manufacture something there is always thoughts of how to be more profitable, save money and, something that recently is getting more important, to be more environmentally friendly. To be more environmental friendly is to recycle. Recycling is not only reducing material costs for a company it also reduces waste. Today’s generation get to hear more about the environmental importance and how big companies need to think more about the environment. It is a demanding task for a company to cut down or reduce processing methods because of this, but the actions can also be a positive thing and ideas and suggestions of doing so are always welcome for a company that needs to show their contribution to the environment.

Plastone Oy is a manufacturing company in Finland that is manufacturing thermoplastic products from injection moulding machines. The company has specialized in manufacturing state of the art products for demanding use and applications in the medical industry, electronic industry and among other fields as well.

One of the products that Plastone Oy manufactures for the medical industry is a micro plate which goes under the product name “Bioscreen HC” (HC = Honeycomb). The company gave some thoughts on what the possibilities would be to recycle the Bioscreen HC product. Bioscreen HC is made of transparent polystyrene (PS) and is of top quality. The product undergoes deep quality control and is manufactured in a clean room environment. Since the product is so demanding there is no room for any defects or errors. In most cases when a product is manufactured there are some leftover. From the Bioscreen HC there is as well some left overs, which in this case is mostly the sprue channels that comes along when the product is produced from the injection moulding machine. Other waste material can be some contamination or some other error that the product has received from the manufacturing process or the quality control department.

This thesis is about what are the changes in the mechanical and optical properties when the Bioscreen HC product is recycled. As mentioned earlier the material that is used when producing the Bioscreen HC is made out from polystyrene. When the product is manufactured at Plastone Oy there is an amount of portion that goes to waste and is not used. These parts have had no notable error or any other contamination whatsoever that can be found by the naked eye. The student has collected the waste material and has been using that for the research. Also, unused raw material of polystyrene has been used for comparison of the difference in the two types.

## 1.1 Aim and objectives

The aims and objectives of this thesis are listed below:

- Determine what are the recycling possibilities for the Bioscreen HC product.
- Define the new mechanical and optical properties of the product if it has been recycled.
- Determine what are the benefits of polystyrene when recycling it.

## 1.2 Acknowledgements

All the machines that have been used in the thesis have been located in Arcada's plastic lab and in the chemistry lab. A deeper explanation of the different machines and parameters will be explained in the literature review section and the method section.

As mentioned earlier the recycle method that has been used is a mechanical recycle method. The student has been using a grinder to shred down the existing product into small pieces that are similar to what new, raw and non-recycled plastic granulates are shaped and formed like.

An injection-moulding machine has been used to produce test pieces. A tensile testing machine has been used to find the mechanical properties of the material. The material is also analysed optically to find possible contamination of the transparency in the material using a UV-NIR machine and a Zeiss Microscope for optical analyzing. The same test pieces have been used in all mentioned testing machines for a comparable test result.

## 1.3 Company background

Plastone Oy is a subsidiary company of Mekalasi Oy, which is a sales and marketing health care supplier. Mekalasi Oy was founded in 1952 in Finland. Since then the company has been working together with Plastone Oy. Plastone Oy is a supplier and provider of plastic parts for Mekalasi Oy. Examples of these products are disposable laboratory- and health care accessories. Both Mekalasi Oy and Plastone Oy still remain their roots in Finland. In 2011 Mekalasi Oy and Plastone Oy employed around 100 people and is located in Finland in Nurmijärvi and its turnover was around 18 million euros.
Plastone Oy in Nurmijärvi consists of several departments. The company has a production plant, which has over 20 injection-moulding machines and microinjection moulding machines, which can produce big to small plastic parts. There are also machines, which produce silicone parts, which is a very meticulous process and demanding product that Plastone Oy offers. Plastone Oy also has a moulding and tooling department for maintenance, making new moulds and new products. Today Plastone Oy also has established a factory in Estonia, which is concentrating on electrical equipment and solutions.
(Mekalasi Oy AB 2012)

### 1.3.1 Bioscreen HC and clean room

**Figure 1** *Honeycomb 2 C (Bioscreen 2012)*

Figure 1 is a picture of the product Bioscreen HC. The first Bioscreen HC baby was created in 1980s that was developed from the company called Labsystems Oy, which is now called Growth Curves Ltd. It has been working very well since then and has received positive feedback from researcher all around the world. After a couple of decades on the market the product is now mostly used as a tool for automating routine microbiology growth experiments. Because of the good material properties the product can be used for high temperature control. (Bioscreen 2013)

The product consists of two parts, the plate and the lid. The plate consists of 10x10 wells that make it looks like a “honeycomb” which is suitable for the chosen name of the product. Figure 2 below is a 3D drawing of the two parts of the product, the plate and the lid.

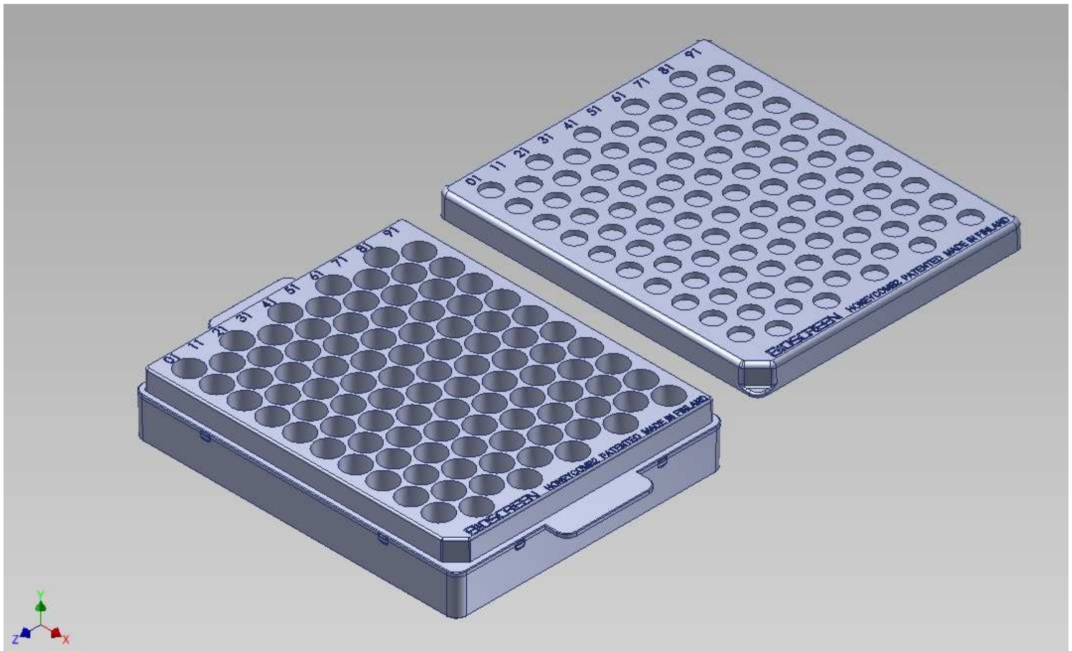


**Figure 2** *3D drawing of the plate (left) and the lid (right) (Courtesy of Plastone Oy 2013. Adjusted by Jonas Eklöf)*

As mentioned earlier Bioscreen is made out of Polystyrene (PS) and is manufactured with an injection−moulding machine. When the product is produced it is then sterilized by radiation with gamma rays to take out any possible contamination.

The Bioscreen HC is manufactured in a clean room environment. Instead of the word “clean room” the word “aseptic” could also be used, but is more used for more chemically or more medically production plants. The word aseptic means that it is “free from contamination caused by harmful bacteria, viruses or other microorganisms” This means that the product is manufactured in a controlled environment to protect it from any unnecessary contamination. In a manufacturing factory a clean room is often an enclosed space in the factory. People that are in a clean room area like the factory workers and guests must wear full protection clothing such as gloves, overalls, shoe protection and hair net protection. According to ISO 14644-1 a clean room is *"A room which the concentration of airborne particles is* ***controlled,*** *and which is constructed and used in a manner to minimize the* ***introduction, generation,*** *and* ***retention*** *of particles & microbes inside the room and in which other relevant* ***parameters****, e.g. temperature, humidity and pressure, are controlled as necessary."* (CERHB 2003)

# 2 LITERATURE REVIEW

This chapter covers the main characters of PS, the properties, market and consumption, possible recycling methods and finally, a description of the different machines that was used for the test is also found.

## 2.1 Polystyrene (PS)

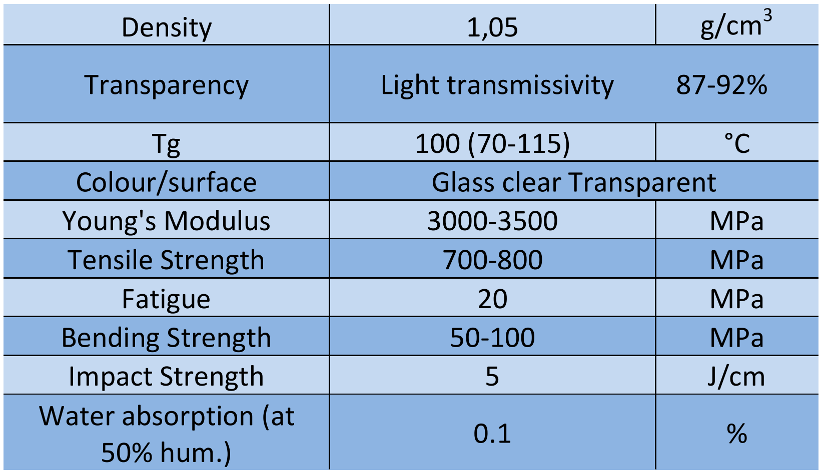
Polystyrene has advantages and some disadvantages that are worth taking into consideration when working with it. Depending on what application it is used for it is beneficial to know its main characteristics that can be both good and bad. PS is mostly used because of its transparency and hardness. The material is easy to process since it has low water absorption and therefore very seldom needs pre drying before processing it. The price is also low comparing with other plastics with the same characteristics. Drawbacks of the material are that it burns easily, it is brittle and when exposed outside it gets degraded and a yellow colour. Other common characteristics of PS are shown in table 1.

**Table 1** *Common Characteristics of Polystyrene (Holst 2013)*

| Advantage | Disadvantage |
|---|---|
| ▪ Very stiff and hard | ▪ Burns easily |
| ▪ Good Electrical insulation properties | ▪ Poor temperature resistance |
| ▪ Low Mould shrinkage<br>▪ Low water absorption 0,05% | ▪ Get yellowish more fragile when outside (because of UV radiation) |
| ▪ Low Price<br>▪ Easy to work with<br>▪ Unlimited staining opportunities | ▪ Low resistance against oil and solvents<br>▪ Brittle |

Table 2 below shows the common properties of PS. One the most common property that PS has is the transmissivity. The transmissivity or transparency is almost the same as glass. The common colour and surface is often clear and transparent. The lack of polarity in the molecule results in low water absorption, as mentioned earlier. Because of the brittleness the material has a quite low bending strength and tensile strength. (Lindberg 2013: 71)

**Table 2** *Common Properties of PS (Holst 2013)*



| | | |
|---|---|---|
| Density | 1,05 | g/cm$^3$ |
| Transparency | Light transmissivity | 87-92% |
| Tg | 100 (70-115) | °C |
| Colour/surface | Glass clear Transparent | |
| Young's Modulus | 3000-3500 | MPa |
| Tensile Strength | 700-800 | MPa |
| Fatigue | 20 | MPa |
| Bending Strength | 50-100 | MPa |
| Impact Strength | 5 | J/cm |
| Water absorption (at 50% hum.) | 0.1 | % |

### 2.1.1 Polystyrene background

The first chemical recognition of PS can be characterized by the styrene monomer in polystyrene. The structure has a carbon−carbon double bond to which a benzene ring is attached. The benzene ring is also called an aromatic ring. The aromatic ring reduces the ability of the polymer chain to bend and interferes substantially with other parts of the molecule. Because of this the PS prevent the formation of any crystalline regions and therefore PS is usually considered to be fully amorphous. The aromatic benzene rings also increase the tensile strength. Light passes through the structure without significant refraction because of the high properties of amorphous that PS has and makes it transparent and clear, which will be explained more in the opacity section. The aging of PS is quite short. PS tends to get yellowish with exposure to UV light and oxygen. The material is also subject to environmental stress cracking. PS is therefore appropriate for applications for short duration and not for long-term use. (Strong 2006:247−250)

The strength of PS is strongly determined by the molecular weight. Normal uses of PS do not usually depend upon high strength, and so the molecular weight is often kept at moderate levels to facilitate easy processing. PS has a wide range between the softening point and decomposition point, which makes it easy to process (~90°C to 250°C).
(Strong 2006:247 ff.)

### 2.1.2 Thermoplastics

The most common consumer plastics like polyethylene (PE), polyethylene terephthalate (PET), polycarbonate (PC), polypropylene (PP) and Polystyrene (PS) are thermoplastic. Comparing thermosets and thermoplastic, the latter has the advantage that it can be remelted when it is heated up. When it is reheated it can be remoulded to its desired form and then cooled again to maintain that form. Different processing methods that are used with thermoplastic are injection moulding, extrusion, film blow moulding, rotational moulding and thermoforming. It could even be possible that the best property of thermoplastics is that they can be melted several times for reuse and therefore recycled. Though due to the degradation in the recycle process small molecules harm the plastic, like oxygen molecules, UV-light and chemical contaminations it is therefore often that only a small amount that is recycled when comparing the total use of plastics. (Bruder 2010:3 ff.). A thermoplastic can be either classified as amorphous or semi−crystalline, which will be explained in the next section. Figure 3 below is an illustration of classification of amorphous and semi−crystalline thermoplastics by morphology.

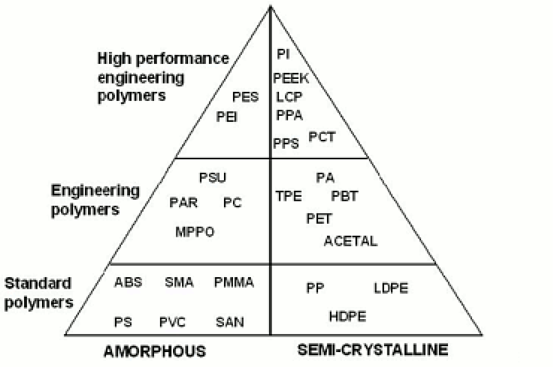


**Figure 3** *Classification of amorphous and semi-crystalline polymers (DuPont 2013)*

### 2.1.3 Morphology

A thermoplastic material can be amorphous or semi−crystalline, as mentioned earlier. The recognition of this comes from how the polymer chain and the side groups are located in the polymer. When the molecules in the polymer are twisted randomly together it is amorphous. A Crystalline material is usually symmetrical or parallel packed together into different noticeable patterns. What is worth mentioning is that no polymer can be completely crystalline and therefore the word semi−crystalline is used when talking about crystalline regions. One feature to determine if it is amorphous or crystalline is to see the shape of the polymer−repeating unit. If the repeat unit is complex, especially with large pendant groups, the polymer cannot pack tightly together and will be amorphous.

When a polymer is heated the molecule chains starts to twist, move and will entangle with each other. Depending on the molecules, the bonds can pull and pack the molecules together to form crystalline regions. When it is then fully cooled, it depends on the amount of amorphous or crystalline regions that determines whether it has more amorphous or crystalline properties. What is worth mentioning is that all polymers are, when heated, first in an amorphous stage but when it is cooled and it solidifies it can go into a more amorphous stage or a more semi−crystalline stage depending on the amount of amorphous and crystalline regions in the polymer. (Strong 2006:75)

Figure 4 below illustrates how the structure of a semi crystalline and an amorphous region look like, note that the crystalline regions are more symmetrical and parallel packed, while the amorphous regions are twisted and unsymmetrically packed:

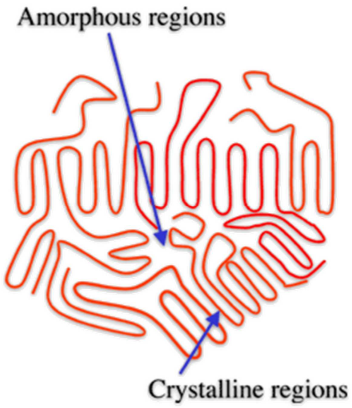


**Figure 4** *Illustration of an amorphous region and crystalline regions in a polymer (Elsevier 2013)*

A rule of thumb to determine whether a plastic material is amorphous or crystalline, can be that glass is amorphous (clear and transparent) and metals are crystalline (opaque or translucent). (Crawford 1998:4 f.)

Table 3 below characterizes the essential recognition of qualities of amorphous and crystalline plastics.

**Table 3** *Common recognitions of qualities of amorphous and crystalline plastics (Crawford 1998)*

| Amorphous | Crystalline |
|---|---|
| ▪ Often transparent | ▪ Sharp melting point when the structure is closely packed result that the secondary bonds are broken at the same time |
| ▪ Low shrinkage because the random arrangement of molecules produces little volume change | ▪ Usually opaque depending on the amount of crystalline regions but can also be translucent |
| ▪ Low chemical resistant because again of the random arrangement of molecules are more open and enables chemicals to penetrate deep into the material and destroy many of the secondary bonds | ▪ High shrinkage because when it solidifies the molecules in the polymer are closely packed to a high aligned structure |
| ▪ Poor fatigue and wear resistance because of the random structure | ▪ High chemical resistance because of the tightly packed structure prevents chemicals to strike deep into the material |
|  | ▪ Good fatigue and wear resistance because of the uniform structure |

Amorphous polymers are often transparent and polystyrene is about 88% transparent, which is quite high comparing with glass that has about the similar transparency. Amorphous materials have no melting temperature, so it is defined in $T_g$ (glass transition temperature) when the molecule chains start to move. Semi crystalline polymers can stand generally an increase in temperature better than amorphous polymers. Because of this, semi−crystalline materials tend to have a better fatigue strength and chemical resistance. Semi−crystalline polymers are not as brittle as amorphous materials and therefore do not crack so easily. This means that semi crystalline has a higher flexural strength than the amorphous polymers. Amorphous polymers also have a lower shrinkage than semi−crystalline materials. (Bruder 20010:3 ff.)

The glass transition temperature, or $T_g$, is around 90°C for amorphous materials and also for PS. The specific volume is increasing linearly before and, even in some cases, after the $T_g$. For semi−crystalline the $T_g$ is around 170°C. In amorphous polymers, the change in flexibility is quite dramatic because the amorphous regions have considerable more space and relatively unrestricted molecules that can participate in these long-range movements. Amorphous polymers might become leathery or rubbery above $T_g$. Highly semi−crystalline polymers exhibit much less change through the glass transition temperature, $T_g$, because the crystalline structure restricts the polymers and limits the long-range movements to only small actions due to the high increase in $T_g$ for semi crystalline materials, indicates why it has higher shrinkage. (Strong 2006:73)

Due to the linear increase of the amorphous material, the energy consumption is considerably lower than semi crystalline polymers and constant above $T_g$. That is why it can be more challenging for a plastic machine operator to find the right parameters when using semi−crystalline material because they are the opposite. (Bruder 20010: 7 ff.)

### 2.1.4 Chemical background

Polystyrene is made from the monomer styrene. It consists of an aromatic ring that is attached with a vinyl group. The styrene monomer reacts with other styrene monomers (with each other) during the initiation process to become polystyrene. During the initiation process the vinyl group loses its double bond and therefore it is in the vinyl group that the polymerization takes place, which is illustrated in figure 5 below.

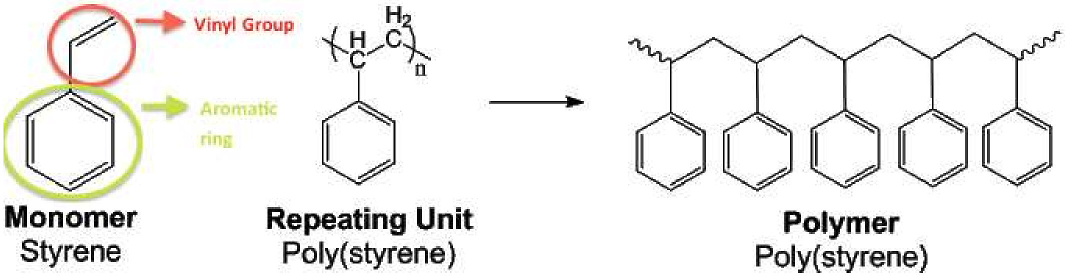


**Figure 5** *Chemical composition of polystyrene (University of Liverpool 2013)*

Polystyrene is normally atactic, which means is has a randomly irregular structure, in this case for polystyrene it is the benzene rings, which are randomly placed in the polymer structure. (Bruder 2006: 11 ff.) There is isotactic (all have same repeating structural elements) and sydotactic (in which the repeating units have alternating stereo chemical configurations.) polystyrene, but the atactic polystyrene is mostly used. (Edshammar 2002: 95). Figure 6 show how the three types distinguish from each other. Figure 7 is the chemical structure of PS.

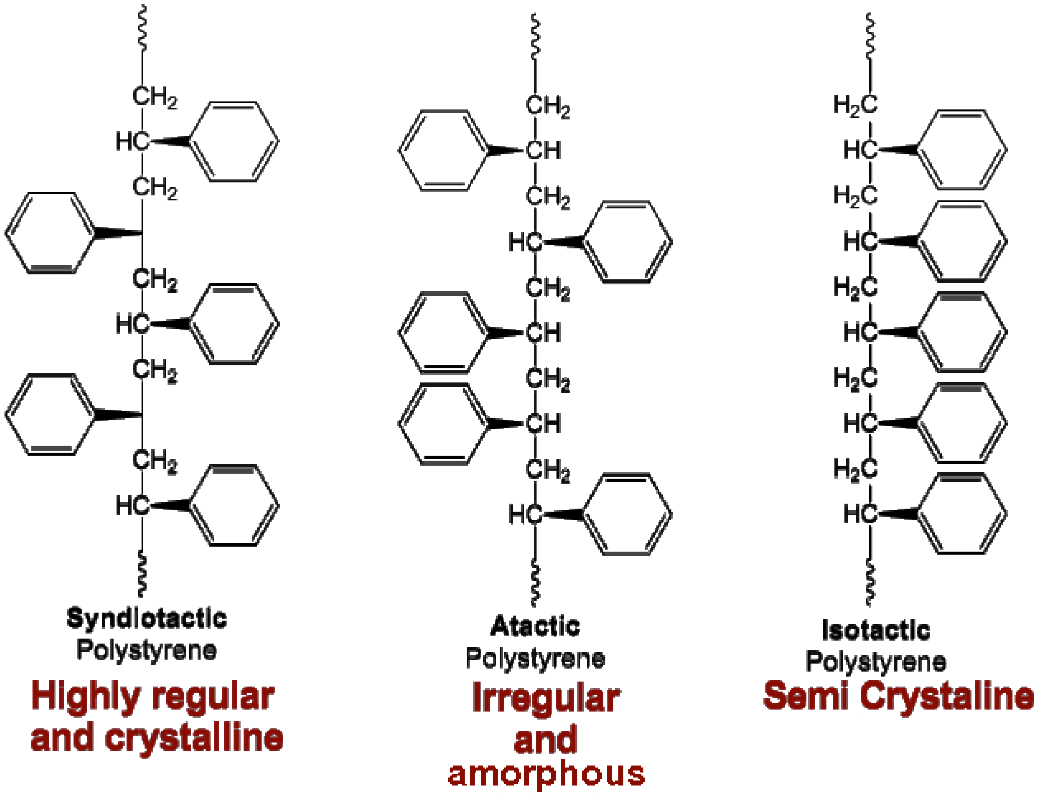


**Figure 6** *The different structures of polystyrene (University of Liverpool 2013)*

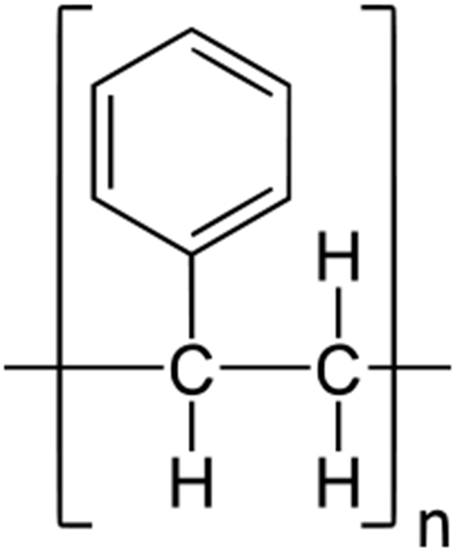


**Figure 7** *Chemical structure of polystyrene (Wikipedia 2013)*

### 2.1.5 Polymerization

The common polymerization process of polystyrene is chain growth polymerization. Another name for the polymerization process is also called addition polymerization, as mentioned earlier. Addition polymerization comes from when free radicals are created in which bonds with a monomer and then creates a new free radical, which can bond with another monomer. This continues as long as there are monomers to react with. The process, containing of many steps, is not easy to explain and therefore will be briefly explained of the main steps.

