Index

Co-funded by the Erasmus+ Programme of the European Union

1. Introduction to polymer materials and polymer processing

In this lesson the differences between polymeric materials regarding their capacity to get recycled will be analysed.

1.1 Types of polymeric materials

Understanding of the nature and behavior of polymeric materials is necessary in order to recycle a plastic.
Depending on their molecular structure and processing routes, polymeric materials can be classified into three main categories: thermoplastics, thermosets and elastomers.
Elastomers will not be dealt with in this course, as their applications in packaging and consumer goods are rare.
Let’s have a closer look at thermoplastics and thermosets.

1.2 Thermoplastics

Thermoplastics can be defined as materials whose structure softens and hardens in a reversible way on heating and cooling. Because of this, thermoplastic materials can be melted and reprocessed in order to recycle them.
In theory, these changes are reversible and do not entail a modification in the chemical structure of the polymer. So, in an ideal situation, thermoplastic materials could be recycled many-fold.
In practice, some thermal and oxidative degradation occurs during the recycling process and a change in the properties of the final material may be expected.
When thermoplastics are melted, polymer molecules do not chemically bond with each other. Thermoplastic chains are held together by weak chemical attractions (i.e. van del Waals forces) or by entanglement of the molecule chains.
Thermoplastics, e.g. polyolefins, polyamides, and polyesters, are used to make many consumer goods such as bottles, pouches and films. The list below displays some common thermoplastic materials and selected applications.

Thermoplastic polymer	**Applications**
High density polyethylene (HDPE)	Packaging, tanks, bottles, crates, films
Low density polyethylene (LDPE)	Packaging, grocery bags, toys, lids
Linear low density polyethylene (LLDPE)	Packaging
Polypropylene (PP)	Caps, pots, bottles, films, yoghurt pots, suitcases, tubes, buckets, rugs, battery casings, ropes
Polystyrene (PS)	Yoghurt pots, foamed trays, transparent caps

Polyamide (PA)	Vacuum bags, fishing lines, skate wheels, clothing
Polyethylene terephthalate (PET)	Bottles, pots
Polyvinyl chloride (PVC)	Food packaging, flooring, pipes

Thermosets are usually melt processed in a similar way than thermoplastics but they become irreversibly hard on heating or by addition of special chemicals. This hardening involves a curing process that involves the generation of chemical bonds between linear polymeric molecules to form a single cross-linked macromolecule. The following figure illustrates the molecular structure differences between thermoplastic and thermoset materials.

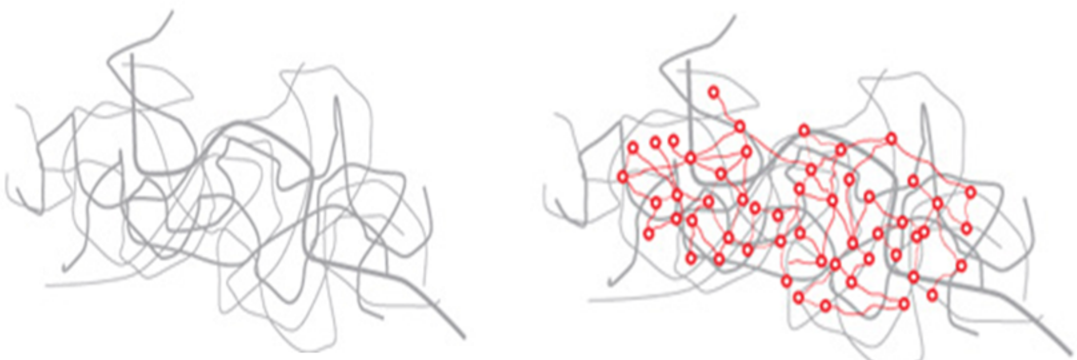


Figure. Arrangements of thermoplastic (left) and thermoset (right) molecular chains.

Once formed, thermoset plastics cannot be reprocessed and important structural changes occur before they can melt again. Hence, scrap thermoset materials cannot be recycled as thermoplastic scraps.
Thermosets are used where strength and durability are required. Some examples of common thermoset materials and their applications are displayed in the following list.

Thermoset Polymer	Application
Epoxy	Adhesives, insulators, technical pavements
Melamine-formaldehyde resin	Heat resistant laminates, hard surfaces
Phenolic	Heat resistant handles kitchenware

Polyurethane (PU)	Rigid or flexible foams for upholstery and insulation
Unsaturated polyesters	Building partitions, toaster sides

1.3 Thermoplastics vs. Thermosets

So, having in mind their properties, how do thermoplastic and thermoset polymers compare?

Thermoplastic polymers exhibit the following properties:

- Weak molecules, straight-chain bonds between them that can be broken by heating.
- They are polymerized by the material supplier in a first step.
- They are elastic and flexible.
- They dissolve in organic solvents.
- When heating, they soften and eventually melt.
- Their melting point is lower than their degradation point.
- They are in the form of solid pellets of already polymerized material before processing.
- In solid state, they exhibit a relatively soft structure made of hard crystalline regions together with elastic amorphous regions.

Thermoset polymers exhibit the following properties:

- They have strong chemical bonds, including cross-linkages.
- They do not separate on heating.
- They undergo a two-stage polymerization during processing.
- They are hard and brittle.
- They do not dissolve in organic solvents.
- When heating, they char, not melt.
- Their degradation point is lower than their melting point.
- They are in liquid state before processing.
- In solid state, their structure consists of a resin interspersed with reinforcing fibre.

1.4 Short questions:

- Thermoplastic materials, which are normally present in many packaging solutions, are usually more flexible, easy to process and recyclable than thermoset materials. Is it true? (**Y**/N)
- Classify the following materials considering their nature (thermoplastic or thermoset). 1) High-density polyethylene; 2) Polyethylene terephthalate; 3) Nylon 66; 4) Epoxy adhesive; 5) Expanded polyurethane (**1) thermoplastic – polyolefin; 2) thermoplastic – polyester; 3) thermoplastic – polyamide; 4) thermoset – resin; 5) thermoset - foam**).

2. Processing of recycled plastics.

In this lesson you will learn the main aspects to consider when reprocessing plastic materials.

2.1 Selection of processing techniques

When selecting processing techniques for recycled materials, it is important to distinguish the type of waste we wish to process.

A homogeneous waste stream can be reprocessed on the same machinery that virgin materials are processed on.

A heterogeneous mixed plastic waste stream may also be processed, in some cases, on these machines, but a number of specific reprocessing techniques may be applicable. A brief introduction to each of these processes will be provided in this lesson, along with examples of their use.

2.2 Extrusion

Extrusion is a continuous process for the production of components such as pipes or sheets. Please revise module 2 lessons for a detailed description of extrusion as plastics processing technique.

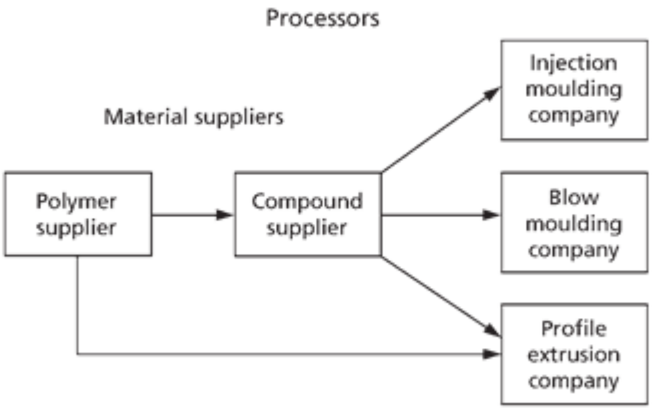
Extruders can be of two types, single-screw or twin-screw machines. These two types of equipment perform slightly different tasks although the basic principles apply to both. We will begin with a discussion on extrusion compounding as this is of particular importance in the field of mechanical recycling.