In the addition polymerization process for polystyrene the vinyl groups, in which the carbon-carbon double bond is, reacts with similar groups in another styrene monomer group in a reaction vessel. The reaction occurs under very high temperature conditions. An Initiator is then used to mix the both monomers together to start the polymerization process. The most common initiator that is used is a peroxide compound and is also used for polystyrene. The peroxide easily forms radicals. Radicals means that a molecule which contain of unpaired electron, a radical, look for something to pair with and then start the reaction. Initiators can also be called catalysts. However, there is an argument that the name catalysts cannot be used in the same way. According to New Oxford American Dictionary the word ”Catalyst” means “*A substance that increases the rate of* *a chemical reaction without itself undergoing any permanent chemical change.*" In this case the catalyst are not heated, they are used up and used as reactants in the polymerization process. (Strong 2006: 51 f.)

During the initiation step there are electrons that are ready to be used with the free radicals and the bonding begins. The chain can continue to grow when free radicals are created and bonded with a new monomer and then creates a new free radical as long as there are monomers to interact with. For simplification, a repeating unit replaces the long chain, by the unit that is added to the chain in each step, which is the monomer. The polymer is recognized by the monomer, in this case the styrene, which is often how the polymer is chemically recognized. (Strong: 2006: 53 f.)

## 2.2 Mechanical properties

**Tensile strength**

Tensile strength is most common mechanical property to test when it comes to investigate the mechanical properties of a material. There are two important mechanical properties, Tensile Stress and yield stress. (Strong 2006:121) Tensile Stress at Yield or Yield Stress is the first stress at which an increase in strain occurs without an increase in stress. It is expressed commonly in megapascals (MPa). Tensile Strain at break is when the test specimen breaks. It is measured in percentage (%). (ISO 527-1 1993:2). A stress vs. strain graph displays the relation between stress and strain (ISO 527-1 1993: 8).

**Tensile Stress or Tensile Strength**

There are other mechanical properties as well. (Strong 2006:122) As mentioned earlier stress-strain determines the force it is required to pull in order to deform and, if possible, eventually break a material. When this happens it is named to be at stress. There is another stress that needs to be mentioned, called "Engineering stress", that also can be obtained using the same method but it will not be used in this research and therefore not be going into that. Stress is measured in $N/m^2$ and defined in Pascal and often uses the greater value Mega Pascal (MPa). Stress is the applied force over the cross sectional area as shown on the formula 1 below. (Brown 2002:97)

$$\sigma = \frac{F}{A}$$

[1]

σ = Stress or tensile strength, measured in N/mm$^2$ [MPa]

F = Force, measured in Newton [N]

A = Area, cross sectional area of the piece measured in [mm$^2$]

(Brown 2002: 97)

### Strain

Strain is a dimensionless value and therefore can have many different expressions. A percentage value is often used to determine the strain and is calculated of how much a designated deformation differs locally from a rigid body deformation (Wikipedia 2013: Deformation (Mechanics)). The strain is defined from formula 2 below. Notice how the units cancel each other out.

$$Strain = \frac{\text{Extension}\,\delta\text{L [mm]}}{\text{Original length l}o\,\text{[mm]}}$$

[2]

(Brown 2002: 98)

To convert the result into percentage is simply done by multiplying by 100 shown in formula 3.

$$\text{Strain [\%]} = \frac{\text{Extension}\,\delta\text{L [mm]}}{\text{Original length l}o\,\text{[mm]}} \times 100$$

[3]

(Brown 2002: 98)

Figure 8 below is a typical stress-strain curve for brittle plastic materials. Ductile plastics have the same approach but do not rupture, instead they will continue to stretch and the curve will keep rising and reach a maximum point (where the ultimate strength is then measured) and eventually decrease until it reaches a fracture point. (Brown 2002:99)

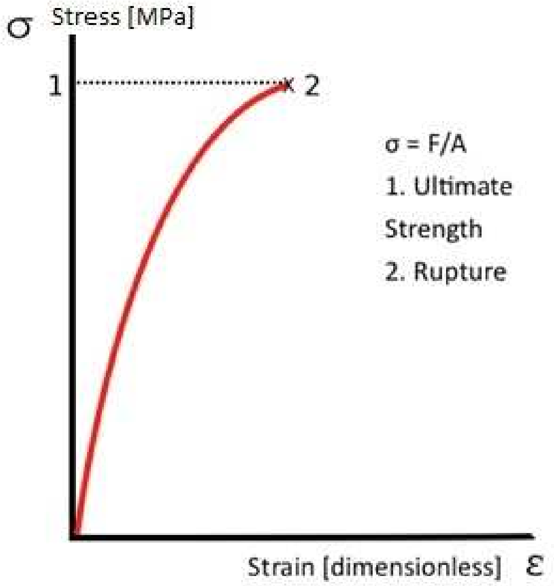


**Figure 8** *A typical stress-strain curve for brittle polymer materials (Wikipedia 2013. Modified by Jonas Eklöf)*

### Modulus of Elasticity in Tension

The modulus of elasticity, or Young’s modulus, is a very common value that is used much in with plastics properties. Young’s modulus determines how stiff a material is. The modulus is constantly changing due to the amount of grades in a plastic. Young’s modulus depends on a variety of properties such as Density, tensile strength, flexural modulus and elongation at break. Young’s modulus can be used either in tension or in compression. (Crawford 1998: 21-22)

## 2.3 Spectrophotometry

Spectrophotometry is the definition of finding the optical properties of a material. Studying the optical properties or finding the opacity of the polymer is a deep morphology of looking deep into the depths of a polymer. Opacity is a study to understand the optical properties how a polymer interacts when it comes to contact with light. There are different types of which the light interacts with the plastic. These are absorption, transmission and reflection. Also the colour of the plastic has an influence on the optical properties and will be explained in the next section. Transmission will be mainly focused here. (Strong 2006:176 f.)

The transparency of a material depends on the crystallinity of the polymer. The crystalline regions in the polymer are larger than the wavelengths of visible light (between 400−700 nm), the light that you are able to see through something. Semi−crystalline polymers are therefore opaque or translucent. There are mixed materials have either transparent or translucent characteristics. HIPS is one material that you might think be transparent, but because of more crystalline regions that appears due to the mixing with the butadiene rubber, it can be either transparent or translucent depending on the size of the wavelength or the amount of the crystalline regions. (Osswald et al. 2003:553)

Transmission or light transmission is defined how well light will be passed through a plastic material. Another definition of transmission is transmittance, which means according to New Oxford American Dictionary 2010, “*The ratio of the light energy falling on a body to that transmitted through it*” is amount of light that passes through the plastic material.

A plastic is usually transparent when light passes straight through the material and the light beam is not usually changed. When a plastic material does not allow light to pass through it is named to be opaque. There is also some plastic that is somewhat a little transparent but also opaque that when looking through the material it might be blurry or dense. These plastics are named to be translucent. They allow light to partly pass through and may only show some contours or shadows. What is worth mentioning is that a plastic material can never be fully transparent. There is always some light that is absorbed. When light passes through an amount is absorbed in to the material, which causes minor heating. Some plastics have higher protection against light transmission. A harmful light that can cause degradation of a plastic is the ultraviolet light. Depending on the properties of the plastic the material may get yellowish when exposed to a high-energy ultraviolet light. In many cases of the yellowish colour is caused by a preferential absorption of blue light (Strong 2006:177)

There is a way to know how much light that may pass through a plastic material or to know how high the transmission is of a plastic material. It can be compared with how much light passes through clean air or a vacuum in the same environment. By using standard ASTM D1003 you can investigate the light transmittance. The transmittance values are measured in percentage and the name for the commonly transmittance is luminous transmittance. The luminous transmittance is defined as the ratio of transmitted light to the incident light. (Strong 2006:178)

Since PS is amorphous it is transparent because it consists of less crystalline regions. Because of the lack of crystalline regions the light can pass through without any reductions. Plastics with more crystals in the polymer, or polymers that are semi−crystalline are more translucent. As mentioned earlier is that amorphous materials are often transparent while semi−crystalline materials are more translucent. What is still worth mentioning is that semi−crystalline material can still be transparent depending on the crystal size of the polymer. If the crystals are smaller than the wavelength of the visible light that surpasses the material it is not reducing and therefore no light is reduced. One of these plastics is polyethylene terephthalate, PET. (Strong 2006: 178)

As mentioned earlier the colour is also important when it comes to measuring the intensity of the transmission (Osswald et al 2003:560). In the process of processing a material, especially when recycling a material, some unexpected additives may affect the colour of the plastic. These types of colours are called colorants. Colorants can affect how the light is absorbed into the material. Depending on the colorant it also affects the transmission (Strong 2006:178).

### 2.3.1 Opponent-colour theory

The opponent- colour theory, or opponent process, is a theory that explains how the human eye perceives colour. There are three main opponent colours; red vs. green, blue vs. yellow and black vs. white. From with this scale all the colours in between, like violet, brown and orange, can be found and measured. As mentioned this theory explains much how the different sections in the human eye perceives and process colour and is therefore not relevant in this thesis to go in further, but in order to understand the L*a*b colour analyse in the transmittance spectra it is good to know what the foundation of the theory comes from (Wikipedia 2014: Opponent process).

The L*a*b colour analyse are scaled according to the opponent- colour Theory. The scales can be seen as a Cartesian x, y, and z coordinate system. Table 4 below shows how the colours are split. (HunterLab 2012)

**Table 4** *The colour scaling of the L*a*b scale (HunterLab 2012)*

| Scale | Colour | Percent | |
|---|---|---|---|
| L | Light vs. dark | 0-50 (white) | 51-100 (black) |
| a | Red vs. Green | Positive (red) | Negative (green) |
| b | Yellow vs. Blue | Positive (yellow) | Negative (blue) |

Figure 9 is a CIELAB colour chart illustration of scale +60 to -60 and figure 10 shows how the colours are distinguished with their corresponding and the contrast colour.

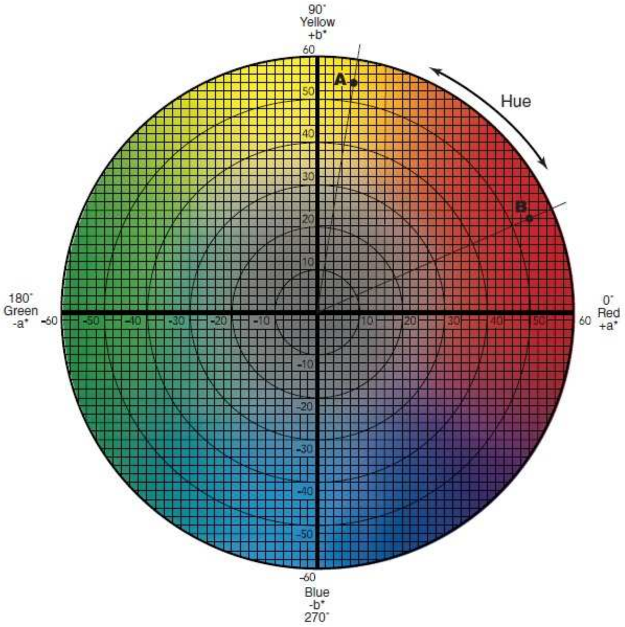


**Figure 9** *+60 to -60 colour scale (CIELAB 2013)*

**Figure 10** *L*a*b and colour scale and their colour distinguish. Notice that the white is on the Y-axis and the black is on the negative -Y axis (HunterLab 2012)*

## 2.4 Processing and applications

PS is a very flexible plastic material and can be used for many different processing methods. The most common are Injection moulding, extrusion, injection blow moulding and thermoforming. It is worth mentioning that some qualities shrink in the beginning of the use. Other methods that PS can be used for are sizing, embossing, cutting and vacuum metallizing. In Table 5 is a short list of common applications for PS (Lindberg 2013:71)

**Table 5** *Common applications for PS (Holst 213 & Lindberg 2013)*

- Disposables (mugs, cutlery)
- Simple house holding goods
- Expanded PS as insulation (Styrofoam)
- Windows profiles
- Packaging
- Dashboards

- Isolation, Capacitors
- Pipes

## 2.5 Market and consumption

It was hard to find what the current application fields and pricing for PS are. Instead an interesting lifespan from the current decade were found that is shown in figure 10. When studying the market value of PS during year 2000 to 2008 it has notably been under some changes. Since raw plastic material is not so expensive, comparing with other materials with similar properties and application use, more customers have been starting to take this advantage. Because of this the material has increased its value. The unit price in euros per kilograms year 2000 was about 0,90 e/kg. By the end of the decade the unit price almost doubled and increased to roughly 1,40 e/kg (Muovifakta Oy 2008:75).

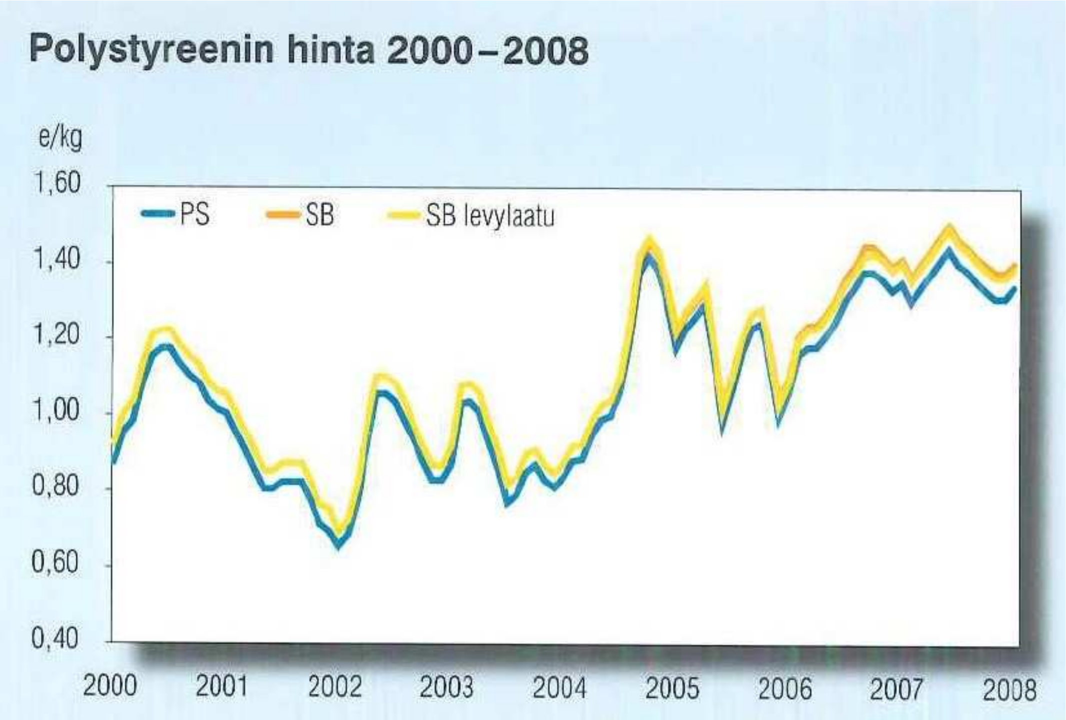


**Figure 11** *Polystyrene (PS), Styrene-Butadiene (SB) and SB plate quality pricing from year 2000 to 2008 (Muovifakta Oy 2008)*

Figure 11 illustrates the different application fields for PS. In year 2007 approximately 2,4 tonnes of PS and SB where produced in Europe. The largest market for PS is still in the packaging sector. Other field PS is also used in is for refrigerator panels, household goods, machines and equipment. XPS panels or extruded polystyrene foam is a material used much in the construction and packaging industry to produce EPS, expanded polystyrene material. (Muovifakta Oy 2008:74)

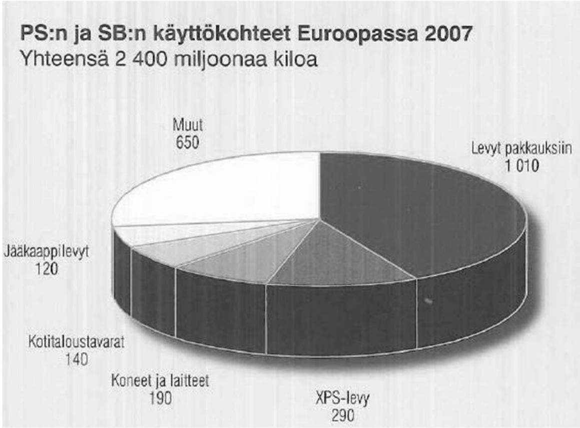
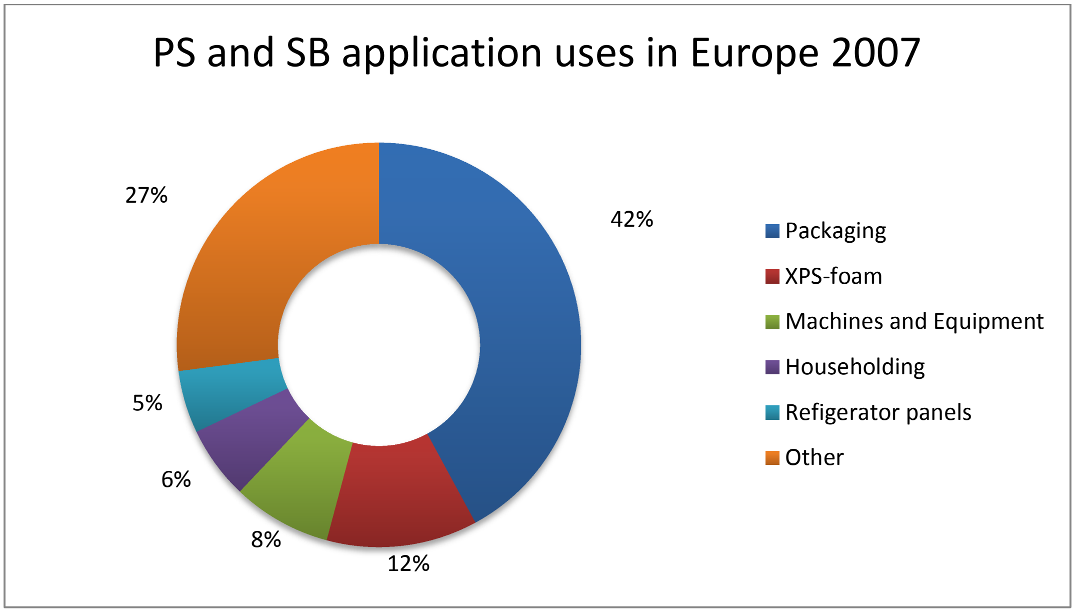


**Figure 12** *PS and SB application fields in Europe 2007 (Muovifakta Oy 2008)*

Table 6 below is a clarification of the information from figure 11. The amount is presented in percent from the total amount of 2,4 tonnes of PS used in year 2007.

**Table 6** *PS and SB application field 2007 (Muovifakta Oy 2008)*



## 2.6 Recycling

Plastics today are almost similarly consumed in all sorts like paper. Even though plastics do not have similar properties like paper, both materials are still used much all over the world and are used for disposable application, which means that once it has been used it is thrown away. The big consequence, especially for plastics, is that once the plastic has been used it leads to an environmentally concern of how to dispose it properly. EU has tried to confront the problem by legislation for plastic materials to recycle the material as much as possible. The mandate goal is to completely recycle all the plastic materials so there are zero landfills and pollutions (Strong 2006:826). In Europe recycling is still the minority when it comes to the after-life of the plastic as shown in figure 3. Most material is still left as landfill disposal. Even though the percent seems small, Europe is still the leading country when it comes to recycling and development of a sustainable environment. (PlasticEurope 2012)

**Figure 13** *The after-life distribution of plastic use (PlasticEurope 2012)*

Before considering if PS should be recycled it has to be sorted out among all other mixed plastics and materials. All day-to-day thermoplastics are sorted out by the grade of the plastic. This does not mean that they are used for recycling, only sorted out. Once the plastics are sorted out the materials are packed, also called that they are baled. Once they are baled they can then be sold to companies that have interest in using bales of recycled materials. If there are no interests, the bales are then profitless, marked as waste and not used. (Vernon 2011)

Companies perhaps have their own method of how to collect their own bale and reuse their material, but for a plastic like PS that is not so expensive; the material is often thrown away as waste and not reused. Because of this PS has not gained any popularity and do not yet lead to any interest for establishing a valuable product for recycling. For a company to even start considering recycle plastic there has to be a large market for the reprocessed products in order for them to survive as an interesting product at the company and for the customers. By achieving a usable, meaningful product from PS it is important for the company to take all three types of recycle possibilities into consideration to maintain an effective recycle environment solution. The three most common recycle methods, mechanical, chemical and energy recovery as fuel, will therefore be explained so an awareness of the possibilities of how PS could be recycled in order to reduce its waste portion from plastic waste. (Plasticeurope 2012)

As mentioned earlier the most common thermoplastics are sorted out by different grades of the plastic. An ASTM standard has been set to label out all materials with what resin they are made up from. Six common thermoplastics are sorted with ID codes to classify the grade of the plastic. PS has ID code six and in figure 12 are all the most common ID codes when sorting plastics. Notice that there are 7 different types whereas ID number 7 is labeled as “other”, which can be a mixture of different types of plastics, and ID code 3 is Polyvinylchloride (PVC) and marked with the letter “V”. Both ID code number 7 and 3 is a recycle problem and is very hard to burn.

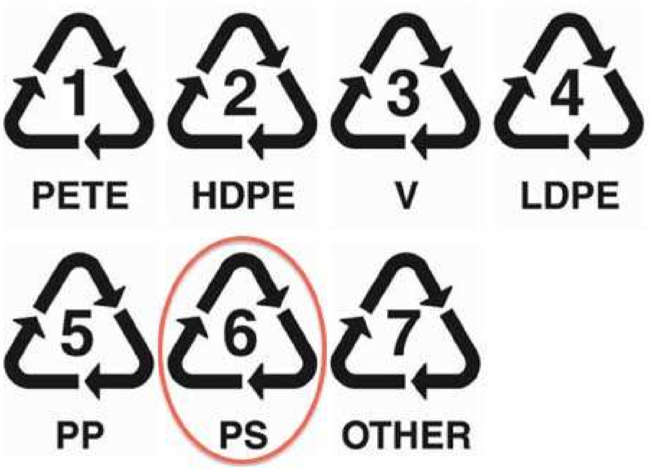


**Figure 14** *The thermoplastics ID code when sorting the different grades of plastic (Luke 2009)*

### 2.6.1 Mechanical recycling

With mechanical recycling the main goal is to recycle the plastic material for making new products by decreasing the use of new raw material trough a mechanical process. (Al-Salem et al 2009)

Mechanical recycling consists of many steps and it varies from material to material, like different foams and materials used as fibers, but the main procedure of how mixed plastics are sorted, mechanically recycled, and then reused will be explained so the main principals are understood.

The first step starts with size reduction, which can be done by grinding, shredding or milling. The big pieces of plastics are cut down to small flakes to be further processed. Once the pieces have been cut down they are transported to a cyclone to again be separated from any contamination, which could be dust or any other harmful impurity. The different plastics flakes are then floated in a tank where they separate each other according to the density of the polymer. This is the stage where the plastic now separate each other from other plastics so same plastics with the same molecular weight can then milled together and start to be reproduced. The material is then treated with washing and drying. Water is used to wash the material and chemicals can also be used for washing. Examples of this can be adhesives that might still occur on the surface of the materials or any other contamination that might harm the end use properties of the plastic. The material is then agglutinated and some extra pigments, additives or new raw material are added so the quality has similar visual and physical properties as new raw material would have. Once agglutinated, the material is then extruded to long threads that are then cut or pelletized. Finally the material reaches its final stage, quenching, where it is cooled with water so it later can be sold as a final product. The material is now ready to be reprocessed and shaped in any of the machines that produce plastic parts. (Aznar et al. 2007)

### 2.6.2 Chemical recycling

Chemical recycling is a complex but probably the most profitable recycling method. The use of the monomer side groups in the polymers can be used to make different kinds of feedstock's that could be used as chemicals for making other plastics. The use of chemical recycling could also be used to reproduce usable molecules, liquids or gases. For example, the styrene monomer in polystyrene is used when making copolymers and is a very useful product. (Al-Salem et al 2009)

Chemical recycling has both advantages and disadvantages. The material that are reproduced chemically is a potential product that is useful for many chemical production plants, which means that there is a good market for the product and the price of the material can be sold for a decent price. The disadvantage is that there are a lot of expensive elements that are used in the production of the chemical recycle process that is used to attain the demanded material. The question that has to be asked in the company is then if the production is beneficial enough to be reproduced so it can survive as a potential product. (Schmidt 2012)

As mentioned earlier there are many different ways of how to make use of the polymer if recycling the material through a chemical recycling process. For PS the most used chemical recycling process would be to either depolymerise the material down to the styrene monomer group or use thermolysis, so the material is heated to brake down the molecules to be used as energy or fuel. (Al-Salem et al 2009)

In order to chemically recycle PS back the plastic is depolymerised through pyrolysis. The plastic is threated in a very high temperature with the right catalysts and other atomic elements to achieve the right outcome. Recently, according to chemistryworld, Phillip Broadwith explains briefly how PS could be depolymerised in order to get to the useful styrene monomer. A catalysts, either platinum or rhodium has to be combined with cerium on alumina spheres. PS particles are continuously fed into the reactor, where the catalysts are which occur under very high temperature. In the reactor the material undergoes pyrolysis, which mean that PS decomposes through heating under high temperature, into styrene. The styrene is then removed, as a gas, through a gaseous system. (Broadwith 2012)

### 2.6.3 Energy recovery

Energy recovery or energy recycling is simply by burning the plastic waste to extract energy from the combusted heat. (Al-Salem et al 2009) The energy can be used as heat, steam and electricity. When plastics are burned they give out high energy. This energy is called calorific value. Crude oil has a calorific value between 41−46 MJ/kg. (Jatro 2012) PS has a calorific value of 41.90 MJ/kg and show a potentially good value to be used as fuel. The value is seemingly high considering that the plastic comes from the production of crude oil. (Al-Salem et al 2009)

The treatment has some advantages but also some drawbacks. The main advantage is that the waste can be used for something useful, by producing energy, which is more useful than landfill. The drawback is when the plastic is combusted it causes large quantity of air pollutant emissions that are harmful for the environment. Like the five most common thermoplastics PS is known to soot notably much when it is burned. By using energy recycling the material has to be held under careful treatment with strict standards and constructions.

### 2.6.4 Expanded polystyrene

One example where PS would be beneficial to use, once the material has been successfully recycled, is to reproduce the material into expanded polystyrene (EPS). EPS is a foam material that is used much for thermal insulation. It is used much in the packaging and the construction industry (PlasticEurope 2014). Figure 4 shows a schematic guideline how EPS beads are manufactured from the styrene monomer in order to produce EPS products.

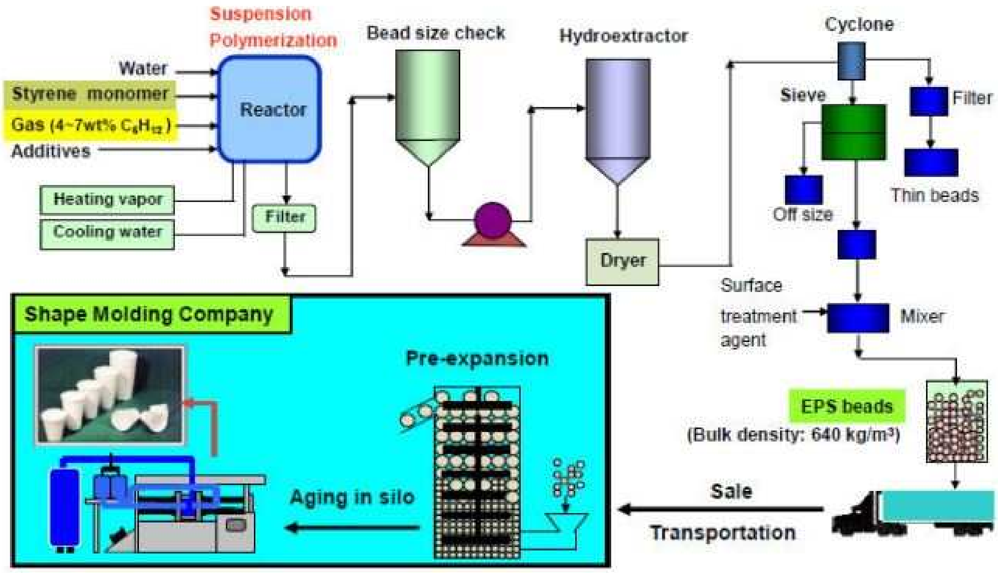


**Figure 15** *EPS manufacturing process. The PS has now become EPS beads that are larger in size and contain some pentane (Lee 2010)*

Once the EPS bead material has been produced there are still some steps that need to be mentioned. The main components that consist in the EPS beads are solid PS and a material, which is called a blowing agent. Pentane is usually used as a blowing agent. The production of EPS consists of three main stages, which happen at the shape moulding company. The first stage is the pre-expansion stage, where the PS beads are inserted to a steam machine that heats the material up to 100−200 ˚C (Lee 2010). When the pentane gas releases the PS beads start to expand and the density drops tremendously. (BPF recycling group 2014)

In the second stage the pre expanded PS are stored in silos where the material is cooled and some pentane is still released in the silos. In the third and final stage the material is produced according to the application area it is going to be used. The material is formed in a vacuum atmosphere. The typical products that are produced are mainly blocks for insulation or cartons for packaging (BPF recycling group 2014).

### 2.6.5 Microwave assisted pyrolysis (MAP) chemical recycle process

There is a case where polystyrene is chemically recycled using a microwave assisted pyrolysis (MAP). The material that is attained in the process is mainly styrene, some amount of char and gas are also found as well. (Andrea Undri et al 2013)

The process requires a treating temperature of 350 ˚C, but can also be higher. The char amount increase when the temperature rise and may not be so inadequate since styrene is more valuable. To gain more styrene a catalyst can be used, but is a more expensive approach. (Andrea Undri et al 2013)

To use a MAP an absorber has to be used that can tolerate much more heat than the plastic in order to achieve the product, which in this case is primarily styrene. Metals like iron can be used for the process and absorb microwave (MW) heat. The absorber then converts the MW into heat. The result depends on the temperature that take place in the MAP process and it is hard to estimate what the correct temperature is to use, but as mentioned earlier, it requires a treating temperature of at least 350 ˚C. (Andrea Undri et al 2013)

From the case of using MAP the goal were mainly to decrease PS from landfill waste. It is hard to estimate the exact result but the amount of PS were over half of the outcome and the gas that was attained were a potential product to be used for energy recovery without any handling of NOx or other air pollutants. (Andrea Undri et al 2013)

## 2.7 Machines

All the machines that have been used have been located in Arcadas' facilities. Introduction about the main use, how to operate it and preparation are explained as well as what the outcome is when the machines have been used.

### 2.7.1 Plastic shredder

By using a plastic shredder a plastic material can begin the process of being rapidly and effectively recycled mechanically. The principle is simple and requires few steps. Plastic material is inserted into a bucket or hopper where the material is then transported to a shredder and which cuts the material. The material circulates numerous of times through the shredder depending of the filter, which determines the size of the outcome. The outcome after the shredding are small flakes, similar to virgin pellet−looking plastic, that can be used as recycled plastic resin, for example to an injection moulding machine. Depending on the material and the design of the shredding blades, it is recommended to run the shredding process numerous times in order to get small and even shaped flake pieces. Otherwise if the shredded plastic flakes are uneven and, for example, inserted to an injection-moulding machine, it may damage the injection process. Figure 16 is a picture of the shredder used for the experiment.

**Figure 16** *The plastic shredder (Arcada 2013 Jonas Eklöf)*

### 2.7.2 Injection moulding machine

Injection moulding is one of the most common processing methods for thermoplastics. It can make a large variety of complex products in any size, big or small. The process is fully automated which makes it operational for a large quantity production. When a plastic part is made with the injection moulding technique little finishing is required. This means that when a plastic part has been processed through the injection−moulding machine it can usually be immediately packed and be ready for shipping which considerably reduces the labour costs. Surprisingly the Injection moulding machine itself is not the only expensive unit. The moulding part, shown in figure 17, is an essential part in the whole injection-moulding machine and can be almost as expensive as the whole injection-moulding machine itself in some cases. (Strong 2006: 431)

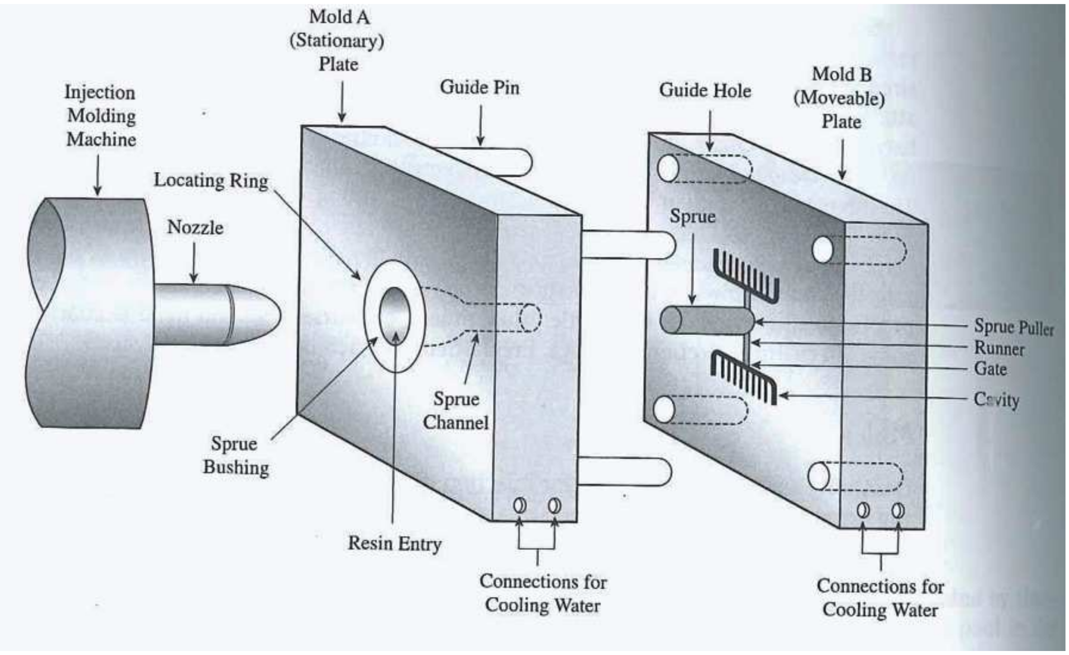


**Figure 17** *The main parts of the mould in the injection moulding machine (Strong 2006)*

The process of how the plastic is transported and moulded in the injection-moulding machine is quite simple. Imagine when toothpaste is pushed out from the hole of the tube. The toothpaste shape itself according to the shape of the outlet of the tube. The plastics in the injection moulding machine does the same, except that it is pushed further in to a mould where it then is cooled down and shaped to a figure. In practical this means that raw plastic materials in form of small pellets are inserted in a hopper. The pellets are then melted into a paste looking substance, when the plastic has melted (to a substance like tooth paste) to a certain temperature it is then pushed into the mould or the cavity and is then clamped and closed. The moulding process requires cooling, which is the longest process in the whole production. Once the cooling time is reached the mould is opened and then the part is removed either manually by a human or automatically by a robot. (Strong 2006: 432 f.)

The process of how to actually create the product or in other words to “mould” a part or product in the injection moulding machine has some important steps. As mentioned earlier the phase that takes the longest time in the injection moulding process is the cooling time for the plastic to harden, which starts immediately when the plastic has reached the mould and the clamping starts, and continues until the mould is opened. Besides that the process can be divided into 4 steps. The first step is the melting of the plastic, where the plastic is melted to a certain temperature and then pushed forward. The second step is the injection of the plastic in to the mould and keeping it there by holding pressure. The third step is then to hold it for a certain time while the plastic cools down by the moulding temperature and once the cooling time is satisfactory the mould opens. Figure 18 is an illustration of the total cycle time for the plastic process when inserted to an injection moulding machine and figure 19 an illustration of a typical injection moulding machine. (Strong 2006: 462)

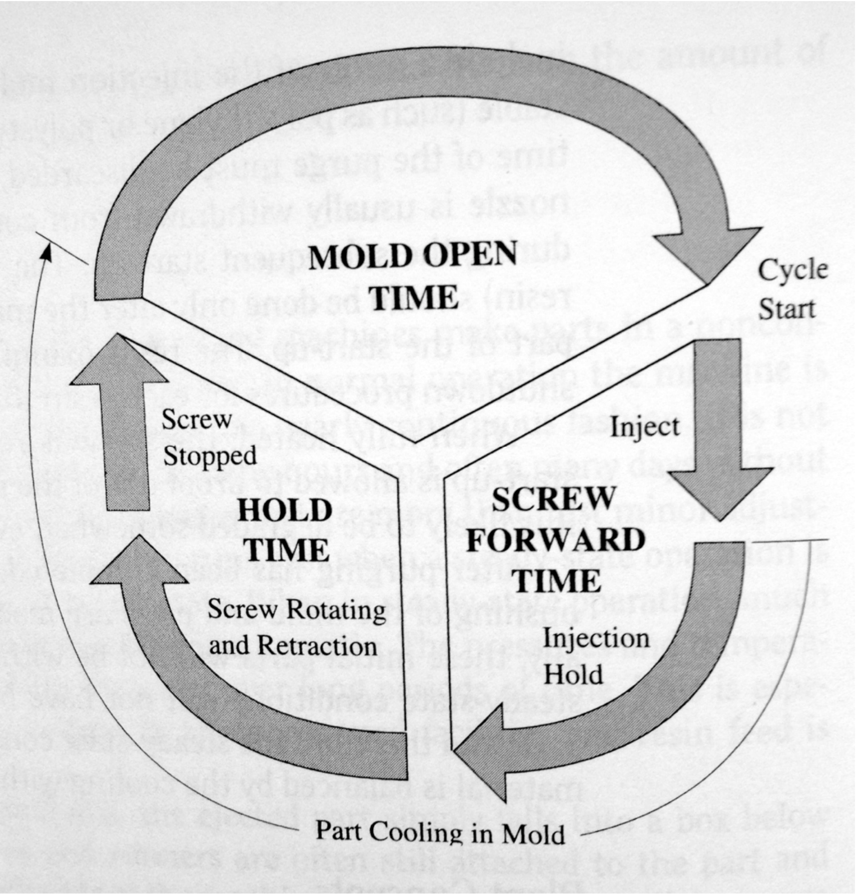


**Figure 18** *Illustration of total mould cycle and process of an injection moulding machine (Strong 2006)*

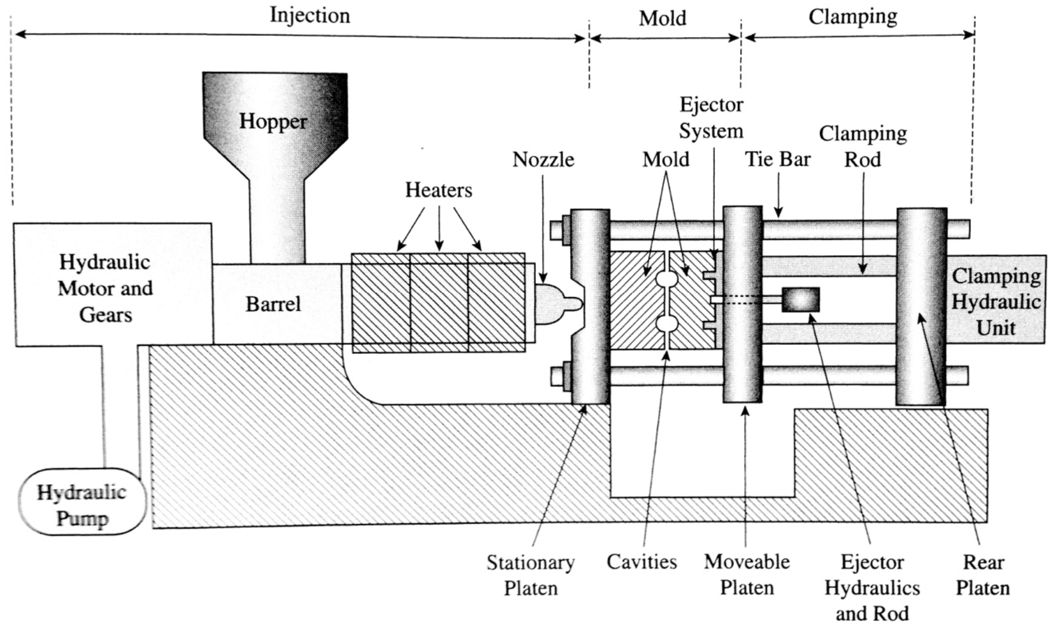


**Figure 19** *Illustration of an injection moulding machine showing the main sections and parts (Strong 2006)*

The injection unit is where the process starts. Plastic resin or pellets is filled in the hopper where the pre heating starts. Then by gravity and its own weight the resin is moved down to the barrel where a screw is located that feeds, compress and metering the resin whereas the first step is that the mould is closed, resin is pushed forward and the melting of the plastic starts as shown in figure 20. (Strong 2006: 434 ff.)

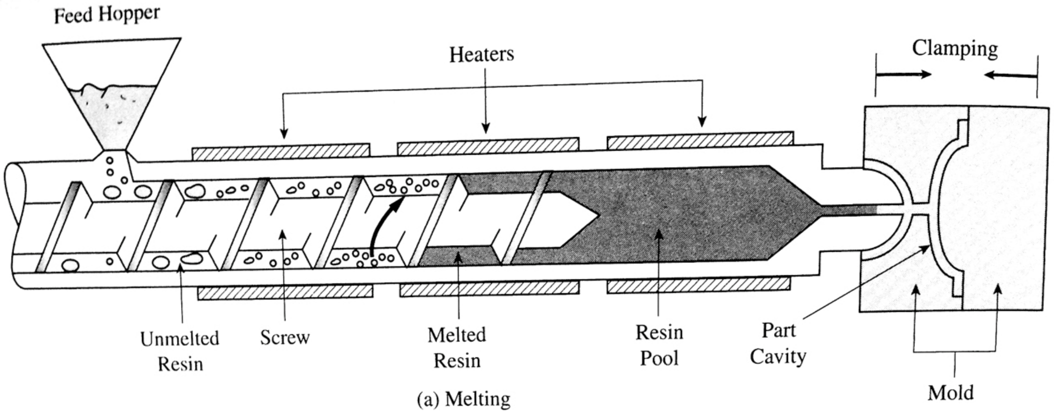


**Figure 20** *Melting process (Strong 2006)*

In the second stage, shown in figure 21, when the resin has melted it then extrudes forward to be completely moved away from the barrel. The plastic is now a dosage, which is the amount that will be formed in the mould. The dosage that is moved forward is called shot size. This step is also called the injection cycle where the plastic also initially gets in contact with the mould. (Strong 2006: 437)

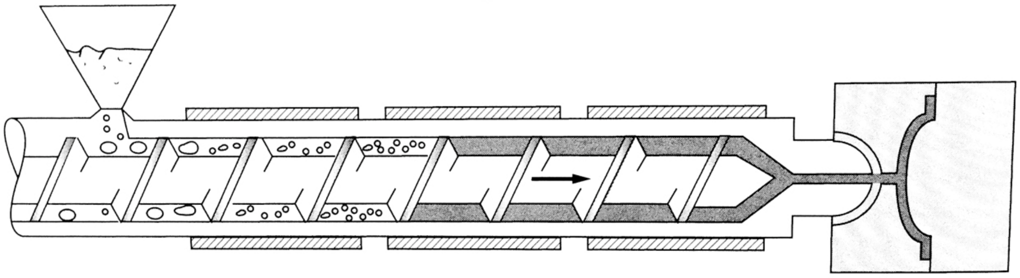


**Figure 21** *The injection process of the resin (Strong 2006)*

The temperature often starts low, then in the middle stage the temperature raises and then goes down before it reaches the nozzle.

In the third stage the part is cooling and then clamped in the mould cavities while the screw is moved back simultaneously as shown in figure 22. (Strong 2006: 439)

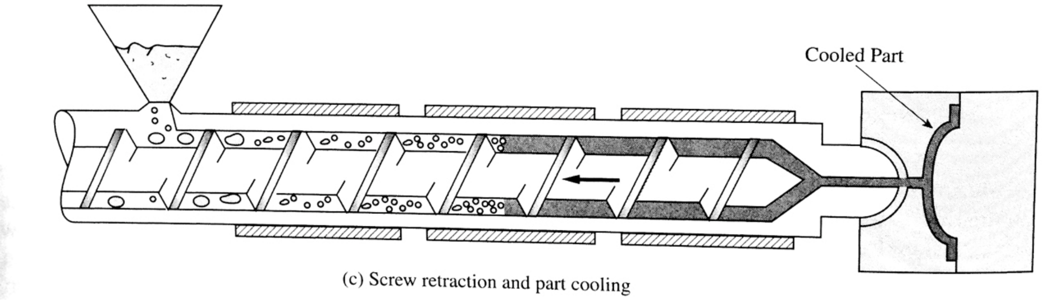


**Figure 22** *Screw go back to its starting position and part begins to cool (Strong 2006)*

In the fourth and last step while holding pressure is compressing the part the screw is moved backwards at the same time to again receive and melt a dosage from the hopper. Once the cooling is over the mould opens, the part is removed and the cycle starts over again as shown in figure 23 below. (Strong 2006: 440)

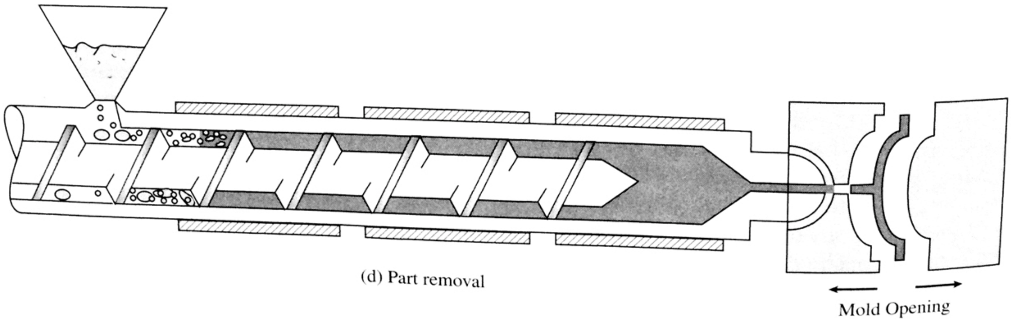


**Figure 23** *When cooling time is reached the mould is opened and part is removed (Strong 2006)*

To set up the parameters on the injection-moulding machine can be struggling sometimes, in order to get top quality results. Most of the time the work is done either by computer software or through test with different parameters. The parameters are often tested by trial and error attempts with the nozzle temperature, pressure, cooling time, mould temperature and dosage. There are also mathematical ways of how in theory achieve the correct parameters, but are always needed to be tested practically and adjusted in order to get the best results. When the desired parameters have been achieved there are some important steps to follow in order to start-up the injection moulding machine properly, keep the production in a steady-state and how to shut down the machine in a correct way. The starts up steps, production and shut down of the machine have been taken into consideration and are listed in appendix [III].