The term compounding encompasses a variety of steps between the synthesis of the polymer and its final formation in a process machine. This could include feeding or conveying the material into a machine, metering the correct quantity and mixing the polymer with other materials such as additives. Finally, this would include pelletising the final plastic material, for example, for use as feedstock for injection moulding or blow moulding machines. The compounding route is outlined in the following figure.

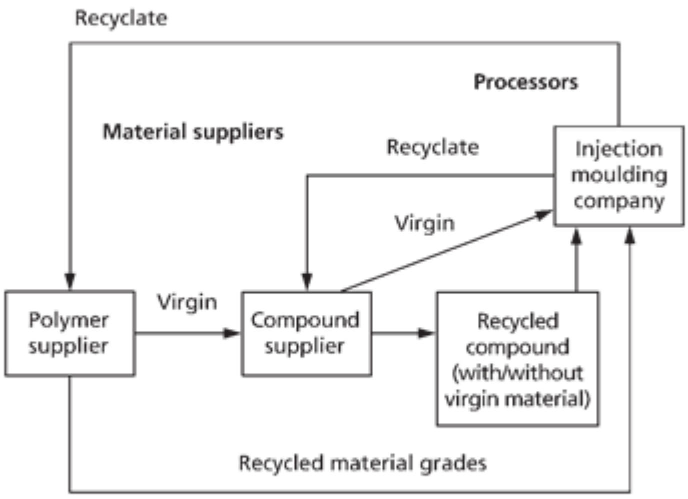
Generally, **metering and feeding** involves the use of mechanical conveyors such as fed screws, conveyor belts or vibrating shutes. Larger operations may employ pressure or vacuum operated silos to deliver material to the extruder or mixing stations. Accurate metering is required in many cases and gravimetric or volumetric type feeders can achieve this. Of these, gravimetric systems have a higher accuracy but a higher price. Once the required compound ingredients are metered, they need to be mixed.

The aim of **mixing** is to disperse the ingredients to produce a homogeneous mixture. This can be done at room temperature by simply tumble blending to produce a dry blend. Alternatively,

the ingredients can be hot mixed. Generally hot mixers are situated directly above the extruder so that the melted mixture can be poured directly into the extruder.
Plastication is necessary in order to mix and melt the material to produce a mixture that is both homogeneous and formable. This work is done by the extruder screw.
The **cutting** device used will depend on the product. Pipes, sheets and profiles need to be cut into specific lengths using a saw. Rotary pelletisers, also known as strand cutters, are used to produce pellets.
The plastic material suppliers often carry out compounding. They will receive a quantity of virgin base polymer, such as polypropylene, from a polymer manufacturer and create a number of different formulations and grades for sales to their customers, who will require materials that can meet the specific needs of their end use applications. For example, simply by adding pigments, they can create a range of colours. In some cases, this process might be continuous: instead of pelletising, the result may be an extruded product such as pipe.
When considering the thermal history of plastics, most material will already have passed through some kind of a processing cycle before it even goes to the final manufacturer to make saleable production components. Examples of possible supply chains are shown in the figure below.



When considering recycling of these materials, a similar supply chain may operate. Recyclate materials may be utilised by either the polymer supplier or the compound supplier to produce grades containing all recyclate materials, a mixture of recyclate and additives, or a mixture of recyclate and virgin material. A possible supply chain for recyclates is shown in the next figure.



2.3 Injection moulding

Injection moulding is one of the most common manufacturing processes in use today. It lends itself to high volume production of both complex and precision parts with a variety of uses. Please revise the lesson in module 2 for a detailed description of this technique.

As well as reject injection mouldings, waste is also generated through the channels used to fee d molten plastic from the injection unit into the mould. These, as well as reject mouldings, can be fed back into the machine if care is taken to avoid contamination.

Injection moulding is complex and controlled by a number of parameters. A range of materials and material viscosities can be utilised, however mixtures of plastics, if not homogeneous, can cause fluctuations in the process and make mouldings of consistent quality difficult to achieve.

If mixtures of materials with different melting points are used there can be problems, unless the temperature of the highest melting fraction is reached. Unmelted material will be visible in the mouldings, severely affecting the mechanical integrity. Likewise contaminants such as dirt, wood and other residues will also be visible in the mouldings.

Melt filters can be used to trap relatively minor contaminants that do not melt and prevent them getting into the mouldings. One way to prevent this type of visible contamination is to use co-injection moulding.

There are a number of variations of the injection moulding process, one that is particularly applicable to recyclates is **co-injection moulding**. Co-injection moulding produces a sandwich like structure that can be used to encapsulate recyclate materials, covering them in a layer of virgin skin material (see next figure).

2.4 Blow molding

Blow moulding is the third most commercially important process for plastics production after extrusion and injection moulding. It is used to produce a range of hollow articles, for example, bottles, fuel tanks and other large containers. A detailed description of blow molding techniques is provided in module 2.

Recyclates coming from other waste streams are more difficult to process through blow molding due to the problems of contamination and changes in the mechanical properties of the melted recyclates. Remember that the criteria for a blow moulding material are quite specific:

- It must be of suitable viscosity.
- It must have high melt strength.
- It must be extendable when inflating (this is often given as the inflation ratio for the material).
- It must be able to seal at the base of the moulding.

This makes blow moulding of recycled materials not impossible but tricky, as proper arrangements need to be made before the resulting material can be processed in the same way as the original one.

As well as the possible effects of contaminants on viscosity, they can also cause problems with the inflation process. During inflation the material expands at a constant rate to give a constant wall thickness across the body of the moulding. Contaminants can cause bursting, tearing or affect the ability of the parison to seal at the base. Finally, there is the colour limitation of reprocessing materials, especially mixtures of different colours. Often to get a uniform colour, a black masterbatch is added to mask the underlying colours of the recyclates. This can limit potential outlets for products. However, one solution to overcome this is to use more than one extruder to produce a multi-layer parison. This process is called **multi-layer extrusion blow moulding**.

Multi-layers provide a means of incorporating recyclates and masking the inherent colour of the recyclate itself. For example, consider a two-layer bottle structure that used blue virgin material as the outer visible layer and black recyclate as the inner layer. If you actually looked into the bottle you would see the black recyclate material, but all of the outer surface would be blue.

Possible layer configurations are shown in the attached figure. A 3-layer configuration for recyclates may be preferable to 2-layers as the inner layer primarily affects the strength of the weld line on the base of the moulding. This seam can be potentially weakened with recyclate. There is another potential problem with a 2-layer configuration: the recyclate may not be a suitable material to come into contact with the contents of the container. This could be either due to chemical compatibility problems or simply that the surface finish on the recyclate material would not be of a high enough quality for the desired product. A 3-layer configuration overcomes this issue. Blow moulding machines allow accurate control of thickness of the individual layers, so that the level of each of the layers can be optimised. Generally the inner and outer layer would take up 10-20% of the overall thickness with the rest made up of recyclate material.