### 2.7.3 Tensile testing machine

The universal testing machine of the brand “Testometric” model M 350- 5CT was used for the tensile test as shown in the picture in figure 24. The universal testing machine is mainly used for three types of testing; tensile test, flexural test and compression test. The tensile test, which is considered as a pull test, was used in this research. The tensile test was used following ISO Standard 527. In a tensile test, pull tests can be done to determine tensile stress at yield and tensile strain at break. The other two tests, flexural test and compression test, are mainly used for testing bodies with different structure and material properties. (Brown 2002:97)

**Figure 24** *A Testometric tensile testing machine and software (Arcada 2013 Jonas Eklöf)*

### Tensile stress-strain test

Tensile tests or pull tests are the mostly used testing method. These are the essential facts that are used for production or research of any polymeric material. The test method is exceptional in many ways; is fast and easy to use and gives a result that can be quickly studied. The core aspect in pull tests is to determine the strength and deformation of a material. (Brown 2002:97)

Tensile stress-strain is measured in the amount of force that is required to pull a material apart. The tensile stress-strain also determines the displacement of what the material result in such approach at a constant deformation rate. (Brown 2002:97)

**Flexural Stress-strain test**

Flexural stress-strain is used to find the bending properties and displacement of a material. The force is applied perpendicular to the surface. This gives the flexural properties and the displacement of what the material undergoes as a result of the force applied. (Brown 2002: 143) Most used flexural test method is the three-point method where both ends of the test piece rest and a loading are applied in the middle. This results in a bending of the test piece. A common materials used for testing flexural stress is composites with a sandwich structure. (Brown 2002:148)

**Compression test**

Compression, as the name states, is used to find the compression of a material. It examines the opposite to what tensile stress−strain does. Same machine can be used to test both tensile and compression but in the latter case it is needed to have an even higher force and high stiffness which might make it a bit difficult. A compression cage can be used when working with the tensile testing machine. The mainly used materials used to examine compression are rubber and foam to study special characteristics in elasticity and deformation. (Brown 2002:127)

### 2.7.4 UV-VIS-NIR Spectroscopy

UV−VIS−NIR stands for Ultraviolet−Visible−Near Infrared. The UV light is a wavelength that is shorter than the visible wavelength. The UV-VIS Spectroscopy is used to study the chemistry interactions between electromagnetic radiation, atoms and molecules (Anglient 200:151). The spectroscope has gained much popularity because of its fast technique. Samples can be quickly tested and analyzed without any pre-treatment. Both solids and liquids samples can be used with the spectroscope (Xiaobo et al. 2010: 14:32). UV−VIS−NIR spectroscopy is known as electronic spectroscopy because it deals with the absorption of energy by electrons in molecules. The electrons are arranged in three different configurations in the molecule. The two bonds are called the π (pi) − bonds and σ (sigma) − bonds. The last one is η (eta) − electron configurations. When these electrons get in contact with the light, depending on the electrons, they get in different states, which can be the excited state or anti-bonding state between the transitions when the light that passes through a sample. These states are the origin of what is studied with the UV−VIS−NIR spectroscopy (Mehta 2011). The molecule absorbs a portion of light and a spectroscope record the phase when light transmits through the sample. The data, which the spectroscope record, is plotted in a graph where the x- and y- axis is represented of the absorption (A) and (arbitrary unit) the wavelength (in nm) (λ). When the spectroscope is finished and has plotted the amount of absorption in the different wavelengths the result is called a spectrum (PharmaxChange 2011). Figure 25 is a picture of a UV-NIR/VIS workstation.

**Figure 25** *UV-NIR/VIS set up workstation. Software for calibrating results (left) and UV-NIR machine (right) (Arcada 2013 Jonas Eklöf)*

### 2.7.5 Zeiss Microscope – Optical microscopy

The optical microscope is the most common and oldest tool for observations of test specimens. With the use of an optical microscope, scientists can examine a specimen that cannot be seen with the human eye alone.

The optical microscope uses the light, different lenses and a set of objective magnification objectives in order to get the right intensification. The optical microscope use the wavelength between visible light, which means that it is between the light of wavelengths that the human eye can mostly catch up. Other microscopes can use electrons in order to study deeper into the sample.

The model Zeiss Axio Scope A1 is a compound microscope that can use different kinds of lenses and do many different types of tests, which can be modified depending on the test specimen and type of research attainment. It can focus on transmitted-light or reflective light.

For the thesis research, the goal was to study the transmittance, the amount of light that passes through and investigate if any defects were found, so the set up for the microscope used was transmitted-light. The reason why the transmitted light is used and not the reflected light is done because the main purpose is to see through the test pieces and with the help from the visible light, spot any defects or contaminations that may not be observed with the naked eye inside the test sample. The reflected light set up is the study of the surface of a specimen and study how much is reflected back. Using a digital camera the images can be saved and documented for further study. The drawings in figure 26 below illustrate an overview measurements of the Zeiss Axio Scope A1 and figure 27 is an overview of different functions of the Zeiss Axio Scope A1 microscope. (Carl Zeiss MicroImaging GmbH 2013)

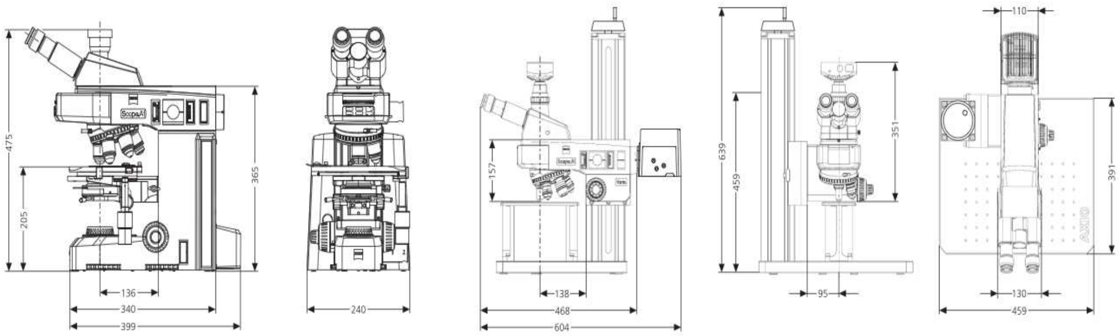
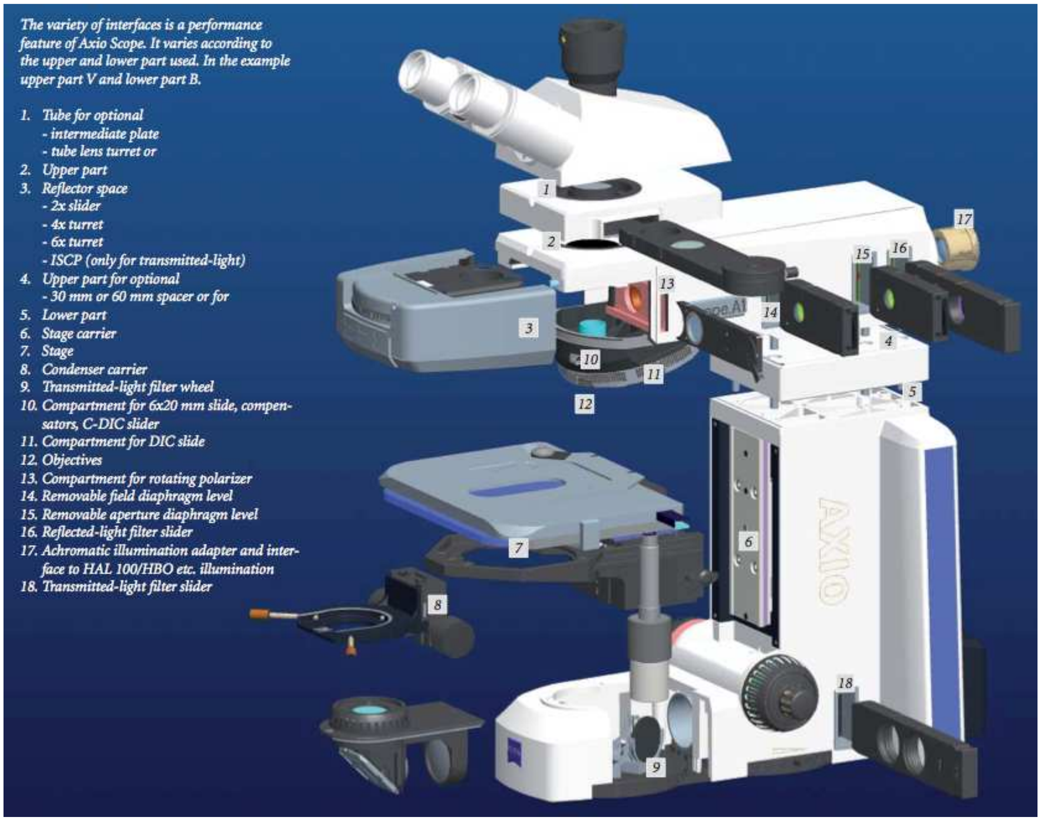


**Figure 26** *Drawings and measurements in mm of the Zeiss Axio Scope (Courtesy of Carl Zeiss MicroImaging GmBH 2013)*


*The variety of interfaces is a performance feature of Axio Scope. It varies according to the upper and lower part used. In the example upper part V and lower part B.*

1. *Tube for optional*
   - *intermediate plate*
   - *tube lens turret or*
2. *Upper part*
3. *Reflector space*
   - *2x slider*
   - *4x turret*
   - *6x turret*
   - *ISCP (only for transmitted-light)*
4. *Upper part for optional*
   - *30 mm or 60 mm spacer or for*
5. *Lower part*
6. *Stage carrier*
7. *Stage*
8. *Condenser carrier*
9. *Transmitted-light filter wheel*
10. *Compartment for 6x20 mm slide, compensators, C-DIC slider*
11. *Compartment for DIC slide*
12. *Objectives*
13. *Compartment for rotating polarizer*
14. *Removable field diaphragm level*
15. *Removable aperture diaphragm level*
16. *Reflected-light filter slider*
17. *Achromatic illumination adapter and interface to HAL 100/HBO etc. illumination*
18. *Transmitted-light filter slider*

**Figure 27** *Overview of different functions of the Zeiss Axio Scope (Courtesy of Carl Zeiss MicroImaging GmBH 2013)*

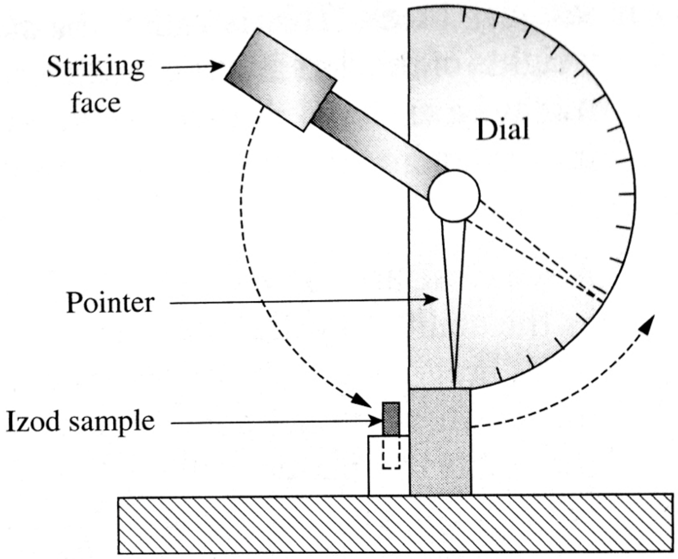
### 2.7.6 Charpy/Izod impact test

The charpy or izod test is a very common testing method. The test is used as much as the tensile stress-strain tests when investigating a material behaviour. The charpy or izod test is a common testing method to quickly and practically investigate the behaviour from a sudden impact on a material.

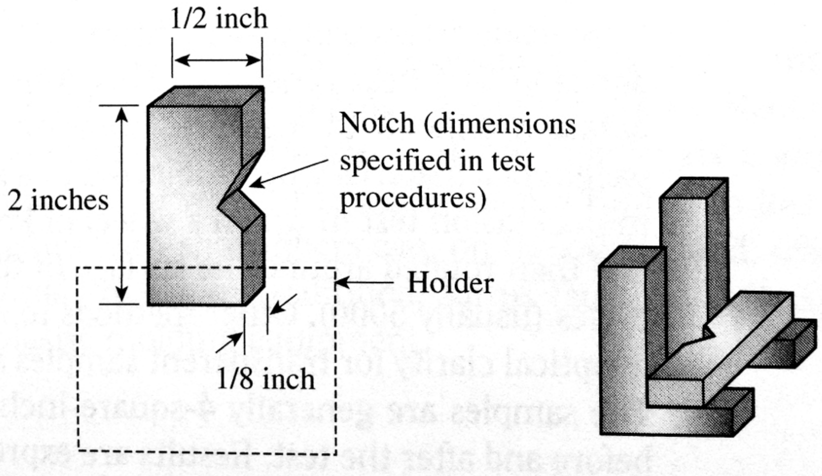
The tensile stress-strain test is considered to be equilibrium toughness. This means that all the same tests are related to the region or area under the same stress-strain curve. This is good for comparison with other materials and to get a balanced test. The charpy or izod test uses a more sudden impact test on the test piece under a shorter time and is called to also be impact toughness test. This is another approach to investigate the material stress-strain behavior in a way because the test depends on the main properties of the material if it is either tough or brittle. The impact test piece is direct proportional to the impact. This means that, depending on the material, the material will internally move or deform by the impact individually. An impact test material can be either tough or brittle. A material is tough when it has a long elongation and low modulus, which means little change. A material is brittle when it has low elongation and high modulus, great change.

Materials with high molecular weight usually have a higher toughness because they usually have higher strength and tolerate higher toughness. This is because these materials will send out the impact along the polymer chain and will make the atoms vibrate along it so it shares the total energy of the impact.

The principal for utilizing the charpy or izod impact test is quite simple. Depending if it is a charpy test or izod test sample is placed and clamped horizontally or vertically respectively. Then, a standard notch is used for the test pieces and a pendulum swings and slices the test piece. The pendulum will swing across the sliced test piece and some of the energy will go into the test piece. From there the loss in height, the potential energy, can be directly related to the energy that was absorbed to the test piece. A pointer records the height of the swing. The test results are often measured in [J/M] and are expressed as impact toughness. As mentioned earlier the test sample is first prepared so it follows the ASTM D 256 or ISO standard. The sample has a v-shaped cut so it initiates the rupture. (Strong 2006:141 ff.)



(a) Test apparatus



(b) Izod

(c) Charpy

**Figure 28** *Charpy and Izod impact test showing the difference of the both methods (Strong 2006)*

Figure 28 above shows the difference between a charpy and izod impact test. The charpy and izod test have their differences with not only the positioning of the test piece. The charpy test, when it is positioned horizontally, creates a tensile stress inside the notch. For the izod test where the test piece is clamped vertically the notch is bended that is struck by the swinging pendulum or hammer. What is also notable for the izod and the charpy tests is that the notch on the test piece has a different radius. (Osswald et al 2003:473 f.:475 ff.).

Some say that the charpy or izod impact tests are unreliable. For example, the test can be used for other materials like metals, where you expect to get a more straightforward result. However even for those results there has been an argument that the results are to unpredictable. The author suggests that the test can be used for quality control and specification purposes but not for end-product performance. The test is still useful and is good for the examiner to get more general knowledge of how a material behaves. (Crawford 1998:152 f.)

As mentioned earlier the impact toughness or impact strength can be calculated as follows in formula 4:

$$Impact\ Strength = \frac{Energy\ to\ break}{area\ at\ notch\ section}\ (\mathrm{J/m^2}) \qquad [4]$$

(Crawford 1998:152)

# 3 METHOD

Test specimens were produced and compared throughout the following tests. The experimental part of this thesis was done using the following methods.

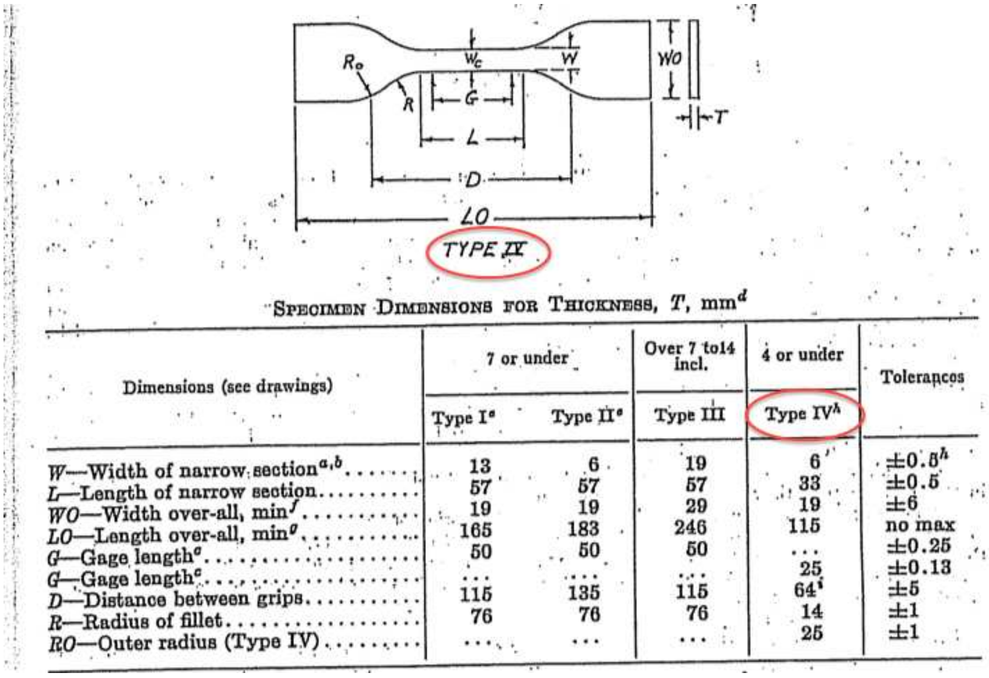
1. Tensile test.
2. UV−Vis−NIR Spectroscopy transmission analysis test.
3. Optical Microscopy test.
4. Expert interviews.

The materials used for the test were the following:

1. GPPS, General Purpose Polystyrene 678E polymer resin. Producer: Styron. Technical information data sheet can be found in the Appendix [I].
2. Recycled PS flakes. Grinded and produced from Bioscreen HC products by Jonas Eklöf. Total number of recycles made can be found in the next section table.

## 3.1 Test specimen

In order to be able to test and compare the results, dog bone test pieces were produced using the injection-moulding machine. The dog bone test specimen is a type IV dog bone that has been produced according to ASTM D638 standard. Bellow in figure 29 is the data that has been used to proceed according to the standards:



SPECIMEN DIMENSIONS FOR THICKNESS, $T$, mm$^d$

| Dimensions (see drawings) | 7 or under | | Over 7 to14 incl. | 4 or under | Tolerances |
|---|---|---|---|---|---|
| | Type I$^e$ | Type II$^e$ | Type III | Type IV$^h$ | |
| $W$—Width of narrow section$^{a,b}$ | 13 | 6 | 19 | 6 | ±0.5$^h$ |
| $L$—Length of narrow section | 57 | 57 | 57 | 33 | ±0.5 |
| $WO$—Width over-all, min$^f$ | 19 | 19 | 29 | 19 | ±6 |
| $LO$—Length over-all, min$^g$ | 165 | 183 | 246 | 115 | no max |
| $G$—Gage length$^c$ | 50 | 50 | 50 | ... | ±0.25 |
| $G$—Gage length$^c$ | ... | ... | ... | 25 | ±0.13 |
| $D$—Distance between grips | 115 | 135 | 115 | 64$^i$ | ±5 |
| $R$—Radius of fillet | 76 | 76 | 76 | 14 | ±1 |
| $RO$—Outer radius (Type IV) | ... | ... | ... | 25 | ±1 |

**Figure 29** *Cut out from the ASTM tentative method of test for tensile properties of plastics (Mathew 2011)*

The variety of the IV dog bone test pieces are listed in table 7 below. In total there are eight different types of tests, which were made from same material when recycled. The first piece is used with pure PS while the other test pieces have been recycled according to the total amount of percentage-recycled material in the test pieces. The second test piece is 100 percent recycled from the first test. The third test use 15 percent of the 100 percent recycled material. The fourth test piece use 30 percent of the 100 percent recycled material and so on. The differences of the different test pieces are the amount of recycled materials and times that the material has been recycled.

**Table 7** *List of amount of tests made (Jonas Eklöf)*

| # | Amount of recycled materials [%] | Times recycled |
|---|---|---|
| 1 | 0 | Non (only raw material) |
| 2 | 100 | One |
| 3 | 15 | One |
| 4 | 30 | One |
| 5 | 15 | Two |
| 6 | 30 | Two |
| 7 | 15 | Three |
| 8 | 30 | Three |

## 3.2 Injection moulding machine preparation and parameters

The steps of how to safely and properly operate an injection moulding machine was followed according to author A. Brent Strong which can be found in the appendix [III]. The parameters used for the injection-moulding machine was not hard to find since PS is easy to work with. The main parameters used for PS in the injection-moulding machine are listed in table 8 below.

**Table 8** *Set up parameters for the injection moulding machine (Jonas Eklöf)*

| **Temperature** | **Value** | **Unit** |
|---|---|---|
| Nozzle | 220 | °C |
| 2. Cylinder | 220 | °C |
| 3. Cylinder | 220 | °C |
| 4. Cylinder | 215 | °C |
| Hopper | 45 | °C |
| **Mould Temperature** | 45 | °C |
| **Mould fastening** | 350 | kN |
| **Cooling time** | 15 | S |
| **Injection** | 130 | Mm/s |
| **Injection time** | 4 | S |
| **Holding time** | 5 | S |
| **Holding pressure** | 140 | Bar |
| **Cushion** | 5 | Mm |
| **Plasticizing stroke** | 25 | Mm |

## 3.3 Tensile test

The mechanical properties for the PS and all the rPS were tested through a tensile testing machine. The tests were conducted at a load speed of 50 mm/min and according to ASTM D638. According to ASTM D638, in order to get a reliable test, each material needs to be tested with 5 dog bones. The length for the type IV standards is approximately 33 mm. Thickness of the dog bone needs to be lower than 4 mm (in this case ~1.61 mm) and width 6 mm (in this case 5.56 mm). Force was 50 mm/min in the standard setup, but because PS is so brittle it was set to 5 mm/min. According to the standards when using 5 mm/min there should be a tolerance of ±20%. A check was made with 50 mm/min and it was 40.9 MPa (which is close enough to run all test again with 50 mm/min). Parameters set for the test is listed in table 9 below. Worth noting is that as mentioned earlier the tensile testing machine can find many more different mechanical properties like compression, flexural strength and shear stress. These tests would require other ISO standards and those tests have not been taken into consideration for the current duty. The reason for this is because of the lack of mould and test pieces for those shapes. (Brown 2002:107)

**Table 9** *Parameter set for the tensile testing machine (Jonas Eklöf)*

| Test speed [**mm/min**] | Force [**kN**] | Distance between grips [**mm**] | Tolerance [**%**] |
|---|---|---|---|
| 50 | 5 | 60 | ±10 |
| 5 | 5 | 33 | ±10 |

## 3.4 Spectrophotometry – Transmission

The UV-VIS-NIR machine was used to find the transmittance and absorbance between wavelengths of 190-2700 nm. The value was set first to be Violet (the wavelength), which is below the Visible wavelength (< 400nm) and then through the visible wavelength up to 2700nm. The final parameters were then set to ~ 190nm – 2700 nm wavelength. The other and final parameters for absorbance are listed in table 10.