Some applications may require the use of an additional barrier layer, for example, fuel tanks require a fuel impermeable barrier, and food containers such as tomato ketchup may require a barrier to prevent odours penetrating through the outer layers. The simplest barrier configuration incorporating recyclate is a 4-layer structure as illustrated in the figure. The adhesive layer is needed to bond the layers together as often the required material combinations do not stick to one another.
The incorporation of scrap into extrusion blow moulding does not usually present a problem. However, given the specific requirements of the blow moulding process in terms of viscosity, melt strength and inflation properties, materials from other waste streams are unlikely to be suitable. The blow moulding process is relatively intolerant to contaminants due to the effects on the ability to inflate the parison and the evenness of the wall thickness that is produced. If using recyclates, special attention must be paid to the seaming area, so that an adequate weld strength is produced.

2.5 Film blowing

Process waste is not generated in great quantities in film blowing machinery and material can be reprocessed providing that it stays free from contamination.

Like in blow moulding, large occlusions or contaminants in the process can cause bursting and inflation problems. Agglomeration may be necessary to aid feeding in some cases, due to the low bulk densities of shredded films.
Large amounts of film scrap are available, because of the short lifetime associated with packaging and industrial film materials such as carrier bags, dustbin liners and plastic sacks. A typical lifetime of products of this type is only two years.
100% recyclate material may be used in low-grade applications such as bin liners. Other products such as carrier bags may incorporate scrap in with the virgin material to reduce cost.
Again, like blow moulding, film blowing has specific material requirements in terms of melt strength, viscosity and inflation characteristics. Generally, film blowing is limited to polyolefin materials, the majority of usage being of LDPE, LLDPE and HDPE.

2.6 Compression moulding

Compression moulding is used to manufacture both thermoplastic and thermoset products.
All the processes up to now have used materials in granular form. Compression moulding however, often utilises raw materials in sheet form. Sections called blanks, of the correct weight, are pre-heated and then placed in the compression moulding tool. This is then closed to form the component. Because of the use of sheets rather than granules the raw material costs are much higher, as it is more expensive to manufacture sheets than granules. One common type of sheet is known as glass mat transfer (GMT); it consists of polypropylene and high levels of glass fibre.
Any recyclate can be used to make further GMT sheets. However, the glass levels and flow characteristics of the sheet may be different. As these are generally provided for the manufacturers by a supplier, recycling of GMT by the compression moulders themselves is not common.
Compression moulding of mixed plastics is possible. Pre-melting materials into a suitable weighted ‘blank’ and placing it into the mould is necessary. Moulding is then carried out in a normal way. Thick sections can be made in this way; however, their properties are usually not very good.

2.7 Thermoforming

Like compression moulding, thermoforming uses sheet rather than granules. In this process the sheets are clamped onto a frame and then heated to soften, but not melt, the plastic. A mould is then brought into contact with the sheet whilst a vacuum is applied. This draws the sheet onto the surface of the mould and forms the moulding. The moulding must be trimmed to remove the excess sheet material. This scrap can be returned to the sheet supplier to be used in the production of new sheet.

2.8 Processes for incorporating mixed plastic waste

The next three processes are suitable for mixed and more contaminated waste streams. There are commercial operations of each of these processes, variations occur depending on the type of waste being processed. Only an overview of each general process is presented here.

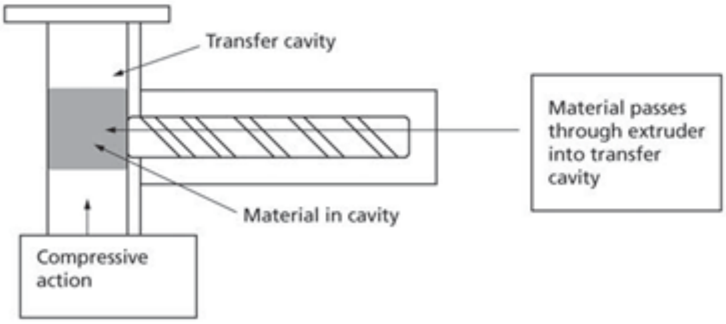
- **Intrusion moulding.**

The intrusion process is suited to mixed plastics. Generally, they are finely ground before processing to aid dispersion. The process has elements of extrusion in that a plasticating unit is used to soften the mixture, which is then fed into a mould and this is then cooled. On rotating systems a number of tools can be filled as others are cooled (usually by submerging them in water). Once the plastic has cooled it can be ejected or removed depending on the type of mould that is used. The process is tolerant to contaminants such as mixed plastics, sand, glass, wood and paper, providing a minimum polyolefin fraction of around 40% is present. Other contaminants become embedded in this low melting fraction. This process is generally used to produce large, geometrically simple shapes such as profiles and panels for wood replacement applications such as fencing, posts and scaffolding.

- **Transfer moulding.**

This process combines elements of injection moulding and compression moulding. It is similar to injection moulding in that a fixed weight of material is transferred into a mould. Transfer moulding was originally developed from compression moulding, to allow production of more complex parts incorporating holes, recesses or inserts. The result was a process whereby the mould was closed first and the moulding material then transferred by a compressive action into the cavity. A number of variations exist as this method is used for the production of thermoset parts as well as for mixed plastics. The process used for mixed plastic waste is now described.

Material is fed from a melt hopper into the heated barrel where it is homogenised and plasticated. It is then fed into a melt accumulator, which meters a fixed weight of material at low pressure into a partially open mould (as opposed to high pressure in the injection moulding process) (see the figure below). When filling is achieved, the press closes the mould and the material is compressed. When the moulding has cooled and has dimensional stability, it can be removed. The low clamping forces required by this process make equipment costs lower than conventional injection moulding. However, it does not lend itself to produce intricate parts and can best be applied to fairly simple parts similar to those produced in the compression moulding processes. One such application is pallets. This process is applicable to both mixed and unmixed plastics. The degree of other contamination that the process can tolerate, for example metal, depends on the design of the extruder and the extruder nozzle. Providing that contaminants are small enough and that sufficient plastic material is present to allow them to flow through the machine and out of the nozzle, no problems should be encountered.



- **Sinter moulding.**

The sinter moulding process can be used with a broad variety of mixed plastics. The process is tolerant to contamination from materials such as aluminium and paper, and panels made with waste wood chips have been manufactured. The formulation can also be varied to produce mouldings with a range of properties for use as panels, sound proofing or packaging materials. In this process plastic flake is plasticised in a heated mould and subjected to pressure.

The material passes through a metal detector to remove large metal fragments and is shredded and dosed into moulds. These then pass through a tower from top to bottom, where they are heated. The compressive pressure increases the further the mould travels down the tower. The lowermost moulds are cooled with ambient air, which then, after additional heating by means of a radiator, is conducted upwards in counter-flow to the moulds. This process allows the production of large area panels of up to 60 mm thickness, with natural finish or lamination in the same operation. An advantage of this process is that the raw material can include the heavy fraction from the density separation of re-granulation plants and materials do not require cleaning prior to processing.

2.9 Additives for recyclates

The two most significant problems associated with the recycling of plastic wastes from post consumer products are:

1. The degradation of the plastics as a result of both processing and service life, and
2. The difficulties associated with getting acceptable material properties when processing mixed plastics.

Stabilization additives may be employed to slow down the degradation of plastics. Other additives such as fillers or modifiers can be incorporated to improve the properties of the recyclates. These modifiers can also be of benefit in mixed plastic fractions. First the issues associated with the degradation of materials will be discussed.

Most plastic producers reprocess their waste in order to reduce their raw material costs as well as the cost of waste disposal. Very often this material is simply fed back into the system along with virgin material. This presents few problems providing attention is paid to cleanliness and the reprocessed material has not been contaminated with dirt, oil or other types of drebris.