**Table 10** *Set up parameters for the UV-VIS spectroscopy*

| | | |
|---|---|---|
| UV-VIS | 5 | Nm |
| UV-NIR | 20 | Nm |
| Scan speed | 1000nm/min | |
| Response | Fast | |

A colour measurment were done in order to differentiate the colour from the light absorption and transmission. There is a standard (ASTM 1729) to measure the colour by colour matching. The test is done analytically and can be done either by absorbance or by light refelectance. The test require colour samples and pigments to compare the colour with the test samples. (Strong 2003: 179) Because of the lack of standard test samples the test were not analyzed using the ASTM 1729.

With the spectra software a L*a*b colour data can be collected and analyzed from the results. The L*a*b colour scale is a colour scale that is used to get an estimation of colour values. The colour analysis test were done comparing the amount of the three basic colours (red,blue,green) to distinguish a difference and comparison between the test samples. (HunterLab 2008)

### 3.4.1 Calculations

The UV-VIS-NIR spectroscope was set to scan the absorbance. Since we wanted to find the transmittance of a material, we need to invert the results using the common Beer-Lambert law as shown in formula 5. There are different approaches to find the absorption and from there find the transmission.

$$A = log10\,(Io/I) = \varepsilon \times c \times L \qquad [5]$$

*Formula 4: Beer-Lambert Law formula*

In the first section A is the Absorbance, measured in Absorbance units, AU, $I_0$ is the intensity of the incident light at a given wavelength, $I$ is the transmitted intensity. Figure

30 below show how $I_0$ is the intensity of the incident light and the transmitted intensity $I$ that is measured.

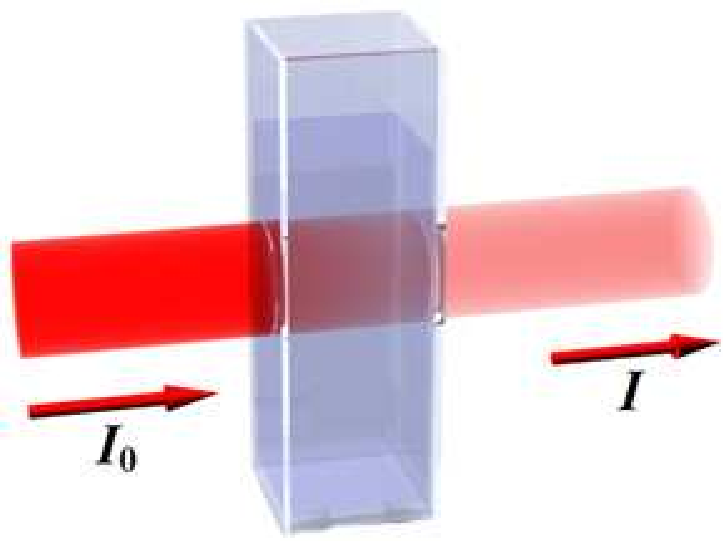


**Figure 30** *Illustration how the transmission is measured from the material. In the picture the sample appear to be a concentration, but the principle is the same for a solid material (Gallik 2011)*

The last portion in formula 5 show is the other common Beer-Lambert formula. The formula shows that same result is approached when ε is epsilon which is a constant, is multiplied with c , which is the concentration of the absorbed sample, and L, which is the pathlength through the sample. In order to get the transmittance the values of the absorption is inversed. One way is to use the formula [5] is to manipulate the equation to get the transmittance. In Appendix [IV] is a proof of how the transmission is the inverse of absorbption using formula [5].

## 3.5 Microscope

The Zeiss Microscope used transmission set up with up to a 50 times enlargement magnification. 50 were to near to study anything within the material. Mostly 5x and 10x magnification objectives were good enough in order to be able to study the transmittance of the solid material.

It is important that the workstation is clean when starting to use the machine. The camera and the objects must be carefully cleaned in order to receive best results and record the best images. There are lots of cleaning agents and materials that can be used in order to prevent bad images (Zölffel 2013:4). There are some steps that can be done in order to check if there is dirt on the results. One thing to start with is the sharpness or quality of the image. Dirt can be spotted when similar contrast of the image follows when adjusting the objectives, specimen or condenser (check figure 21) in result of poor quality of sharpness and contrast (Zölffel 2013:4). There are of course other types of dirt that can be the reason why a bad quality of image appears, but that kind of dirt are usually found when going to a 20x or more objective magnification, which then detects even fingerprints and other particles. (Zölffel 2013:6)

Figure 31 shows how good quality the recorded image appeared from the digital camera. The picture that was captured shows a spot that were found on all the test pieces. It was interesting that all the test pieces had the same pattern on exactly the same spot. The reason for this would probably be a defection that has emerged from the mould during the production process with the injection moulding machine. The spot was best visible with a 5x objective magnification.

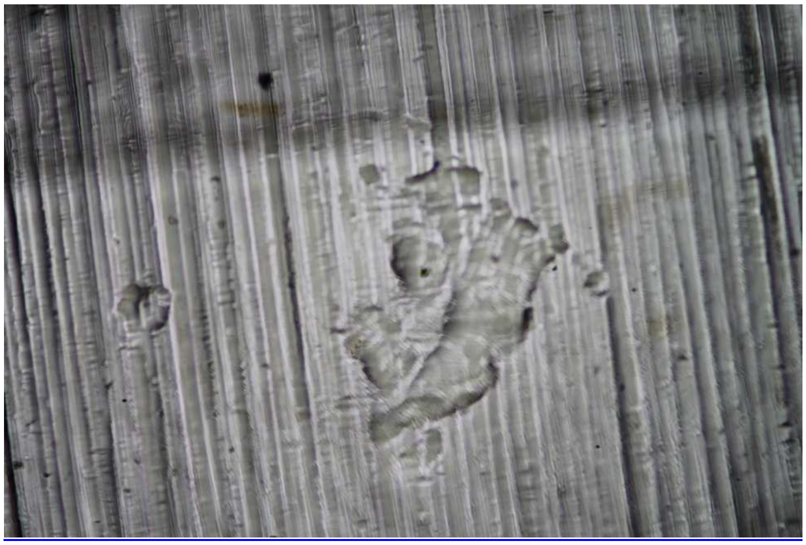


**Figure 31** *Spot that was found on all test pieces (Arcada 2013 Jonas Eklöf)*

## 3.6 Interviews

Interviews from persons from the sub-contracting fair in Tampere were done in order to get an expert opinion on how PS is currently used and suggestions what to do with it when recycled. The name GPPS have been used instead of PS because General-Purpose-Polystyrene might get mixed with the other PS products.

The Tampere sub-contracting fair took place on the 24th to 26th of September 2012. The exhibition is the biggest sub-contracting fair in Finland. The fair has over 1000 exhibitors and involves metal industry, electronic industry, rubber industry, plastic industry, design, consultation, and ICT.

The interviews were done face-to-face with key persons representing different plastic companies. The questions asked are listed below.

1. *What method or recycle process do you think GPPS would be most suitable for? What is your opinion?*

2. *If recycling PS mechanically (able to be re-used for the injection-moulding machine) what product or field do you think rPS would be most suitable or profitable to produce?*

3. *Have you had any experience in recycling GPPS as energy or any other way? If so do you think that would be a good choice to use GPPS waste?*

# 4 RESULTS

In this chapter the main results are shown. The results from each test method are presented in separate sections of this chapter. In the appendix are the rest of the tests results and also the results found from the microscope test.

## 4.1 Tensile test

Results of the tensile test were collected in order to compare all the results. There was some trouble producing the dog bones from the injection-moulding machine at first because the mould, which produced another standard of dog bones were broken and unable to be used further so the mould had to be changed and the process had to reschedule. Since the IV type dog bone mould was produced in the university there is not a 100 percent guarantee that it followed the correct standards. The tests were tested according to ASTM D638. Also, the dog bones got greenish both when recycled and when only raw PS was used. Since the injection-moulding machine at school is not only used with PS the reason for this might be that a green PET material was used before the test, even though it had been properly cleaned. Since all the produced material looked the same it did not change the relative results between the materials. The main goal was to compare the recycled materials with each other.

The PS dog bones snapped remarkably fast with the 50 mm/min set-up. Because of this the test speed was also tested and measured with 5 mm/min, respectively, each for a more comparable result. All results from the tensile testing machine are shown in the appendix [II], but stress at yield, nominal stress at break and Young's modulus was compared and is mainly focused in the results tables below. Table 11−14 reveals the results with the test speed of 5 mm/min. Table 15−18 reveals the results with the test speed of 50 mm/min.

**Table 11** *Tensile test results with 5 mm/min test speed*

| Material and times recycled | Stress at Peak [MPa] | Nominal strain at break [%] | Young's Modulus [MPa] |
|---|---|---|---|
| I. Non rPS | 31.737 | 2.275 | 1479.259 |
| II 100% rPS | 34.022 | 2.881 | 1309.529 |
| III 15% rPS one | 34.508 | 2.819 | 1309.688 |
| IV 15% rPS two | 35.748 | 2.951 | 1267.181 |
| V 15% rPS three | 36.325 | 3.066 | 1210.164 |
| VI 30% rPS one | 36.231 | 3.292 | 1155.65 |
| VII 30% rPS two | 35.264 | 2.951 | 1257.568 |
| VIII 30% rPS three | 35.9 | 3.152 | 1264.892 |

**Table 12** *Stress at peak 5 mm/min*

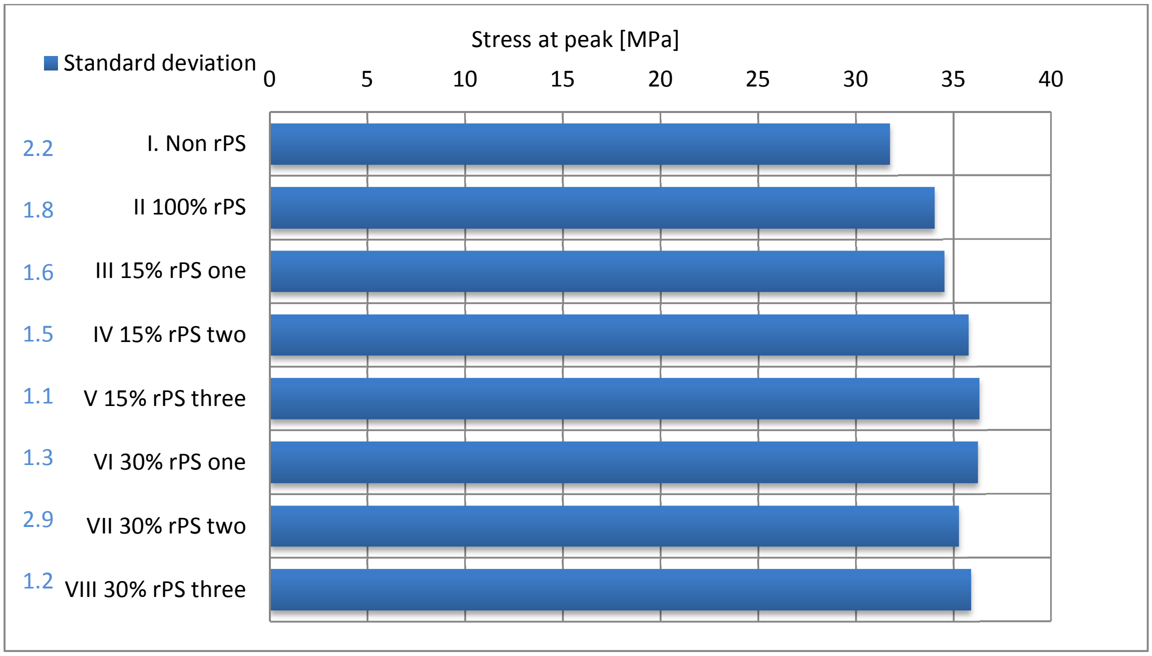


**Table 13** *Nominal strain at break 5 mm/min*

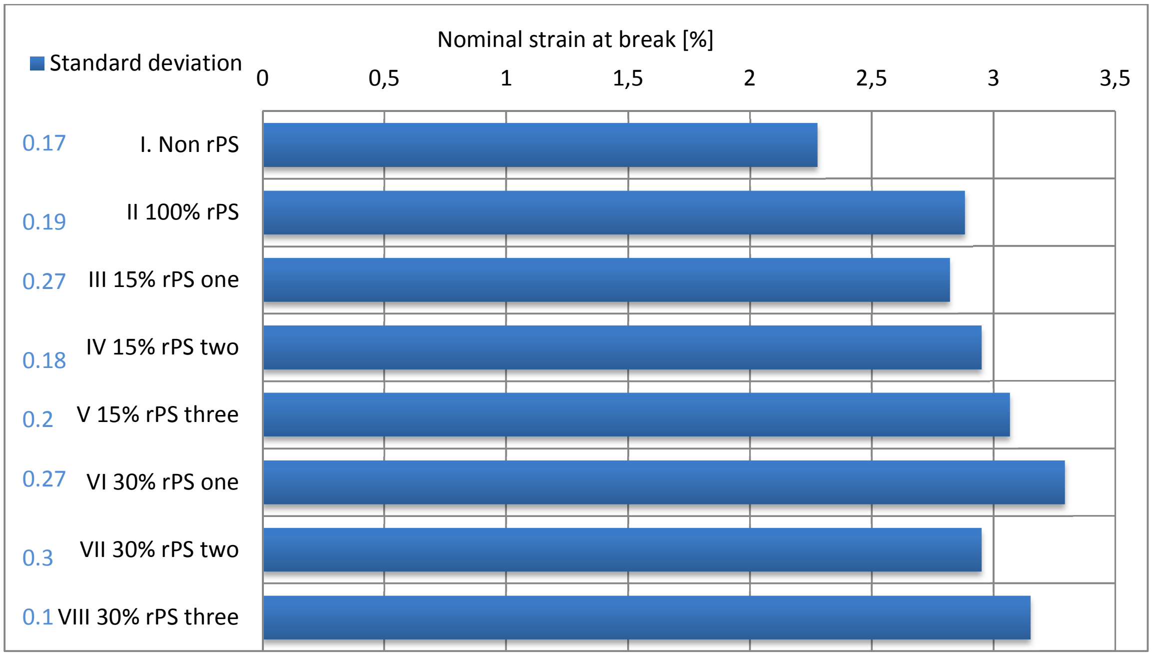


**Table 14** *Young's modulus 5 mm/min*

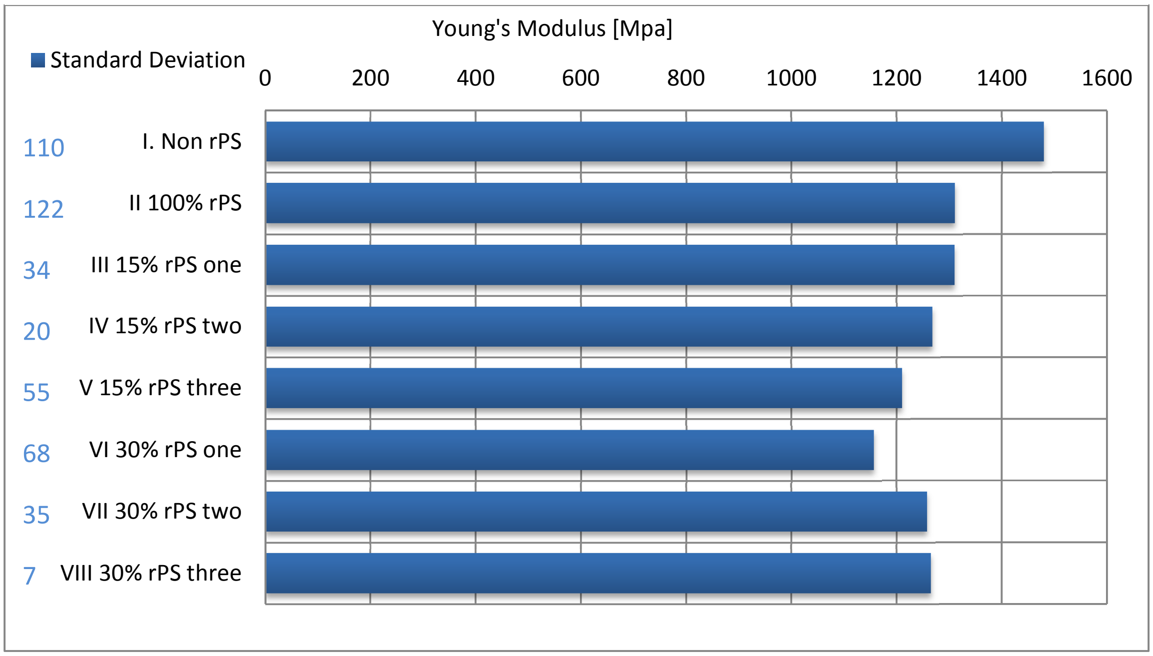


**Table 15** *Tensile test results 50 min/mm*

| Material and times recycled | Stress at Peak [MPa] | Strain at Peak [%] | Young’s Modulus [MPa] |
|---|---|---|---|
| I. Non rPS | 39.592 | 3.478 | 1375.001 |
| II. 100% rPS | 36.143 | 3.547 | 1258.807 |
| III. 15% rPS one | 39.774 | 3.534 | 1308.22 |
| IV. 15% rPS two | 39.074 | 3.393 | 1322.958 |
| V. 15% rPS three | 39.303 | 3.422 | 1352.265 |
| VI. 30% rPS one | 39.547 | 3.479 | 1330.311 |
| VII. 30% rPS two | 37.384 | 3.089 | 1337.184 |
| VIII. 30% rPS three | 38.668 | 3.382 | 1294.302 |

**Table 16** *Stress at peak 50 min/mm*

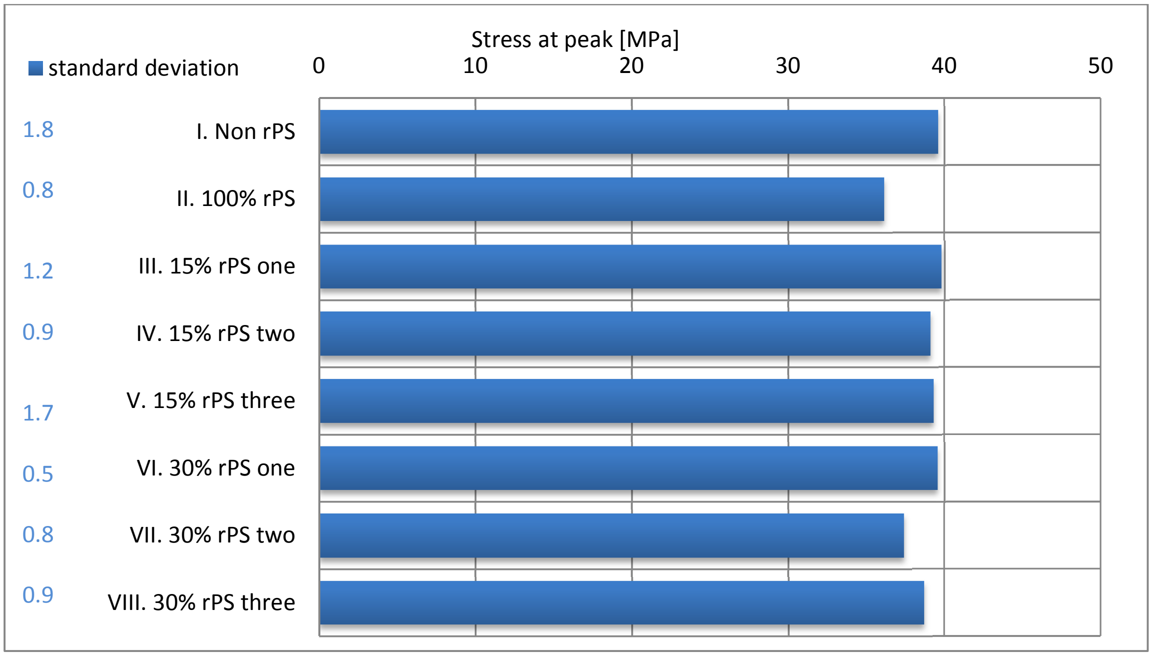


**Table 17** *Nominal strain at yield 50 min/mm*

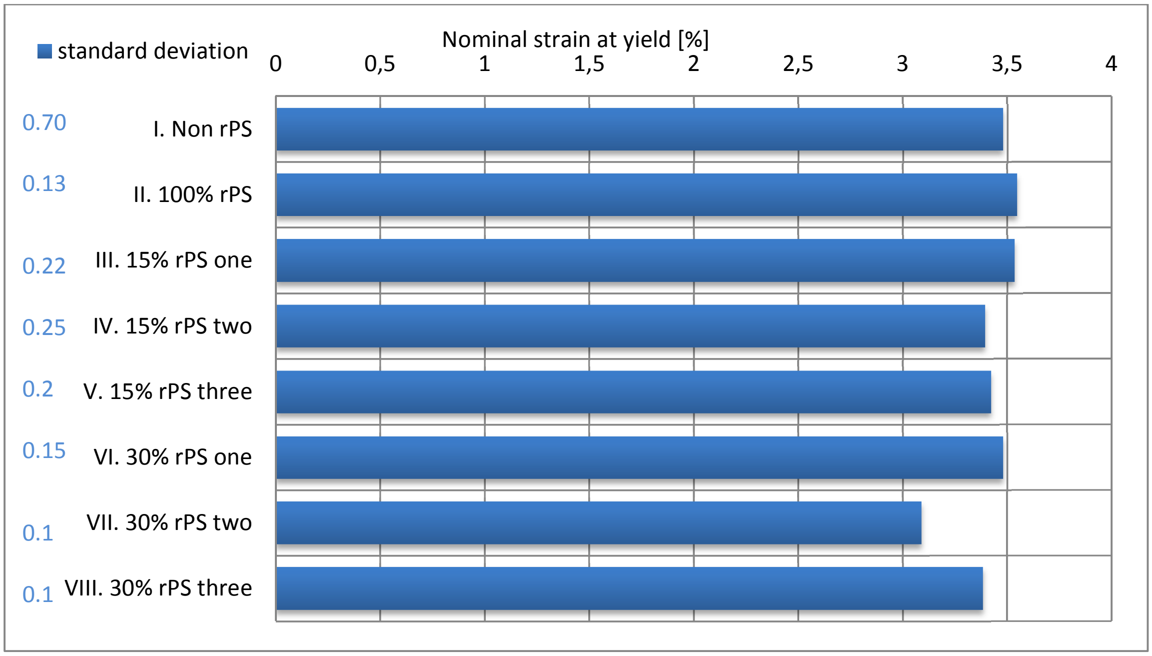
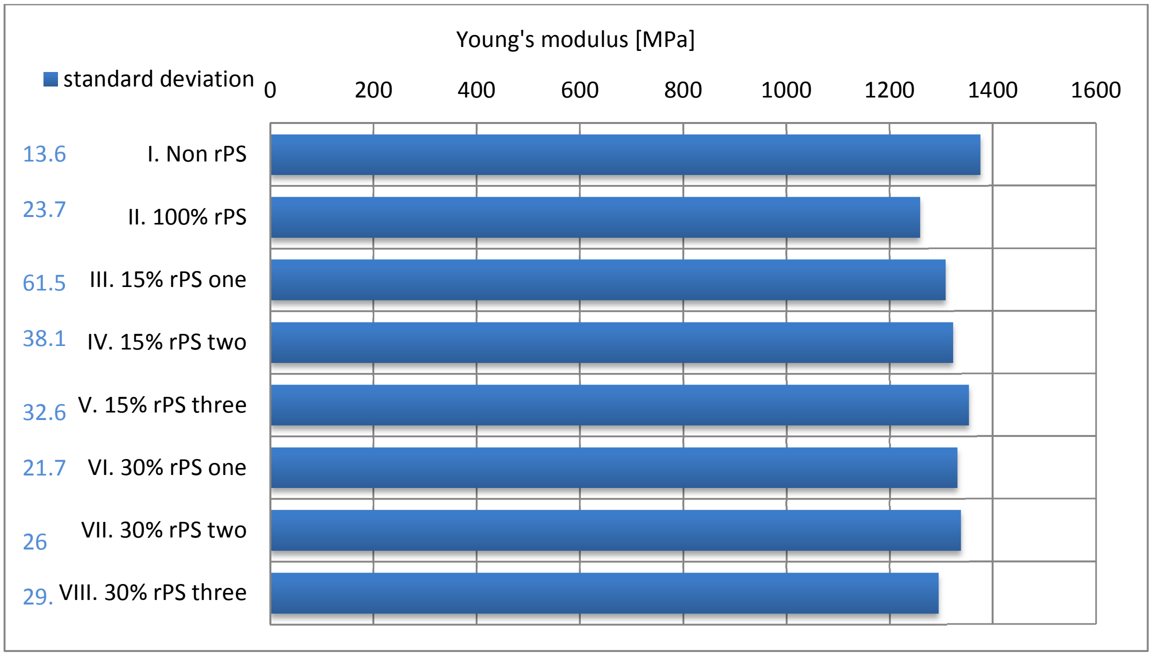


**Table 18** *Young's modulus 50 min/mm*



## 4.2 Transmittance

The transmittance was found using the UV-VIS-NIR machine. The test specimens used in the UV-VIS-NIR test were the same test specimens that had been used for the tensile test. For a more comparable test the test specimens were cleaned and assured that the surface was lapped where the beam would hit the test piece. The very same adjustments were made for all the test pieces so the results would be comparable. The results can be found form figure 32−39. The first test was with non-recycled polystyrene. The second test was with 100 percent recycled polystyrene. The third test was tested with 15 percent recycled polystyrene. The forth test was tested with 15 percent recycled polystyrene with a second time recycled. The fifth test was with 15 percent recycled polystyrene with a third time recycled material. The sixth test was with 30 percent recycled material. The seventh test was tested with 30 percent recycled material with a second time recycled. The eight and the final test were tested with 30 percent recycled material with a third time recycled material. In figure 40 all results are combined for a comparison between the deviations of the different tests.

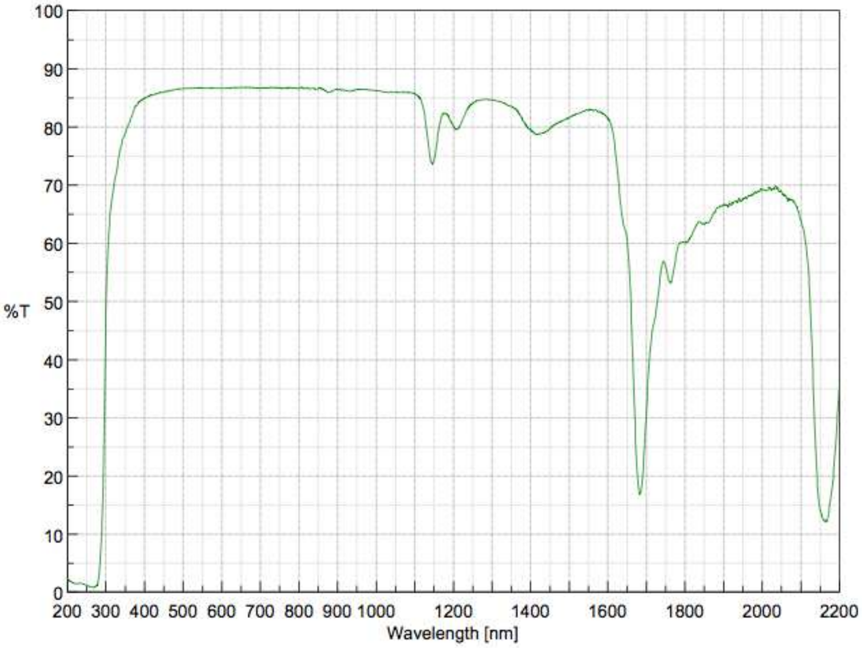


**Figure 32** *First result with non recycled PS UV-VIS spectrum*

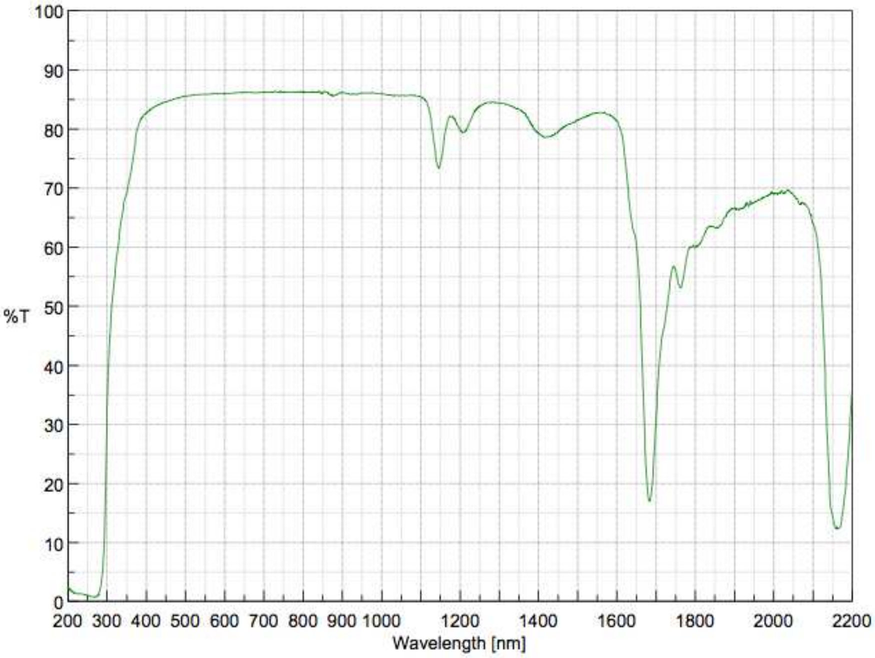


**Figure 33** *Second result with 100 percent recycled PS UV-VIS spectrum*

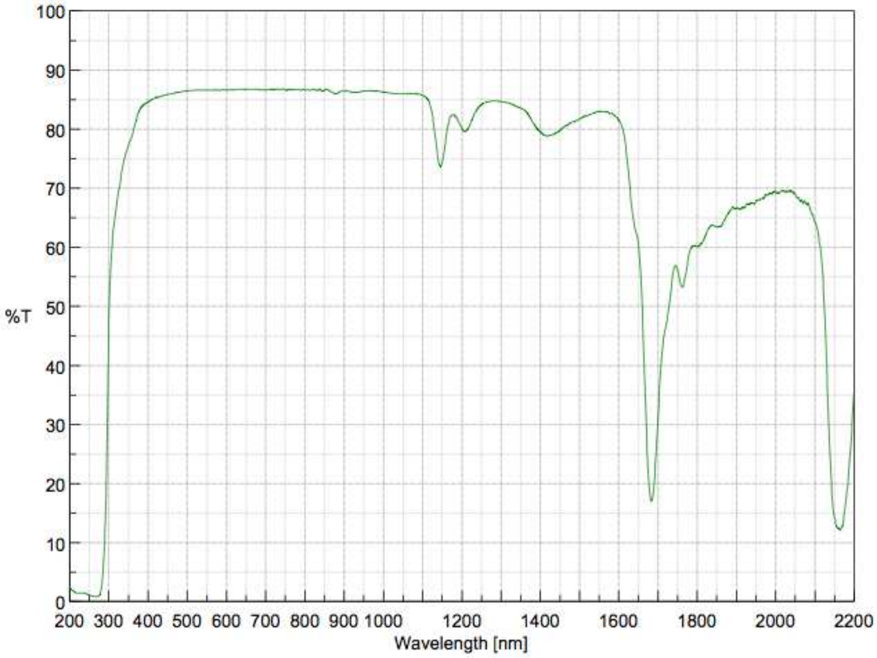


**Figure 34** *Third result with 15 percent recycled PS UV-VIS spectrum*

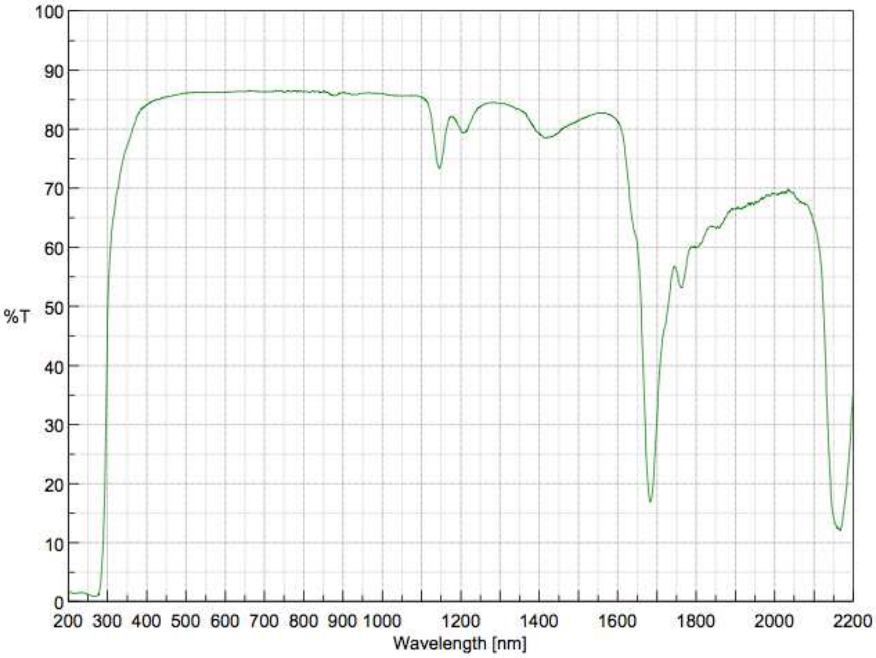


**Figure 35** *Fourth result with 15 percent recycled PS two times UV-VIS spectrum*

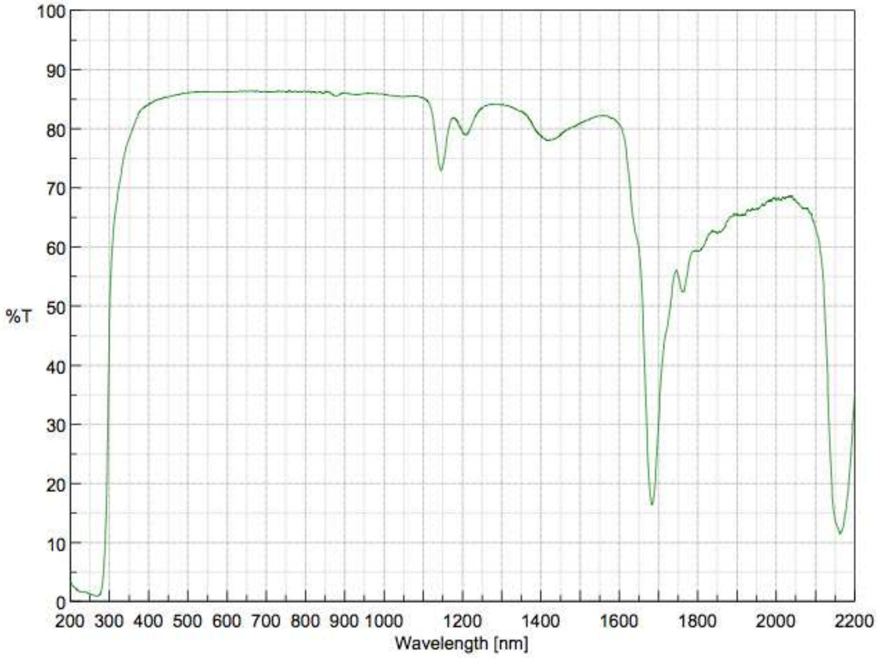


**Figure 36** *Fifth result with 15 percent recycled PS three times UV-VIS spectrum*

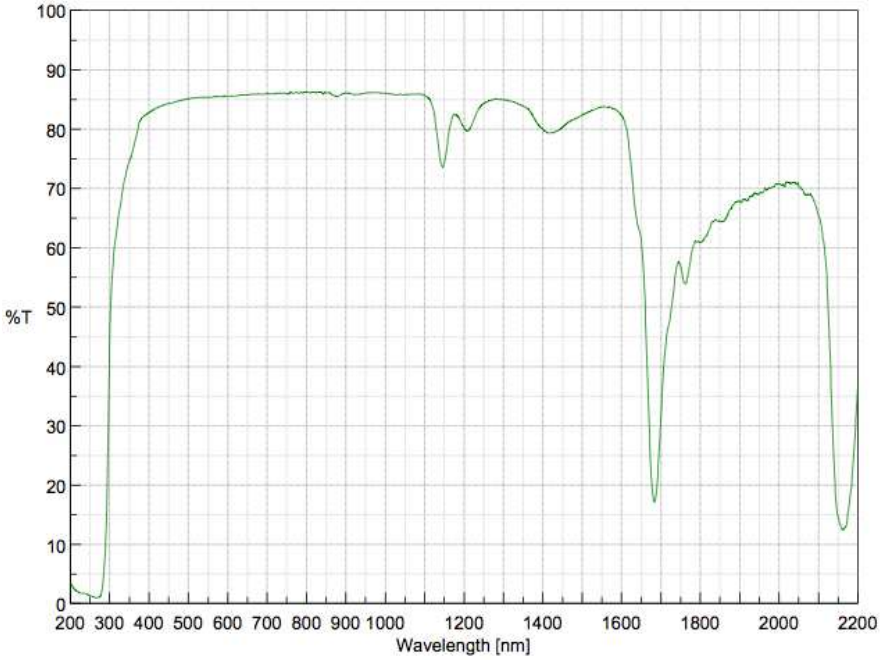


**Figure 37** *Sixth result with 30 percent recycled PS UV-VIS spectrum*

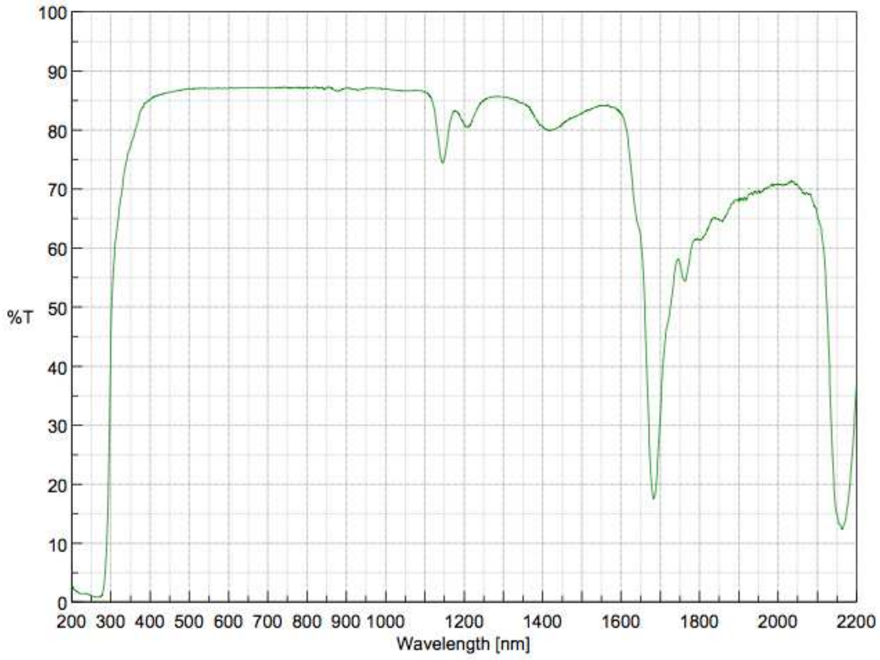
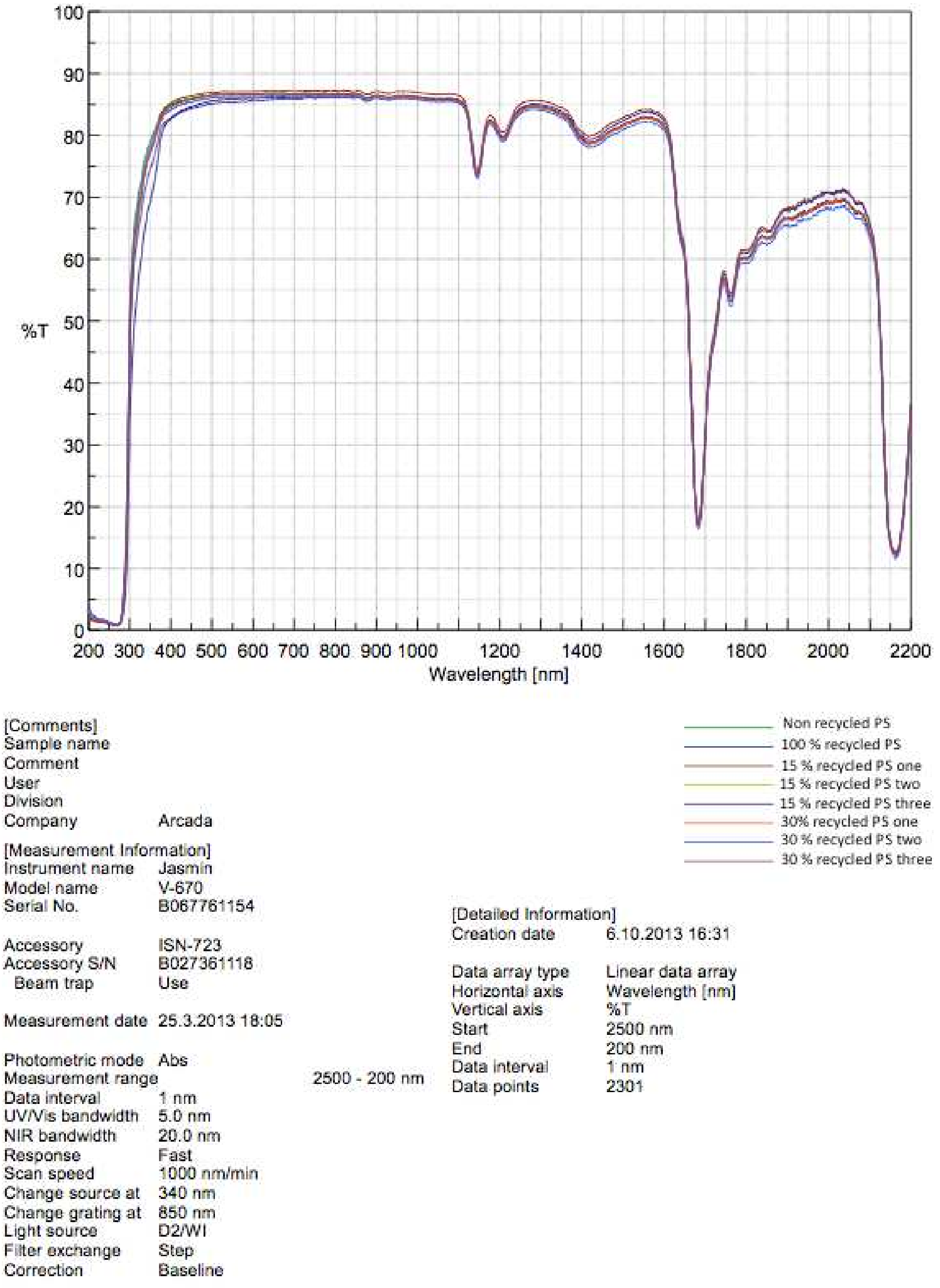


**Figure 38** *Seventh result with 30 percent recycled PS two times UV-VIS spectrum*

**Figure 39** *Eight result with 30 percent recycled PS three times UV-VIS spectrum*



```
[Comments]
Sample name
Comment
User
Division
Company            Arcada

[Measurement Information]
Instrument name    Jasmin
Model name         V-670
Serial No.         B067761154                      [Detailed Information]
                                                   Creation date      6.10.2013 16:31
Accessory          ISN-723
Accessory S/N      B027361118                      Data array type    Linear data array
  Beam trap        Use                             Horizontal axis    Wavelength [nm]
                                                   Vertical axis      %T
Measurement date   25.3.2013 18:05                 Start              2500 nm
                                                   End                200 nm
Photometric mode   Abs                             Data interval      1 nm
Measurement range                  2500 - 200 nm   Data points        2301
Data interval      1 nm
UV/Vis bandwidth   5.0 nm
NIR bandwidth      20.0 nm
Response           Fast
Scan speed         1000 nm/min
Change source at   340 nm
Change grating at  850 nm
Light source       D2/WI
Filter exchange    Step
Correction         Baseline
```

**Figure 40** *All results including the set up information from the UV-VIS machine UV-VIS spectra*

### 4.2.1 L*a*b colour analyse results

The spectra software was used to gain colour analysis values form the tests. The values were in an L*a*b system of measuring colour.  A 3D scatter plot workbook was used in order to plot all the values in the same graph. It was hard to be able to fit all the values since they all had almost the same results but some adjustments were made in order to distinguish between the tests. The scales on the graph were set so the y−axis represent the L value 0 − 100. The x-axis represents the a-value 3 − (-3) and the b value 3 − (-3). Below are the values shown in table 19 and the 3D plot graph of the results in figure 41. The values were so close that the labels are not present.

**Table 19** *L*a*b colour analysis results*

| **L*a*b Analysis** | | | |
|---|---|---|---|
| Value | X | Y | Z |
| | a | L | b |
| Non recycled PS | -0,19 | 94,58 | 0,44 |
| 100 % rPS | -0,23 | 94,23 | 0,88 |
| 15 % rPS one | -0,19 | 94,55 | 0,51 |
| 15 % rPS two | -0,19 | 94,38 | 0,54 |
| 15 % rPS three | -0,22 | 94,38 | 0,56 |
| 30 % rPS one | -0,16 | 94,03 | 0,76 |
| 30 % rPS two | -0,16 | 94,73 | 0,43 |
| 30 % rPS three | -0,19 | 94,53 | 0,52 |

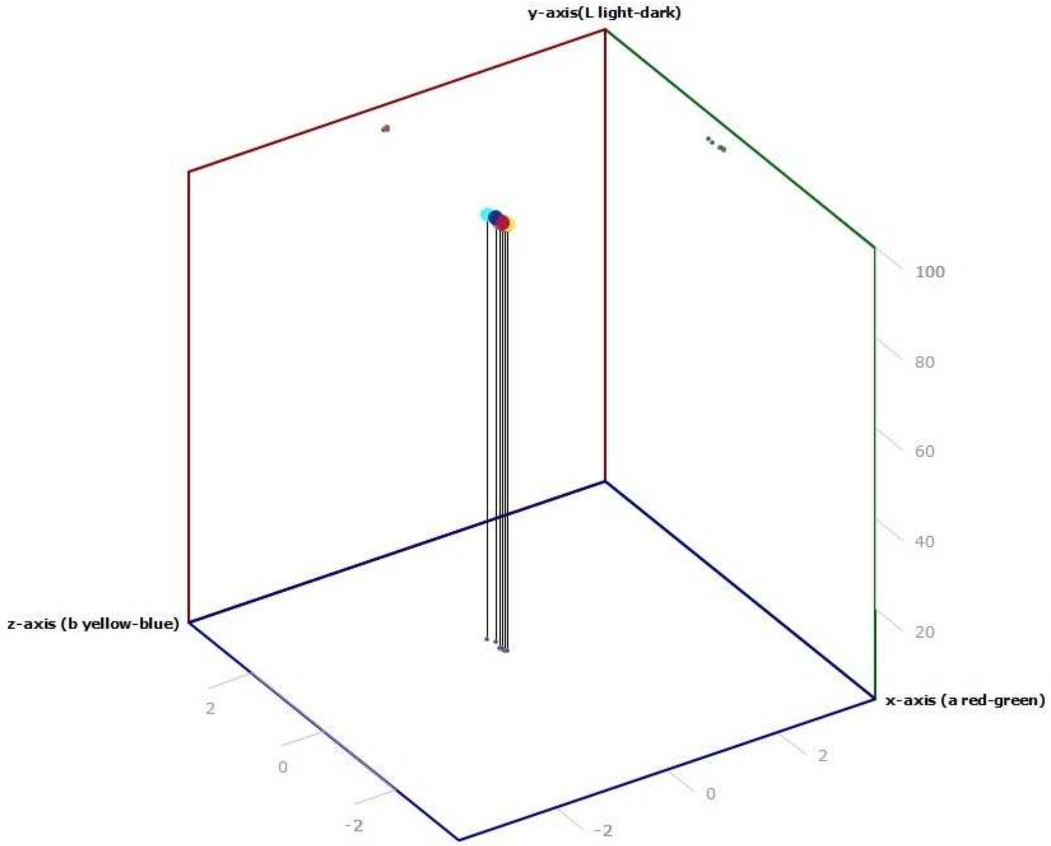


**Figure 41** *3D scatter plots from the results of the colour analysis test*

## 4.3 Zeiss Microscopy

A digital camera was used to take pictures of the findings used with the Zeiss Microscope. Using the transparency set up made it possible to look through the material. Some interesting spots were found that were further investigated, but it was hard to notice any particular difference between the test pieces since all had the same odd-looking particles inside. One particular spot were followed because it clearly distinguished inside the material as seen in figure 42−45. When investigated even further the colour changed when looking with up to 10x magnification.