The amount of degradation undergone by these materials will be dependent on the processing conditions that they were subjected to and the levels of stabilisers present. If these materials are to be used for a second application, it is possible to restabilise them. For this, knowledge of the type and amount of stabiliser originally used is required. Some stabilisers are consumed in the process of protecting the plastic and these materials need to be kept at optimum levels to ensure continued protection. Further testing may be required to assess the resistance to heat and light (both processing and long-term stability).

- Heat stability

A combination of heat and oxygen will cause oxidation in the polymer, resulting in degradation. The mechanism is the formation of free radicals, which are highly reactive chemical species. This reaction can be observed, as the products will tend to show a discoloration to yellow or brown. Antioxidants can be used to interrupt this mechanism. The chemicals most commonly employed are hindered phenols, which act as peroxide radical decomposers.

Other additives can also be employed in addition to hindered phenols. Phosphites combined with hindered phenols, have a synergistic effect. This combination is especially effective for polyolefins such as PE or PP.

Perhaps the most well-known example of the use of additives to prevent thermal degradation is in the thermal stabilisation of polyvinyl chloride. The free radicals produced in this case are chlorine, leading to the formation of hydrochloric acid. The stabilisers must stop these reactions which lead to acid corrosion of the processing equipment.

- Light stability

Light, especially in the ultraviolet range, can induce photooxidation causing degradation and cleavage of the polymer chains. To deter this effect, three classes of additives can be employed. These additives are usually termed UV absorbers, quenchers (scavengers) and radical traps.

2.10 Additive combinations for specific purposes

The additives used in a particular plastic will depend very much on the intended application. Outdoor applications for example, will require both light and heat stability.

Bottle crates, made from a single plastic, high-density polyethylene (HDPE), have been extensively studied. The use of 100% recyclate without further stabilisation resulted in a loss of

mechanical properties, cracking and colour fading after six months. However, when HALS and UV absorbers were incorporated, the recyclates retained their properties for more than four years.
To sum up, for successful applications care must be taken to ensure that the recyclates are adequately protected with suitable additives, depending upon their future use.

2.11 To keep away

Whilst primary mechanical recycling will continue to be common practice amongst plastics processors, secondary recycling is subject to both practical and economic limits for use. Success depends primarily upon the economics of sorting to obtain single polymer materials, and knowledge of material provenance and degradation history. Processes adapted from conventional machinery to take more highly contaminated feedstock exist, however they are limited in application to wood replacement type profiles and panels and cannot overcome the inherent limitations in the make-up of their feedstock. Even these processes also generally require feedstock to have undergone some preliminary sorting.

An overview of the processes discussed in this lesson is provided in the table below:

Comparison of processes					
Process	**Complexity of parts**	**Forming action**	**Mould**	**Plastic types**	**Tolerance to contaminants**
Extrusion	Fairly simple profiles	Extrusion	None	Single	Low
Injection moulding	Complex	Injection	Closed	Single	Low
Co-injection moulding	Complex	Injection	Closed	Single layers	Low
Compression moulding	Simple	Compression	Closed	Single	Medium
Extrusion blow moulding	Complex	Inflation	Closed	Single	Very low
Multi-layer extrusion blow moulding	Complex	Inflation	Closed	Single layers	Very low

Injection blow moulding	Simple	Inflation	Closed	Single	Very low
Film blowing	Simple	Inflation	None	Single	Very low
Intrusion moulding	Simple	Compression	Open	Mixed	High
Sinter moulding	Simple	Compression	Open	Mixed	Very high
Transfer moulding	Simple	Compression	Closed	Mixed	High

3. Effects of processing on thermoplastics

In this lesson we will learn how the properties of plastics are affected by processing.

3.1 Introduction

We know already what is the difference between thermoplastic and a thermoset materials regarding their recyclability.
In this lesson we are going to concentrate on what occurs to thermoplastic materials when they are processed. We will consider three aspects:

- Deformation properties
- Melting properties
- Structural and chemical properties.

3.2 Deformation properties

Let's start with the study of deformation properties. To focus on deformation, we need to talk about rheology.
Rheology is the study of the deformation and flow of fluid products.
Plastics exhibit a viscoelastic response to stress. In other words, plastics are polymers that combine both viscous and elastic properties. What does this exactly mean?
Viscous properties refer to the way a material continues to deform as long as stress is applied.
Elastic properties refer to the capacity of a material of recovering its original shape after a stress is removed.
Polymers are more viscous than most liquids, meaning that their resistance to flow when a stress is applied is higher than that of most liquids. In addition, polymers are more elastic than most solid products, meaning that they tend to get back to their original shape when a stress ceases.

The interaction between viscosity and elasticity frequently determines the fate of any processing operation. Processing must take into account not only how the polymers flow in their molten state but also how rheological properties will change as polymers melt and solidify when temperature increases or decreases.

As a polymer degrades, its viscosity decreases. Charting the changes that occur during repeated recycling of material can give a measure of the degradation processes occurring.

3.3 Deformation properties: an example

Let's exemplify what happens with two common materials are low density polyethylene (LDPE) and nylon (PA).

As a semi-crystalline material, LDPE turns form a solid to a highly viscous fluid and then to a mobile fluid as it is heated.

As an amorphous material, PA turns quite suddenly form a solid to a highly fluid substance.

This means that these polymers react differently to the heat and stress applied to them. So methods and conditions to process them will necessarily be different.

An easy method for comparing the flow of melted plastics under previously defined conditions is by determining it with a Melt Flow Indexer. This device works in a similar way to squeezing toothpaste from a tube. A vertical load is applied to a piston and the polymer melt is squeezed through a die. The amount of polymer that is extruded in a fixed time provides the melt flow index (MFI). Highly viscous materials have low MFIs, whereas very fluid materials exhibit high MFIs.

3.4 Melting properties

Thermoplastics need to be heated above their melting point in order to flow.

As you can see, melting temperature can greatly change from one material to another. Even within a same material, different structures can lead to significant changes in the melting point. Once a polymer is heated above its melting point, viscosity decreases sharply. The rate of change also depends on the particular type of material. Eventually, a point is reached where the materials becomes thermally unstable and starts to degrade. This is a problem when processing blended plastics, because fractions composing the mixture will melt and will start to degrade at different temperatures.

So having a homogeneous mixture is of capital importance in plastic recycling.

Co-funded by the Erasmus+ Programme of the European Union

3.5 Melting properties: an example

To keep it simple at this stage, think of a mixture of more than one plastic as a heterogeneous mixture and a mixture of the same plastic as a homogeneous plastic.

Here you are some of the melting points of common plastic materials.

- Polyethylene (PE): 135 ºC
- Polypropylene (PP): 170 ºC
- Polystyrene (PS): 240 ºC
- Polyethylene terephthalate (PET): 245 ºC
- Polyamide 6 (PA6): 233 ºC

Consider a waste fraction that contains 90% PE and 10% PA6.

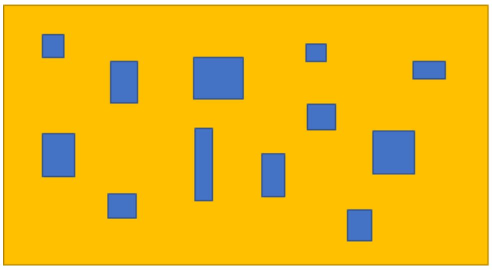
If we process the waste at a temperature suitable for the PE fraction (135 ºC), the PA6 fraction will not melt (233 ºC) and will be carried along in the melt stream. The final product would be a heterogenous blend containing pellets of unmelted material. The unmelted pellets would be points of mechanical weakness in the moulding, as if they were just filling holes with no purpose.