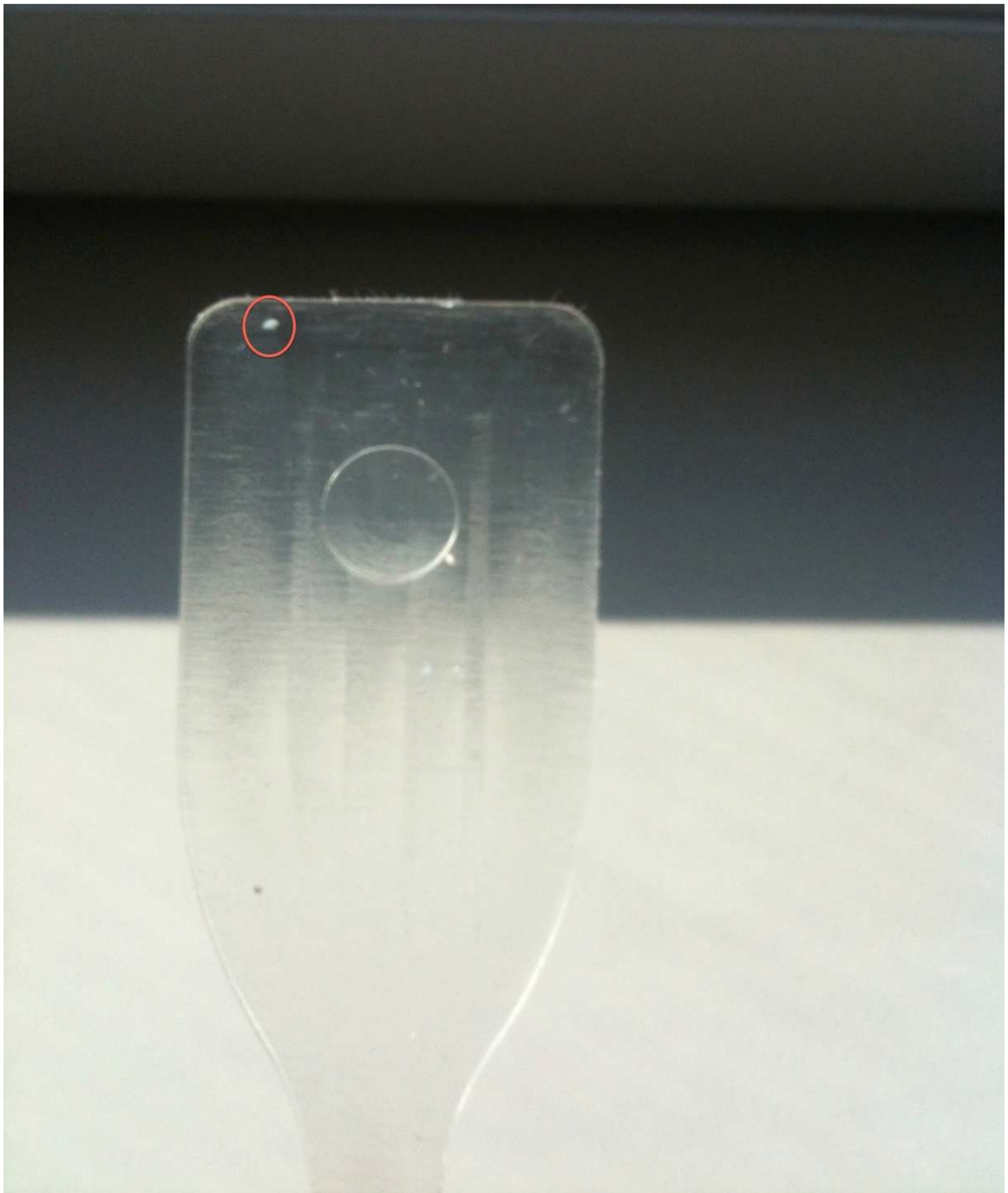


**Figure 42** *A picture taken with a normal 8MP lens camera. Notice the red indication (Arcada 2013 Jonas Eklöf)*

**Figure 43** *Closer look on the indicated spot with a 5x objective magnification (Arcada 2013 Jonas Eklöf)*

**Figure 44** *Same spot as the previous with a 5x objective magnification and more light transmission (Arcada 2013 Jonas Eklöf)*

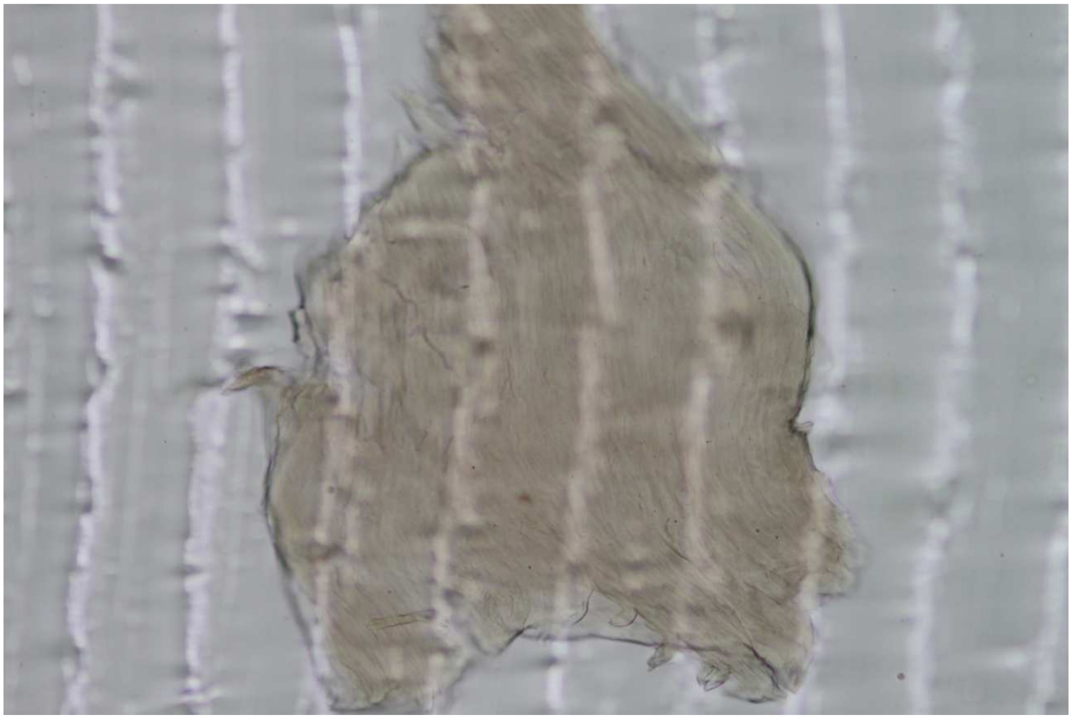


**Figure 45** *Same spot but with a 10x objective magnification (Arcada 2013 Jonas Eklöf)*

All the results recorded images from the microscopy test can be found in Appendix [V]

## 4.4 Interview answers

The answers from the interviews are listed down below from key persons in the plastic industry. Some persons accepted to use their name and company name and some only allowed name. Persons who wanted to be completely anonymous are listed as "Person "X". The Answers are listed according to the question number. The persons are not listed in a specific order.

Joni Henionen, Masamuovi Oy

1. "*You can grind scrap material, that's the easiest way to use it. Another one is to re-pelletize it through extrusion to re-granulate it. That is better for quality but more expensive. The best way is to immediately grind scrap material after producing it and right back to the process.*"

2. "*Various types, but should not be anything with optical or big visual demands. Perhaps a food container or fork that can be used once. Nothing with big demands. Because you have the risk that you will produce more scrap using too much recycled material. Best way is to grind it and immediately use it on the same process, then you will have a small percentage of recycled material and won't need any drying and used immediately is the best way*"

3. "*When the material is mixed for example with some other material it is contaminated and not usable, then you can use it as energy material, energy scrap. Every material except PVC can be used as energy material. It is not the most profitable way but the more eco-friendly (environmental friendly way) use as energy.*"

Person A

1. "*If we can mechanically recycle in our plant it is most efficient for us. For example if you do some products and there are waste parts sprue channels we can immediately after put it on recycle on our own stock so we can re-use it 100%.*"

2. "*Should be simple products. Without any high mechanical or visual demands.*"

3. "*Don't have answer*"

Mika Kantola

1. "*One efficient way would be to mill it back to scrap and use it again*"

2. "*There is no such thing as best product, it can be used to what it meets to demands*"

3. "*For example we recycle in our plant, so we mill it and use it again. When we deliver our product, they may burn it and use it as energy. After a product has been used it can be burned*"

Person B

1. “*There are many techniques that polystyrene is good at. Depends on the product. In our company we grind the sprue and failure pieces*”
2. “*Best products would be where the colour is not so important. Not a part that need to have so big visual demands. Not for food use if not food approved. If it is parts that have to look good you need to be very careful with the recycled material that there is no other materials, no other particles and the colours are the same.*”

3. “*I don’t know that sector*”

Fredrik Holst

2. “*The products should be simple, disposable products. It can be for example flowerboxes and simple storage boxes.*”

## 5 DISCUSSION

In this section the research methods will be explained and why they were used, except the interview answers. They will be evaluated and concluded in the next section.

It was not hard to realize that the most beneficial and practical way to recycle the Bioscreen HC product would be to grind it down to flakes and then use the rPS flakes in the injection moulding machine. The grinding process went fast and smooth with no holdbacks. As mentioned in the theory section it is important that the outcome of the flakes have similar size and because of this it might be good to shred the material numerous of times in order to make sure of that. Surprisingly the rPS flakes were visually good already on the first run but were grinded two times for convenience.

The injection moulding machine was easy to operate when producing the test pieces even though some unexpected scenarios slowed down the project. There was no difference in the parameter set-up for the different materials when operating with the injection moulding machine. Since the machine was not only used for the purpose of the current research other materials had been operated before the production of the test pieces.

As a result of this the injection moulding machine were carefully cleaned. Nevertheless there was still an expectation that the produced test pieces would have an effect on the results. Green PET had been used in the injection moulding machine and the outcome of the test pieces indicated when producing test pieces that a weak greenish colour were found when they were stacked. The reason for this was probably that some PET granulates were still inside the injection moulding machine when producing the test pieces

As for the tensile test the set up was somewhat modified in order to gain a more decent and comparable result with the test pieces. In the beginning the tensile test the force was set to 50 mm/min, as it had been used in the standards, but because the material was so brittle it was set to 5 mm/min. At first the tests seemed to give reliable results, but after all test were done a 20% difference were discovered. Since the standards indicated that changing the test speed the result should have a tolerance of ±20% it seemed to proceed as planned.

The results provided from the tensile tests were not similar to the one as on the technical data sheet. The young's modulus was not done according to the standard since it required different test tools and standard. However the results were all done in the same approach and could therefore be compared simultaneously. The mechanical properties from tensile test results were surprisingly similar to each other. It was expected that the stress at peak, nominal strain at break should be higher and young's modulus lower with the recycled material, since it was expected to be more elastic. It was expected that the most notable difference observed would be with either in the 30 % recycled material that had been recycled three times because the molecule chains in the polymer would have been most broken down here.

The virgin raw material had lower stress at peak and strain at break, but higher young's modulus with test speed of 5 mm/min and test speed of 50 mm/min which supported the assumption that the material might have got slightly more elastic after the recycles.

The charpy/izod test would have been interesting to gain even more mechanical properties of the different materials, which could have been studied and compared. Since such machine was not available at the time it was therefore not used.

When obtaining the optical properties there were no surprisingly big differences even though the greenish colour was distinguished on the test pieces. However, the properties from the UV-Vis-NIR spectroscopy had some restrictions. The same spot were measured on all test pieces for transmittance value and surprisingly all had the similar results. Even though the weak greenish colour could be designated in the recycled test pieces that no notable difference was found in the colour analysis. Perhaps the results would have provided more interesting values if there was a possibility to do a sweep test in order to get a transmittance result from the whole test piece. For the transmittance test the index of refraction was not measured due to the lack of experimental equipment needed for the ASTM D 542 standard test. But as with the previous test, all the tests were done with the same approach and therefore the optical properties could be measured and compared.

The microscope provided some detail information of different shapes and possible contaminant particles that existed in the test samples. Surprisingly, at this test also, there was no significant difference in the test pieces that could separate one test from another. All test pieces had similar particles in them which could mean that it could be contaminants or dust from either the injection moulding machine, the plastic shredder or other unavoidable contamination.

# 6 CONCLUSION

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

## 6.1 What are the recycling possibilities for the Bioscreen HC product?

According to the interviews collected from the key persons in the plastic industries the recycling possibilities for the Bioscreen HC can be observed in three different perspectives, namely the economical perspective, environmental perspective and the technical perspective. On the economical perspective the most beneficial way to recycle the Bioscreen HC product would be using a recycling method so the material could be efficiently reused up to a hundred percent. The reused material would perhaps not be suited for the same product but instead used as another disposable product that does not require high demands. Environmentally speaking there is still no doubt that the material can at least be collected and sorted for further handling as reproduction or burned as energy fuel in order to decrease the material waste quantity. From a technical viewpoint the material has a good potential once it has been recycled either chemically, to obtain the styrene monomer, or mechanically through extrusion with re-pelletizing and re-granulation to maintain an equivalent and competing product quality compared with the raw material.

According to the tests one can argue that the material could be used for the same purpose since the mechanical and optical properties did not differ significantly. Even though the material was tested with the instruments in Arcada, like the injection moulding machine, which does not handle only one material but many different materials, that would expect to change the results. This did surprisingly not show up and did not affect the results in a noteworthy condition. The verdict if the material could be immediately used for the same purpose is still not up to the researcher to decide. Other test methods are still required in order to make sure that the materials would be suited for the same product. Also the reproduction of a plastic into a medical product is also a legal issue that requires further bureaucratic investigations and approaches.

## 6.2 Was the new mechanical and optical properties successfully defined when the product had been recycled?

The results from the different tests were successfully obtained and defined. However since the results were surprisingly similar to each other the conclusions should be taken with great caution. The mechanical property, in terms of stress at peak, nominal strain and young's modulus were compared between results that were found from the first test material, which was the raw polystyrene material that had not been recycled. In theory these values should be able to be compared and distinguished with each other. The percentage values have been calculated so that the differences have been calculated between the non-recycled material, material one, and the corresponding material 2 − 8. Then the average between the two materials has been calculated so the difference could be found in percent. The results of the mechanical properties with the different test speed are listed below in table 19 and 20.

The materials are listed as following:

Material 1: Non recycled PS (only raw material)
Material 2: 100 % recycled PS flakes
Material 3: 15 % recycled PS flakes and 85% raw PS (recycled one time)
Material 4: 15 % recycled PS flakes and 85% raw PS (recycled two times)
Material 5: 15 % recycled PS flakes and 85% raw PS (recycled three times)
Material 6: 30 % recycled PS flakes and 70% raw PS (recycled one time)
Material 7: 30 % recycled PS flakes and 70% raw PS (recycled two times)
Material 8: 30 % recycled PS flakes and 70% raw PS (recycled three times)

**Table 20** *Mechanical properties with test speed 5 mm/min and the difference in percent compared from the first test*

| Mechanical Property 5mm/min | Material equability in percent between material one and the corresponding material | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Stress at peak | 0,0% | 7% | 9% | 13% | 14% | 14% | 11% | 13% |
| Nominal strain at break | 0,0% | 26,64% | 24% | 30% | 35% | 45% | 30% | 39% |
| Young's Modulus | 0,0% | -11% | -11% | -14% | -18% | -22% | -15% | -14% |

**Table 21** *Mechanical properties with test speed 50 mm/min and the difference in percent compared from the first test*

| Mechanical Property 50 mm/min | Material equability in percent between material one and the corresponding material | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Stress at peak | 0% | -8,7% | 0,5% | -1,3% | -0,7% | -0,1% | -5,6% | -2,3% |
| Nominal strain at break | 0% | 2,0% | 1,6% | -2,4% | -1,6% | 0,0% | -11,2% | -2,8% |
| Young's Modulus | 0% | -8,5% | -4,9% | -3,8% | -1,7% | -3,3% | -2,8% | -5,9% |

The percentage difference distinguished much when the test speed was slower. The values could obviously be measured more accurately and the rate of the difference would be more sensitive which would probably be one of the reasons. The values from the tables can be understood so that the higher amount and times the material have been recycled, the higher the risk are that the mechanical properties varies in comparison with the raw material.

As for the optical properties the results were even harder to distinguish since the results were visually identical. In order to make an attempt to differentiate between the results all the eight corresponding results were compared with the first result value, which was also in this test the raw material. The materials are numbered from 1 – 8 and the descriptions are the same and can be seen from the previous, mechanical property test. The extreme values may seem high but when comparing the results on the colour scales in figure 9 the values does not seem to affect much or change colour in the figure.

**Table 22** *L*a*b colour analysis result difference in percent compared with the first result*

| L*a*b colour analysis Axis | Material equability in percent between material one and the corresponding material | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| L | 0% | -0,4% | 0,0% | -0,2% | -0,2% | -0,6% | 0,2% | -0,1% |
| a | 0% | -21% | 0% | 0% | -16% | 16% | 16% | 0% |
| b | 0% | 100% | 16% | 23% | 27% | 73% | -2% | 18% |

The microscopy tests speak for themselves. The possible contaminants reordered were found on all the test pieces and it was not possible to distinguish one material from another since all had the same odd-looking particles. There will always be some particles inside a material.

## 6.3 What are the benefits of polystyrene when recycling it?

According to the theoretical research, the test results and the expert interviews the main benefit from recycling polystyrene is that plastic factories can save material costs if they, through a mechanical recycling method, reuse the material by shredding down the sprue channels or scrap material with no visually error. Since the properties do not remarkably change much it should not affect the end result. However this statement is completely dependent on the values as a result of the research and tests results made by the student. The conclusion should not be followed through all considerations regarding the recycle possibilities of polystyrene.

# 7 SUGGESTIONS FOR FUTURE WORK

There was a suggestion to do a test run in the factory by using scrap material that came from the production of the Bioscreen HC product and use it for the same product. The scrap would be collected and inserted to a shredder, which would produce flakes that would be inserted in the injection moulding machine and work as the recycled material. The times the material would be shredded and amount of recycled material used could be the same as the current research have used in order to have the possibility to do a comparison between the tests collected from the laboratory and lab used in the school and the ones that would be used in the factory. The goal could either be that one would state the argument that an amount of recycled material could be used in the Bioscreen HC product in order to save material costs or investigate if there is any difference when same product have been produced by a certain amount of recycled material. Similar quality check would be made as the original Bioscreen HC product undergoes when it is produced in order to compare the results and find any possible contaminants, followed by other mechanical and optical properties tests to prove it. The challenge would be to use a shredder and an injection moulding machine that has only been used for the Bioscreen HC product so no unwanted material or contaminants would be able to harm the quality of the product. When the recycled Bioscreen HC product has been produced it would undergo the same quality routine check, as the normal product would do in order to find any possible errors or quality absences. If no such error would be found the next step would be to inform customers to test if the recycled product had any effect on the end result.

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Figure 3:

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Figure 4:

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Figure 5 and 6:

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Figure 8:

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**INTERVIEWS**

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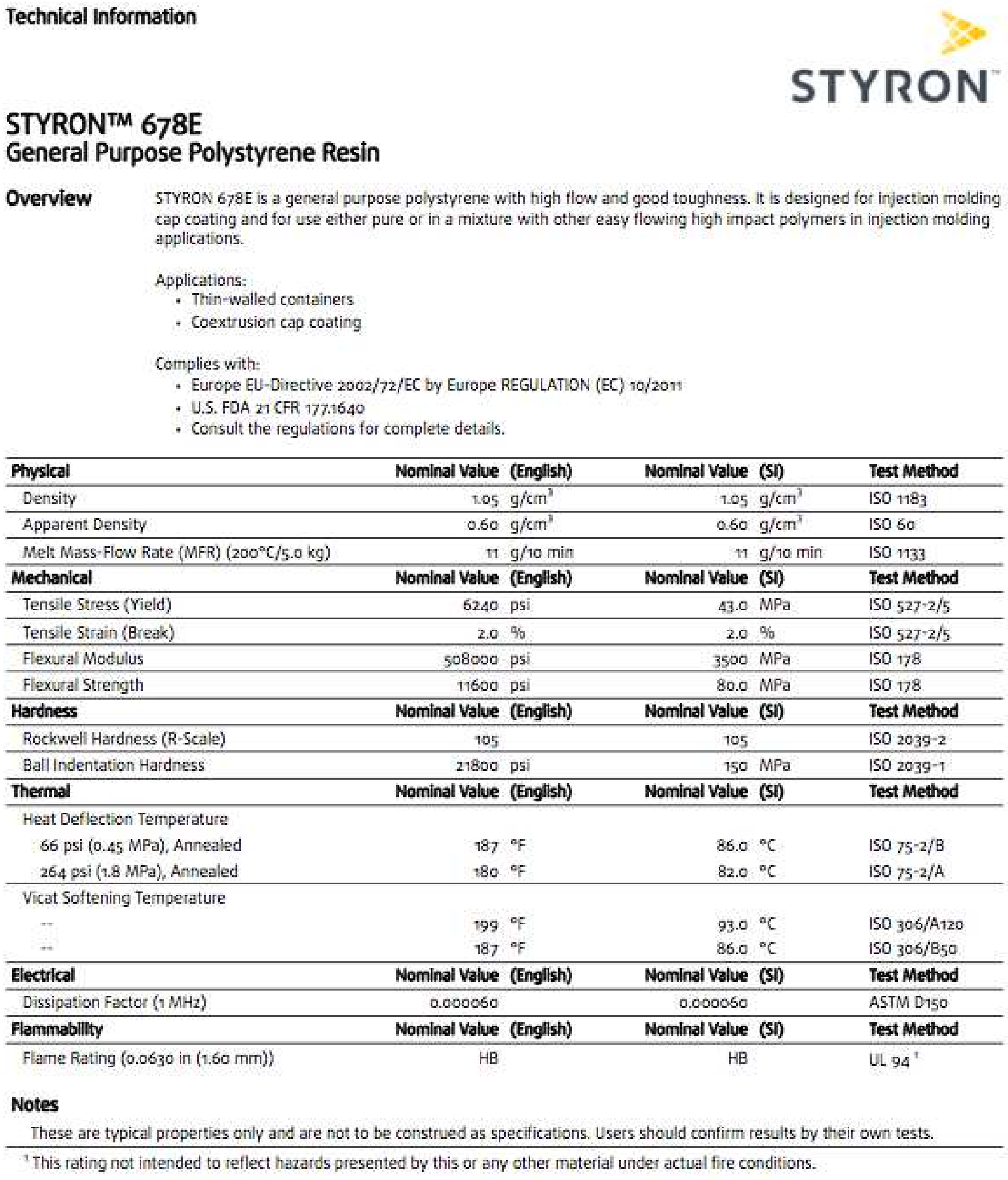
Answer to interview as person A. Asserted to be anonym. 2013. Interview of the recycle possibilities of solid PS.