Only if the unmelted regions are very small would they not be detrimental to the material properties.

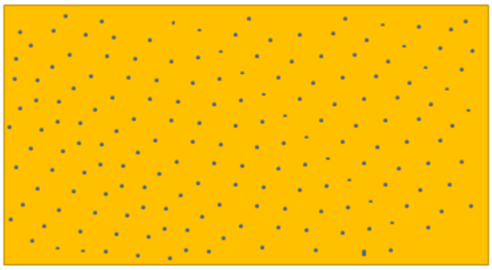
Now consider the same mixture of PA6 and PE again. What would happen if the mixture is processed just above 233 ºC? In this case, the temperature is much higher than PE would generally be processed at, and it may begin to thermally degrade, which is likely to cause a considerable loss in the mechanical properties of the plastic.

Thus, in processing mixed plastics, trials are often required to select the best inlet materials and optimal conditions for processing. But as you can figure out, this gets extremely difficult when processing plastic wastes, as the properties of the input materials is very much difficult to control.

Moulding containing rough pieces of unmelted polymer (bad mechanical properties)



Moulding containing a finely dispersed unmelted polymer (improved mechanical properties)



3.6 Structural and chemical changes

As well as the effects of heat on the polymer, the effects of shear stress forces also need to be considered.
Shear causes mechanical damage and breaks polymer chains. So very high shear forces lead to degradation of the material.
With this is mind, good thermal stability is a requirement for most polymer processing operations, as the combined action of heat and shear can produce degradation.
So, in concomitance with heat, shear will reduce the length of polymer chains. This will affect:

- Molecular weight and viscosity.
- Mechanical properties (e.g. tension and impact resistance)
- Colour

Consideration must be given to the residence time of the material in the processing machine. A typical residence time may be 3-5 minutes. Longer residence times may cause thermal deterioration. Also, within a closed loop cycle, scrap material may be reground and reprocessed many times.

Shear stress is not just applicable to molten polymers. It is also relevant during the steps of grinding and cutting scrap materials while they are in solid state.

The way this affects the material properties will depend on the specific material response each time it undergoes degradation processes and how the regrind is blended for example, with new material. Mechanical shear is the primary mechanism for deterioration in mechanical properties, such as tensile strength. Mechanical grinding in order to reduce the size of solid plastics is the second most important factor. Since the actions of mixing, processing and size reduction have a shearing effect upon the polymer material, the level of damage to the plastic needs to be assessed.

3.7 END OF LESSON ACTIVITY

In the following link you will find an interesting essay on mechanical recycling of plastics for you to keep.

https://onlinelibrary.wiley.com/doi/full/10.1002/marc.202000415

You do not need to read it all, if you do not want to. Concentrate on section 3 (Mechanical recycling of polyethylene terephthalate). Keep the paper, as we will discuss about some of the information that is presented in the online session.
The section reports on the degradation that PET suffers from certain degradation phenomena. Search for information and answer briefly and in your own words the following questions:
a) What is crosslinking and what are the consequences of crosslinking on the properties of PET materials?

a) How do tensile strength and impact resistance of PET change as the number of recyclates increases?

4. Need of sorting plastics

In this lesson you will learn why it is so important to address an effective classification of plastics.

4.1 Why is sorting so critical?

As we have already seen, as thermosets do not re-melt, they cannot be reprocessed in the same way as thermoplastics. Therefore, thermoplastics and thermosets need to be separated prior to recycling.

But do thermoplastic materials need to be separated from each other? Can we just mix all the plastics together and reprocess them?

Regretfully, the answer to the previous questions is no.

If that was feasible, plastics recycling would certainly be much easier. Although mixing and reprocessing may be possible in some specific cases, it is not usually the case.

4.2 An insight on the miscibility of plastics

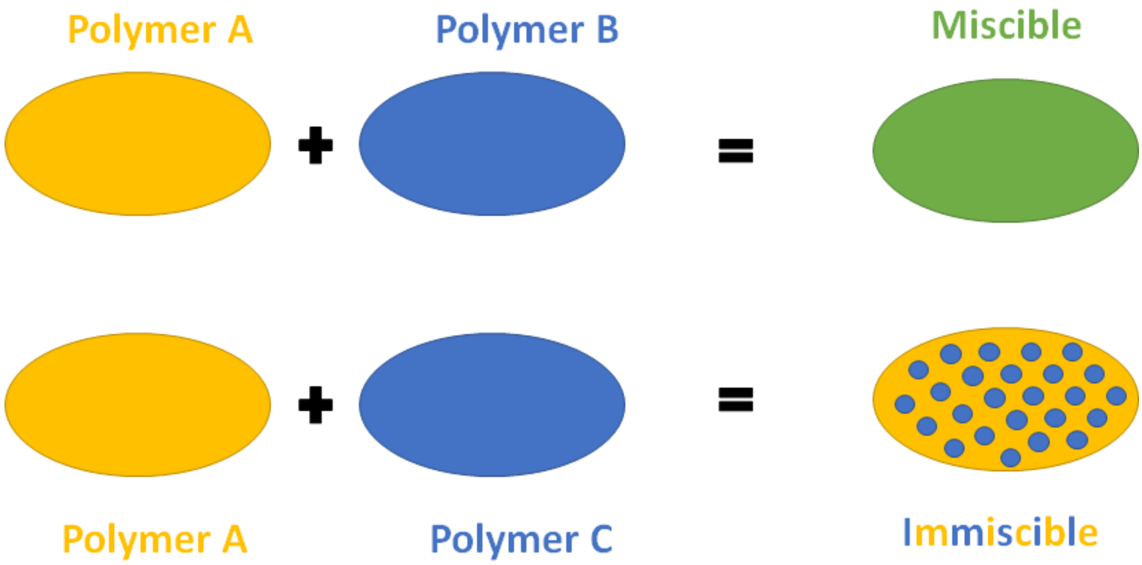
Different plastic materials are not likely to be compatible due to differences in their chemical composition, structure and amounts of other added compounds.

If two immiscible polymers are put together, a phenomenon called phase separation occurs.

As a result, the blended material will contain differentiated regions of each polymer, which would be visible under a microscope or even to the naked eye. In addition, no chemical bonds will exist between these materials, which will definitely have an impact on its mechanical, barrier and optical properties.

A way to imagine this is presented in the next figure. For blends of immiscible polymers, one polymer is dispersed in the other polymer. The strength of these systems depends on how well a polymer is dispersed in the other. Some additives can be used to assist one material to become finely dispersed in the other, hence making them more compatible.

Differences between miscible and immiscible polymer blends. Immiscible blends present one polymer dispersed into another



4.3 An example of blended polymer

There are some commercial examples of this kind of blended materials.

High impact polystyrene, a blend of polystyrene and polybutadiene, is one of them. CD cases are made of high impact polystyrene.

Whilst polystyrene on its own is very brittle, polybutadiene, a rubbery material, is an excellent energy absorber and exhibits high flexibility. When these two materials are blended, the result is a plastic material with improved toughness.

4.4 Compatibility of plastics

The next table provides some examples of how well polymers of different types mix. As you can see, it is very rare to find high compatibility between materials. In general, the better two materials can be dispersed, the better the properties of the final blend will be.

Basic material	Important synthetic design materials	Additive											
		PE	PVC	PS	PC	PP	PA	POM	SAN	ABS	PBT	PET	PMMA
	PE	●	○	○	○	●	○	○	○	○	○	○	○
	PVC	○	●	○	○	○	○	○	●	◉	○	○	●
	PS	○	○	●	○	○	○	○	○	○	○	○	○
	PC	○	⊙	○	●	○	○	○	●	●	●	●	●
	PP	⊙	○	○	○	●	○	○	○	○	○	○	○
	PA	○	○	⊙	○	○	●	○	○	○	⊙	⊙	○
	POM	○	○	○	○	○	○	●	○	○	⊙	○	○
	SAN	○	○	○	●	○	○	○	●	○	○	○	●
	ABS	○	◉	○	●	○	○	⊙	○	●	⊙	⊙	●
	PBT	○	○	○	●	○	⊙	○	○	⊙	●	○	○
	PET	○	○	⊙	●	○	⊙	○	○	⊙	○	●	○
	PMMA	○	●	⊙	●	○	○	⊙	●	●	○	○	●

● Compatible
◉ Limited compatibility
⊙ Compatible in small quantities
○ Not compatible

Figure: Compatibility of plastic materials (adapted from Kovacs, Becker and Cesconetto, 2009).

Co-funded by the
Erasmus+ Programme
of the European Union

But regardless materials are miscible or not, in order to reprocess recycled materials and keep their desirable properties in the reprocessed product, it is much more effective to sort materials rather than blending them.

A recyclate of high purity will also command a higher commercial price, as the quality will be for sure higher. However, a cost effective sorting of the plastic materials is required, as the sorting cost will offset the marketability of the material. Because of this, methods to sort plastics need to be as simple and economically viable as possible.

4.5 To conclude

Remember that reprocessing will always lead, to a higher or lesser extent, to degradation of the material as a result of heat and mechanical shear stress.

Problems associated with the processing of recycled plastic blends are noteworthy provided that:

Plastics have different melting and glass transition properties.

Immiscibility of plastics jeopardizes their structure and leads to a significant decrease in their mechanical performance.

So when we aim at recycling materials by mechanical means, sorting is required. Chemical recycling may be an eligible process when sorting can be applied by no means.

4.6 END OF LESSON ACTIVITY:

In the following link you will find a short paper with interesting information regarding the compatibility of plastics:

https://pmd.igdp.org.br/article/586fc520f7636eea018b45f4/pdf/pmd-7-2-141.pdf

Go through it and state whether the compatibility of the following materials is achievable or not.

A) Poly methyl metacrilate (PMMA) and Polycarbonate (PC)
B) Polyethylene terephtalate (PET) and High density polyethylene (HDPE)
C) Polyvinil chloride (PVC) and Polystyrene (PS)

5. Reprocessing of thermoplastic recyclates

In this lesson you will learn what it takes and what needs to be controlled when reprocessing thermoplastics.

5.1 Introduction.

As we have seen already, it is feasible to recycle and reprocess thermoplastics when they are properly sorted.

In this lesson we are going to address what it needs to be controlled before, during and after the reprocessing of thermoplastic recyclates.
Once the waste materials arrive to the recycling factory, they will probably need to be reduced in size, cleaned, separated and, most likely, recompounded and regranulated before they can be reprocessed. Although the different systems will be further discussed further on within this module, a brief look at the different steps of the process is presented in this lesson.

5.2 Quality control of the input materials.

The waste materials may be received in different forms, such as bales, mouldings or large lumps. Needless to say that, for producing high quality recyclates, high quality waste products are required.
Often little is known about the history of the material to be recycled, including:

- How many times has it been reprocessed previously?
- How much thermal or mechanical stress has it undergone already (e.g. due to processing or exposure to outdoor conditions)?
- What was it used for previously?
- Is it a single material or a combination of plastics?
- Which amount of contaminants does it contain?

5.3 Purity of the inlet materials

Purity of the inlet materials is a matter of utmost importance.
Closed loop environments are more likely to get high benefits from recycling.
A common practice in the plastics industry is to reprocess in-house waste materials generated during the normal production. This primary recycling allows to reduce both production waste and utilization of raw materials. For instance, the start-up waste and rejected parts generated

during injection moulding or termoforming, can be reground and fed directly back into the production machine. Within a closed loop cycle, recycling is easy because knowledge on the waste flows is high and materials are trustworthy.

One example of a closed loop cycle in action is seen in the automotive industry. Since 1991 Volkswagen have recycle scrap bumpers mated of a modified grade of polypropylene. The scrap material is mixed with virgin material and returned to the bumper production process. The properties of the bumpers produced are as good as those made using virgin material alone during at least eight cycles of reprocessing.

Experiments of this kind have shown that short-term properties do not vary too much if glass fibres are not contained within the material. Glass fibre is sometimes used for the reinforcement of some plastics and tends to become damaged when reprocessed.

As mentioned in previous lessons, the presence of mixed polymers and, most especially, of contaminants can be also speed up deterioration processes. Contaminants can include paint, labels, coatings, dust, wood, metals, glue residues or printing inks. If contaminants melt during processing, there is no way to remove them and they will be homogenised within the melt during the processing stage. These contaminants may subsequently be visible in the component.

For this, consideration must be given to a number of factors. It must be determined as to whether the material is pure or commingled and whether it is contaminated, for example, with metal or wood. For ease of feeding into the processing machines be they injection moulding, extrusion or blow moulding, the size and shape of the regrind (i.e., the bulk density) must be suitable. If the material is hygroscopic (water absorbing), for example polyamide, it may require pre-drying. Finally, should the recyclate be reprocessed on its own, mixed with other virgin material or modified with additives?

Metals are a particular problem in reprocessing as they can damage the internal workings of the processing machines. Protection from metal contamination is usually addressed by placing magnets in the feed hoppers.

If the level of other contamination is low and the contaminants do not melt within the melting range of the polymer, they may be removed from the melt without too much difficulty using a filter screen. A filter screen looks like a very fine mesh sieve and traps larger particles, which are unable to pass through. Screens need to be changed at regular intervals. The frequency of changing will depend on the level of contamination. Filter devices of this type can be used on extrusion or injection moulding machines. However, only fairly low levels of contamination can be tolerated, usually 1% or less. It is important that monitoring systems are available to indicate when the filter may need changing, since alterations in the process will change the quality of the materials produced.

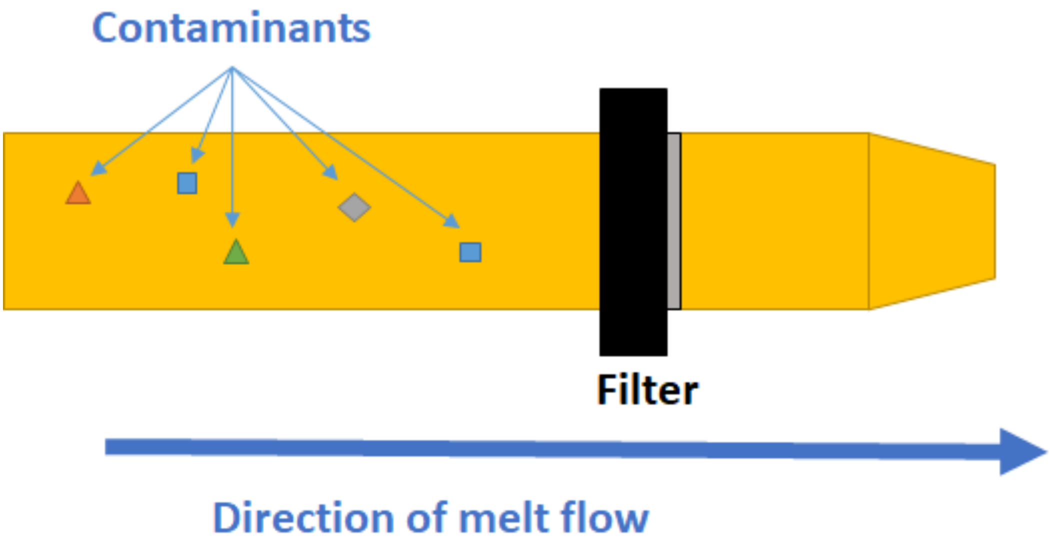


Figure. Schematics of a system to remove unmelted contaminants.