Answer to interview as person B. Asserted to be anonym. 2013. Interview of the recycle possibilities of solid PS.

# APPENDIX I/I (9)



**Technical Information**

## STYRON™ 678E
## General Purpose Polystyrene Resin

**Overview** STYRON 678E is a general purpose polystyrene with high flow and good toughness. It is designed for injection molding cap coating and for use either pure or in a mixture with other easy flowing high impact polymers in injection molding applications.

Applications:
- Thin-walled containers
- Coextrusion cap coating

Complies with:
- Europe EU-Directive 2002/72/EC by Europe REGULATION (EC) 10/2011
- U.S. FDA 21 CFR 177.1640
- Consult the regulations for complete details.

| **Physical** | **Nominal Value** | **(English)** | **Nominal Value** | **(SI)** | **Test Method** |
|---|---|---|---|---|---|
| Density | 1.05 | $g/cm^3$ | 1.05 | $g/cm^3$ | ISO 1183 |
| Apparent Density | 0.60 | $g/cm^3$ | 0.60 | $g/cm^3$ | ISO 60 |
| Melt Mass-Flow Rate (MFR) (200°C/5.0 kg) | 11 | g/10 min | 11 | g/10 min | ISO 1133 |
| **Mechanical** | **Nominal Value** | **(English)** | **Nominal Value** | **(SI)** | **Test Method** |
| Tensile Stress (Yield) | 6240 | psi | 43.0 | MPa | ISO 527-2/5 |
| Tensile Strain (Break) | 2.0 | % | 2.0 | % | ISO 527-2/5 |
| Flexural Modulus | 508000 | psi | 3500 | MPa | ISO 178 |
| Flexural Strength | 11600 | psi | 80.0 | MPa | ISO 178 |
| **Hardness** | **Nominal Value** | **(English)** | **Nominal Value** | **(SI)** | **Test Method** |
| Rockwell Hardness (R-Scale) | 105 | | 105 | | ISO 2039-2 |
| Ball Indentation Hardness | 21800 | psi | 150 | MPa | ISO 2039-1 |
| **Thermal** | **Nominal Value** | **(English)** | **Nominal Value** | **(SI)** | **Test Method** |
| Heat Deflection Temperature | | | | | |
| 66 psi (0.45 MPa), Annealed | 187 | °F | 86.0 | °C | ISO 75-2/B |
| 264 psi (1.8 MPa), Annealed | 180 | °F | 82.0 | °C | ISO 75-2/A |
| Vicat Softening Temperature | | | | | |
| -- | 199 | °F | 93.0 | °C | ISO 306/A120 |
| -- | 187 | °F | 86.0 | °C | ISO 306/B50 |
| **Electrical** | **Nominal Value** | **(English)** | **Nominal Value** | **(SI)** | **Test Method** |
| Dissipation Factor (1 MHz) | 0.000060 | | 0.000060 | | ASTM D150 |
| **Flammability** | **Nominal Value** | **(English)** | **Nominal Value** | **(SI)** | **Test Method** |
| Flame Rating (0.0630 in (1.60 mm)) | HB | | HB | | UL 94 [1] |

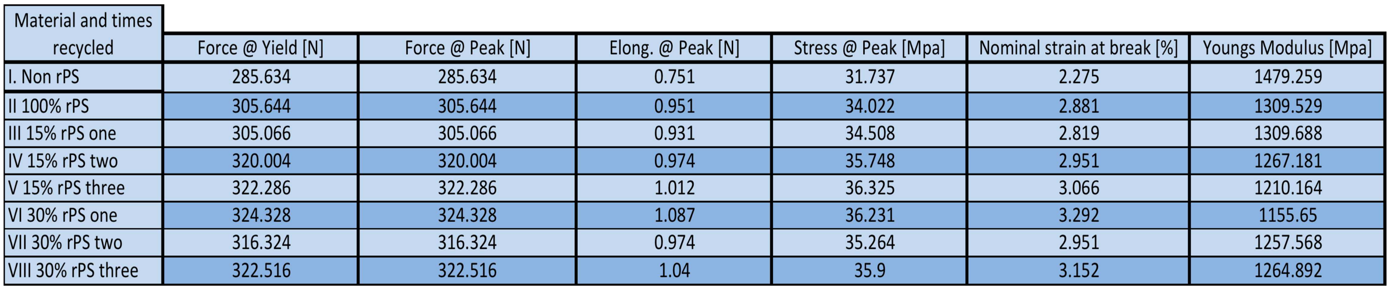
**Notes**

These are typical properties only and are not to be construed as specifications. Users should confirm results by their own tests.

[1] This rating not intended to reflect hazards presented by this or any other material under actual fire conditions.

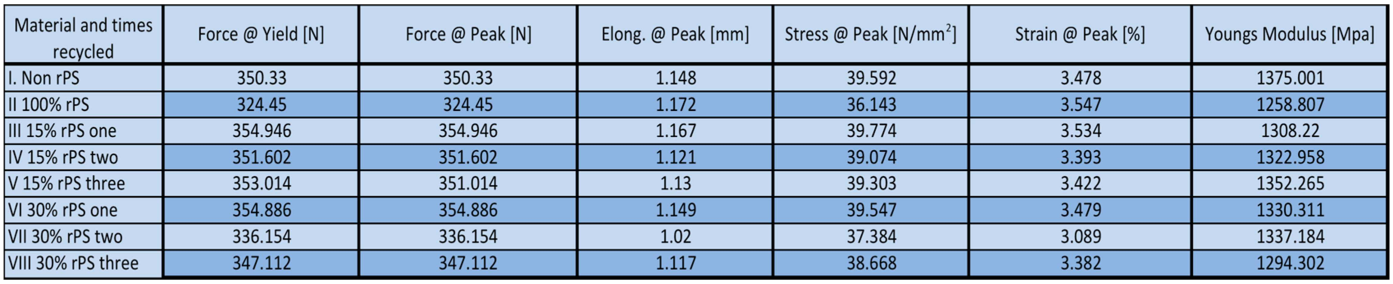
**Figure 46** *Technical data sheet of GPPS STYRON 678E (Styron 2012)*

# APPENDIX II/II (9)



| Material and times recycled | Force @ Yield [N] | Force @ Peak [N] | Elong. @ Peak [N] | Stress @ Peak [Mpa] | Nominal strain at break [%] | Youngs Modulus [Mpa] |
|---|---|---|---|---|---|---|
| I. Non rPS | 285.634 | 285.634 | 0.751 | 31.737 | 2.275 | 1479.259 |
| II 100% rPS | 305.644 | 305.644 | 0.951 | 34.022 | 2.881 | 1309.529 |
| III 15% rPS one | 305.066 | 305.066 | 0.931 | 34.508 | 2.819 | 1309.688 |
| IV 15% rPS two | 320.004 | 320.004 | 0.974 | 35.748 | 2.951 | 1267.181 |
| V 15% rPS three | 322.286 | 322.286 | 1.012 | 36.325 | 3.066 | 1210.164 |
| VI 30% rPS one | 324.328 | 324.328 | 1.087 | 36.231 | 3.292 | 1155.65 |
| VII 30% rPS two | 316.324 | 316.324 | 0.974 | 35.264 | 2.951 | 1257.568 |
| VIII 30% rPS three | 322.516 | 322.516 | 1.04 | 35.9 | 3.152 | 1264.892 |

**Figure 47** *All tests from tensile test from 5 mm/min in graph*



| Material and times recycled | Force @ Yield [N] | Force @ Peak [N] | Elong. @ Peak [mm] | Stress @ Peak [N/mm$^2$] | Strain @ Peak [%] | Youngs Modulus [Mpa] |
|---|---|---|---|---|---|---|
| I. Non rPS | 350.33 | 350.33 | 1.148 | 39.592 | 3.478 | 1375.001 |
| II 100% rPS | 324.45 | 324.45 | 1.172 | 36.143 | 3.547 | 1258.807 |
| III 15% rPS one | 354.946 | 354.946 | 1.167 | 39.774 | 3.534 | 1308.22 |
| IV 15% rPS two | 351.602 | 351.602 | 1.121 | 39.074 | 3.393 | 1322.958 |
| V 15% rPS three | 353.014 | 351.014 | 1.13 | 39.303 | 3.422 | 1352.265 |
| VI 30% rPS one | 354.886 | 354.886 | 1.149 | 39.547 | 3.479 | 1330.311 |
| VII 30% rPS two | 336.154 | 336.154 | 1.02 | 37.384 | 3.089 | 1337.184 |
| VIII 30% rPS three | 347.112 | 347.112 | 1.117 | 38.668 | 3.382 | 1294.302 |

**Figure 48** *All tests from tensile test from 50 mm/min in graph*

# APPENDIX III/III (9)

**Start-up**

Heat barrel and mold sufficiently before starting screw.

Heat system from outlet to inlet.

Open hopper slide gate slowly or fill hopper slowly to avoid bridging.

Allow proper drying/preheating temperature and time for material supply.

Purge old material from barrel.

Run a few manual cycles before engaging automatic controls.

Start mold cooling system.

Ensure proper barrel/sprue bushing seal and alignment.

Inspect electrical wires and connectors.

Inspect water and hydraulic hoses, connections.

Perform necessary mold release application.

Inspect mold for damage.

Ensure proper mold clamping pressure, sealing.

**Steady-state**

Maintain recommended lubrication/release of mold and moving parts.

Adjust temperature as needed.

Keep hopper full, or ensure an unblocked supply hose for the pellets.

**Shutdown**

Retract injection unit.

Close slide gate on hopper or run hopper empty of pellets.

Purge barrel of molten material.

Run barrel and mold cooling until fully cooled.

**Safety**

Always set safety interlock before reaching into mold area.

Be cautious of hot resin ejected during purge or flowchecks.

Do not look into nozzle opening.

(Strong 2006: 861, 862)

## APPENDIX IV/IV (9)

By knowing the principals of inverse calculation the procedure should follow the same pattern as the equation below.

$$a \times b = 1$$

$$a = \frac{1}{b}$$

$$b = \frac{1}{a}$$

Below follows a calculation proving that Transmission is the inverse of Absorption that is used in the Transmission section by formula [5].

$$T = \frac{Io}{I} = 10^{-\varepsilon lc}$$

Both sides are inverted using $a^{-n} = \frac{1}{a^n}$

$$\frac{1}{T} = \frac{1}{10^{-\varepsilon lc}}$$

$$(T)^{-1} = (10^{-\varepsilon lc})^{-1}$$

Multiplying buy using $(a^m)^n = a^{m \cdot n}$

$$\frac{1}{T} = 10^{\varepsilon lc}$$

Both side are added with the logarithmic equation

$$log\left(\frac{1}{T}\right) = log10^{-\varepsilon lc}$$

”log10$^{-\varepsilon lc}$ ” is the same as εlc which gives the formula for absorption

$$A = log\left(\frac{1}{T}\right) = \varepsilon lc$$

# APPENDIX V/V (9)

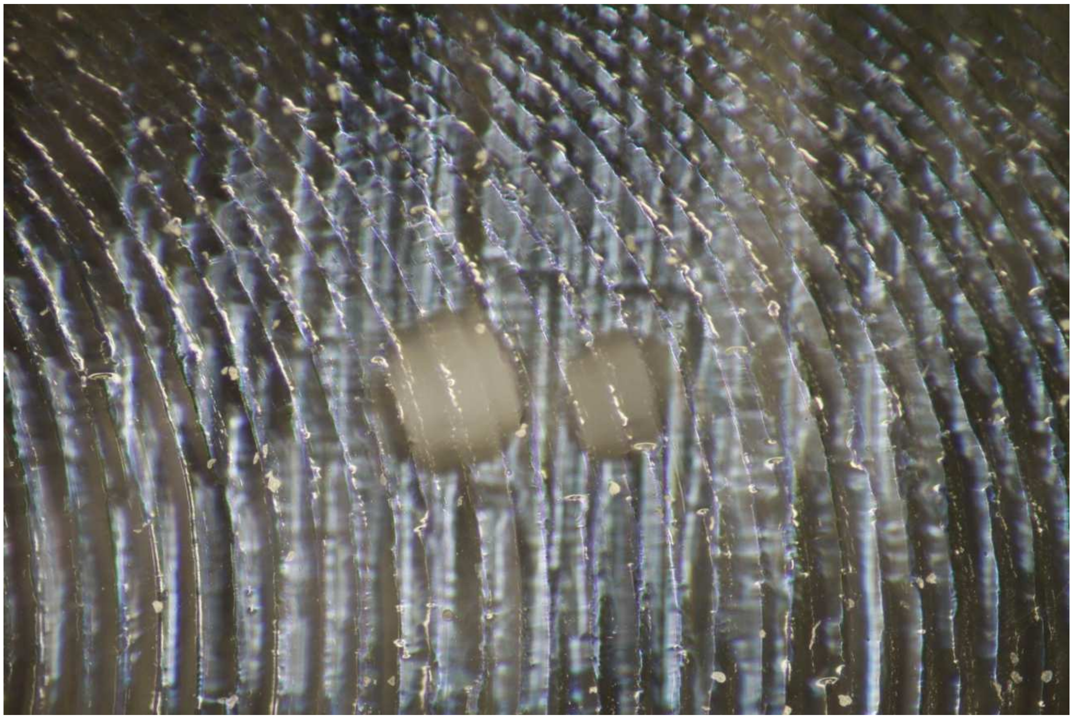


**Figure 49** *Image recording with 5x magnification (Jonas Eklöf)*

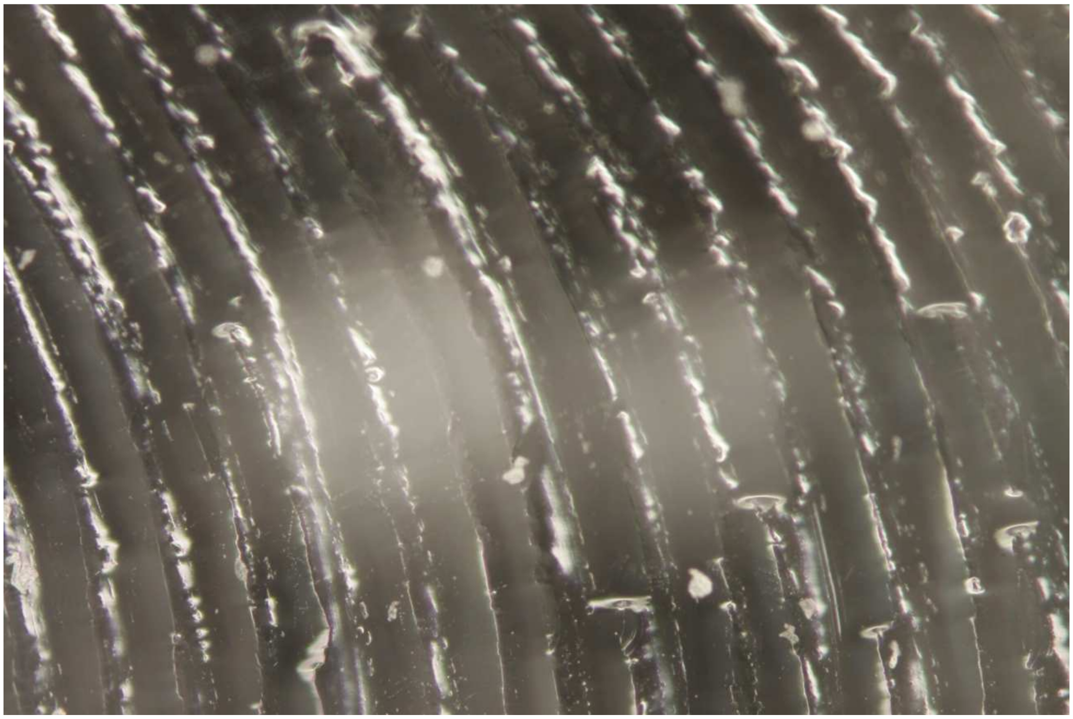


**Figure 50** *Same images as figure 49 but with other transmission parameters (Jonas Eklöf)*

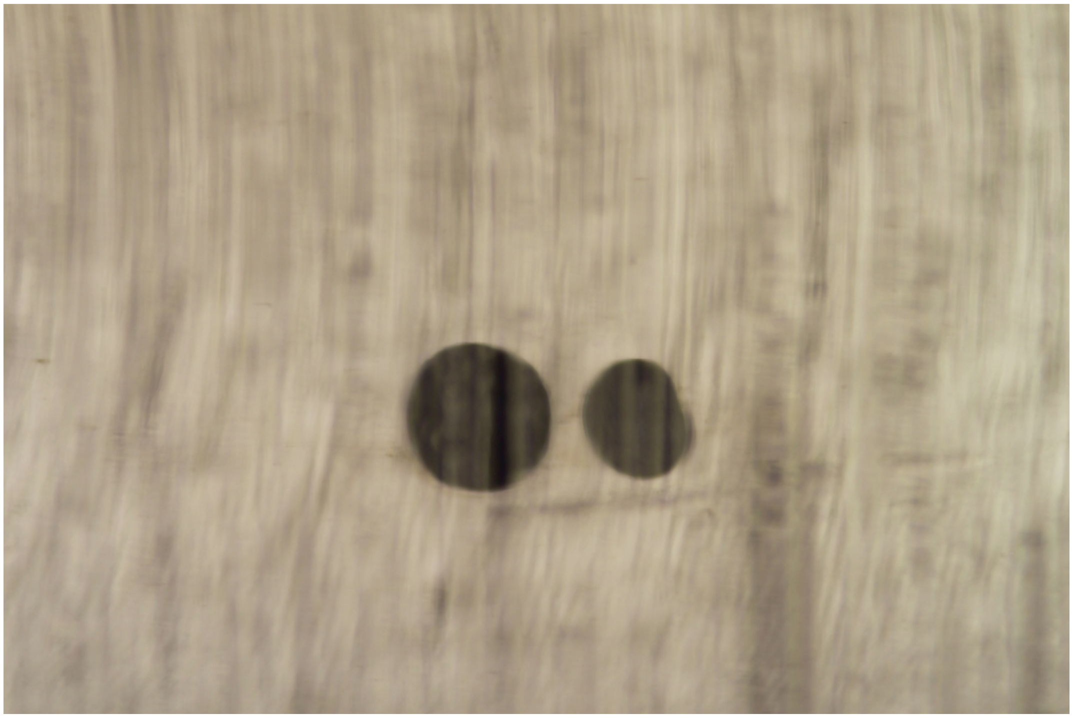


**Figure 51** *Image 49 but with 10x magnification and more transmission intensity (Jonas Eklöf)*

**Figure 52** *Microscope image recording with 10x intensity (Jonas Eklöf)*

**Figure 53** *Microscope image recording with 10x transmission intensity (Jonas Eklöf)*

**Figure 54** *Microscope image recording with 10x and high transmission intensity (Jonas Eklöf)*

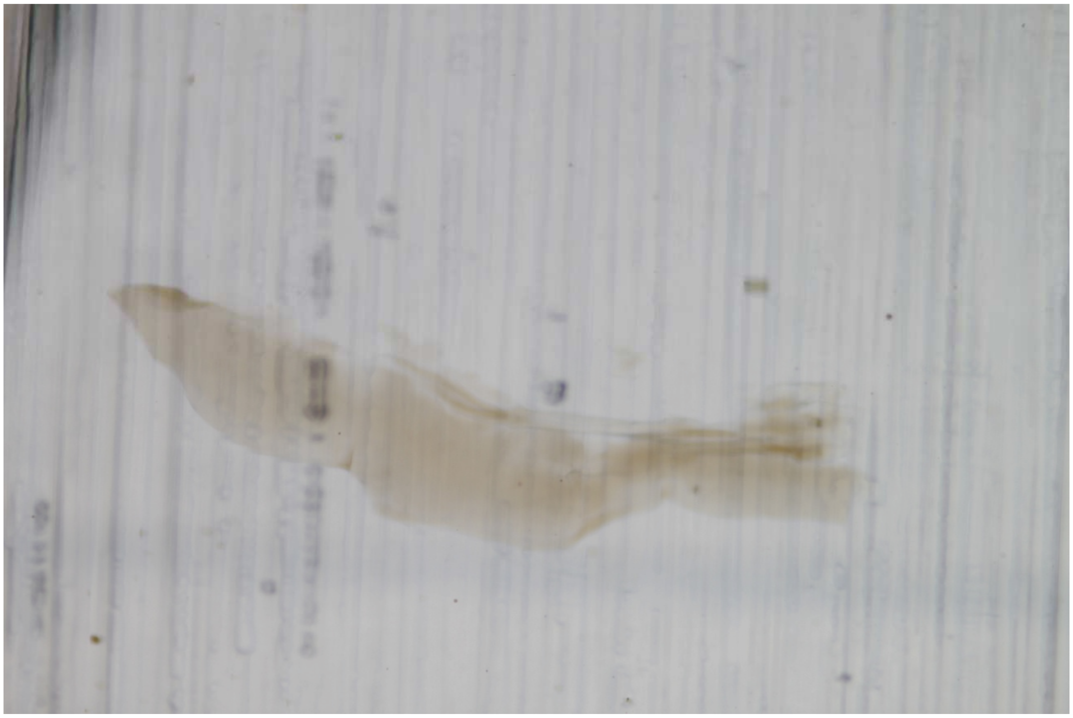


**Figure 55** *Microscope image recording with 10x intensity (Jonas Eklöf)*

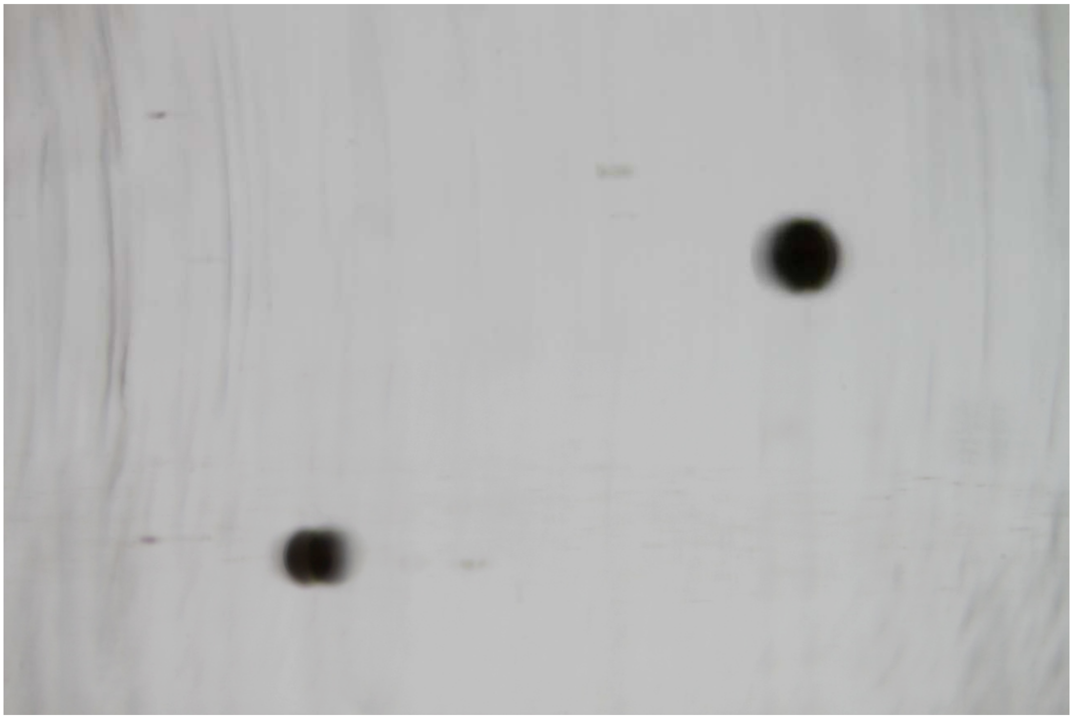


**Figure 56** *Microscopy image recording with 10x magnification (Jonas Eklöf)*

**Figure 57** *Microscope image recording with 10x magnification (Jonas Eklöf)*