Contaminants reduce the mechanical properties of components. Therefore filtration can improve properties. However, this can be offset by the increase in shearing associated with pressure build up in the melt behind the filter screens. Increased shear could cause degradation and reduce mechanical performance. Therefore, the size of the mesh must be selected to balance these two effects.

5.4 Size reduction

Size reduction is necessary to bring material particles to a suitable size for being processed. This may involve a two-stage process.

In a first stage, a shredder is used to produce large particles of about 25-50 mm. These materials can subsequently be flaked with a rotary cutter. The rotary cutter is a device consisting of a rotor and rotating knives, static knives, a grinding chamber and a screen.

As the plastic moves between the stationary and rotating blades it is cut down to size. This size is determined by the mesh size of the screen.

An air extractor is usually used to dissipate the heat generated from the shearing action of the blades. It is important as a design feature that the knives can be rapidly re-set, replaced or removed for resharpening as they are likely to undergo considerable wear.

5.5 Washing

Washing is required to remove any dirt and residues adhering to the waste plastic.

It increases the purity of the plastics and in some cases improves the efficiency of other processes such as sorting. Washing also removes labels and water soluble glue residues.

Once the materials are washed they then need to be dried. This can be done mechanically simply using gravity and a conveyor to allow any liquid to drain away. Thermal methods use hot air to dry the plastic flakes.

5.6 Identification and sorting of plastics

One way to allow easy identification of plastics is to mark the mouldings.
Resin Identification System codes for packaging recycling.

Resin Identification Number	Resin	Resin Identification Code –Option A	Resin Identification Code –Option B
1	Poly(ethylene terephthalate)	1 PETE	01 PET
2	High density polyethylene	2 HDPE	02 PE-HD
3	Poly(vinyl chloride)	3 V	03 PVC
4	Low density polyethylene	4 LDPE	04 PE-LD
5	Polypropylene	5 PP	05 PP
6	Polystyrene	6 PS	06 PS
7	Other resins	7 OTHER	07 O

Figure: Resin Identification System codes for packaging recycling.

This allows the plastics to be sorted manually. However, manual sorting is a very labour intensive process requiring little equipment, but relies on the accuracy of the human labour to produce a high purity product.
An alternative is to use mechanised sorting technologies. This works by assessing differences in material properties.
One example is the use of density to separate polyolefins. The polyolefin fractions (PP, LDPE, HDPE) all have densities below 1 g/cm3. This allows a process called 'float-and-sink' to be used to separate them from the other polymer fractions. Separation is carried out in a flotation tank using water as the separation medium.

Table: Some of the used polyolefins and their density.

Plastic	**Density (g/cm3)**
Polypropylene	0.90

Co-funded by the Erasmus+ Programme of the European Union

Low-density polyethylene (LDPE)	0.90
High-density polyethylene (HDPE)	0.95
Polystyrene	1.05
Polyamide (PA6 or PA66)	1.15
Polyvinyl chloride (PVC)	1.40
Polyethylene terephthalate (PET)	1.40

The principle applies in float-and-sink separators. As the name suggests, this density separation technique involves a floating fraction and a sinking fraction. The lighter polyolefin fraction remains floating on the surface and denser particles sink.
When two plastics have the same density (like PET and PVC) some different parameters need to be used.
Further techniques such as X-ray fluorescence, near infra-red (NIR) spectrometry, or even colour or surface properties determination are possible in order to classify the different kinds of plastics.

5.7 Recycling techniques

Plastic recycling can be achieved by either mechanical or chemical means. These two alternatives are going to be presented in detail within the next weeks of this course.
Mechanical recycling is the most common method of recycling. Here plastics are physically ground back to a suitable size and reprocessed.
In-house recycling of a single flow of plastic materials, also known as primary reclycling, is relatively easy to carry out. However, reclaiming used materials outside of this scenario makes the effort required to reprocess the plastic significantly greater in comparison. This is known as secondary recycling.
Sometimes, these straightforward mechanical recycling methods can be no longer applied. Tertiary recycling involves chemical processes to break down the polymers and produce monomeric feedstocks.
Quaternary recycling is applied to plastics that are unsuitable for any of the above recycling alternatives. In this case, waste materials would be used for producing energy by pyrolysis. This strategy retains little value and contributes to the production of greenhouse gases. So it should remain as the last eligible option.

5.8 Quality control of the output

Simple experiments can be performed to assess the effects of processing on plastic properties, especially on the tensile strength and impact resistance of the materials.
Mouldings should be produced using the same conditions as used for full production to get useful and representative results.

The following experimental procedures explore the recycling limitations of a plastic material. The results of these experiments can be used to determine if and when virgin material needs to be introduced into the recyclate mixtures and the likely properties of the resulting components.

Method A: Closed loop recycling with regrind only.

i. Mould 100% virgin material, keep some mouldings back for evaluation
ii. Regrind a quantity of this 'first pass'
iii. Mould and keep some mouldings back for evaluation
iv. Repeat for required number of passes, e.g., 'second pass', 'third pass', etc.
v. Carry out evaluations on virgin and all passes (mechanical and/or rheological as required)
vi. Examine the results

Method B: Blending with virgin material.

i. Mould a blend of 50% virgin and 50% of the third pass material
ii. Keep some mouldings back for evaluation
iii. Blend 50% of this first blend with 50% virgin
iv. Repeat for a number of passes, e.g., 5
v. Carry out mechanical/rheological evaluation on the blend moulding samples 1-5
vi. Examine the results

Short-term properties (e.g. tensile strength and impact resistence) are important. However, thy should not be the only ones evaluated. The long-term effects of repeated processing on plastic properties need to be carefully investigated as well. Whether these materials, when mixed with virgin, will undergo accelerated degradation needs to be assessed.

Another important criterion for high quality processing is the homogeneity of the material. When recyclates are mixtures of different viscosity and colour, it is important that they are mixed adequately together to form one coherent material. Special screws are available for processing equipment. These homogenising screws improve both the product quality and the reproducibility. In fact, achieving homogeneity with recyclates, especially mixed materials, is difficult and sometimes impossible. This means that quality control for recyclates is definitely as necessary as for virgin material.

Co-funded by the Erasmus+ Programme of the European Union

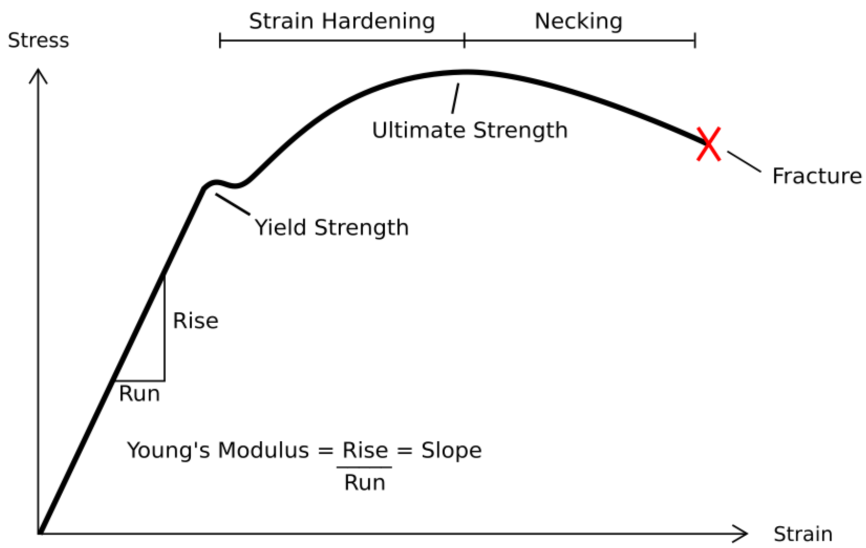


Figure: Typical stress-strain curve of a plastic material. It is obtained from strain tests performed under standard conditions and allow evaluating the material's resistance.

6. Current industry position on plastic production and recycling

In this lesson you will look at some insights regarding the management of plastic wastes from the point of view of industrial processors.

6.1 Introduction

It would be hard to imagine a modern society today without plastics. Plastics have found a myriad of uses in fields as diverse as household appliances, packaging, construction, medicine, electronics, and automotive and aerospace components. As can be seen from this list, plastic technology can be applied with great success in a variety of ways.

So what makes plastic such a versatile material?
The reason for its success in replacing traditional materials such as metals, wood and glass in such a diverse range of applications, is the ability to modify its properties to meet a vast array of designers' needs. This, plus the ease with which plastics can be processed, makes them ideal materials for the production of a variety of components. Look around and you'll be surprised to see just how many different uses plastics have found and how big a market the plastic industry supports.

The plastic material used to make many of these products is what is called 'virgin' grade. These are materials which have come straight from the polymer manufacturer to the factory and have

not yet been processed. If these materials later come to be reprocessed, they are then called 'recyclates'. However not all plastic materials are reprocessed, most are simply thrown away, leading to the need to dispose of them. A continued increase in the use of plastics has led to an increasing amount of plastics ending up in the waste stream.
Management of waste is one of the major problems facing modern society and is not just limited to plastics. However, a combination of legislative measures and government initiatives, the increasing cost of landfill disposal and public interest in support of recycling has meant that plastics recycling must increase. Generally, plastics are made from crude oil. Recycling of plastics therefore helps to conserve this natural resource.

Any strategy for waste management is based around three guidelines:

- Avoidance, i.e., reducing and, if possible, avoiding producing waste at source. No waste = no problem.
- Reclamation, the recovery of materials from the waste stream for recycling.
- Elimination, the disposal of non-recyclable materials, for example by landfill.

The second point can be applied to the problems of plastic waste by reclaiming material that is destined for landfill. Hence, plastic material recovered from the waste stream is termed 'reclaim'.

6.2 Reclamation of recycling plastics

There are several options for how this can be done: reuse, mechanical recycling, feedstock recycling and energy recovery. These are defined next.

- **Reuse:** the most common examples of reuse are with glass containers, where milk and drinks bottles are returned to be cleaned and used again. Reuse is not widely practised in relation to plastic packaging - plastic products in general tend to be discarded after first use. However, there are examples of reuse in the marketplace. For example, a number of detergent manufacturers market refill sachets for bottled washing liquids and fabric softeners. Consumers can refill and hence reuse their plastic bottles at home.
- **Mechanical recycling:** also known as physical recycling. The plastic is ground down and then reprocessed to produce a new component that may or may not be the same as its original use.
- **Feedstock recycling:** the polymer is turned back into its oil/ hydrocarbon component for use as raw materials for new polymer production. This is also known as chemical recycling.
- **Energy recovery:** the materials are incinerated to recover their inherent energy.

Mechanical recycling is the most widely practised of these methods and will be the focus of much of the further chapters. However, the others are valuable options for waste disposal,

especially for materials that do not meet the criteria for mechanical recycling for reasons of practicality or cost-effectiveness.
A number of technologies are available for recovering and recycling plastics. Some are currently in use by industry and capable of processing large quantities of material in a cost-effective manner, whilst others currently exist only in laboratories. Plastic recycling is an area that is constantly developing to try to meet the often competing demands of legislation, market forces and environmental pressure. No manufacturer wishing to stay in business can recycle materials if it is not profitable to do so. Recycled plastics are used in the same market in which they originated. They replace and compete against virgin materials. The price recyclate can command will depend on both the price of the virgin materials and the quality of the recyclate. The price of virgin materials can vary greatly as it is linked to both oil prices and supply and demand within the market. This in turn means that the price that recyclate can command varies greatly.

Environmental pressure may create a demand from the consumer for recycled goods. By creating such a market, a manufacturer can see a profit to be made, and will therefore begin to produce and sell recycled goods. This business will also be subject to the effects of market forces, supply and demand. Environmental pressure may also result in legislation forcing manufacturers to use recycled materials. In this case, a market may not exist already and this legislation will impact upon the 'natural' market force. The result may be less profitable and require subsidies to kick-start such activity. For long- term growth however, the activity must be self-supporting.

A fully sustainable infrastructure for the recycling and recovery of plastics is required if the vast quantities of plastic material available are to be diverted from landfill. However, this will occur only when the demand is created for the end product materials and it is economically viable to recycle them. Currently, this has meant that recycling activities need to be subsidised if they are not commercially profitable. Therefore, it is paramount that the plastic industry continues to educate the public and potential recyclate users in order to create and develop the supply and demand for these materials.

6.3 Research needs

For the development of new recycling technologies sufficient investment is required in both research and development (R&D) and new machinery and technology. Research needs to be targeted at the areas of greatest industrial need and, once developed, technologies need to be successfully transferred to industry. Best practice guidelines need to be available to highlight and disseminate the most up-to-date and effective treatment methods. Design for Disassembly and Recycling interests do not start at the end of a product life. They begin with the conception of a new product. By introducing the need for recyclability in the design stage, the problems of waste disposal can be reduced. If a product is part of a bigger component, disassembly needs to be considered too.

Once the materials enter the recycling stream, both applications and consumers must be found for recyclate materials. This creates demand and allows recycled material to have economic value in the marketplace. If the associated value of the material is sufficient, then recycling of the material will be both cost effective and sustainable. These materials must compete against virgin materials in terms of both cost and quality. One important trend in this area is that plastic manufacturers themselves are marketing grades containing recycled materials, which takes away much of the onus from designers in terms of finding ways of incorporating recycled materials. It also increases confidence in the quality of recyclate materials. The lack of knowledge on consistency of quality and properties, often a cause for resistance to switch to recyclates, is removed.

Aided with standards for these materials, new potential uses for recyclates can be more easily identified. Designing components for disassembly and recycling, and setting up an infrastructure capable of handling the post-consumer materials are issues that must be addressed.

6.4 END QUIZ

1. Which one of the following kinds of plastic materials have a melting temperature below their degradation temperature, hence allowing their recycling?
    a. Elastomers
    b. Any of the above exhibit these properties
    c. Thermoset materials
    d. Thermoplastic materialsç
2. Compounding of recycled materials generally involves the following sequence of operations:
    a. Mixing > Pelletising > Feeding/conveying > Metering > Plastification
    b. Metering > Feeding/conveying > Mixing > Plastification > Pelletising
    c. Feeding/conveying > Metering > Pelletising > Mixing > Plastification
    d. Plastification > Metering > Feeding/conveying > Mixing > Pelletising
3. Which statement is true for injection moulding and blow molding?
    a. The melted material does not generally require filtration of solid unmelted particles.
    b. Homogeneity of the inlet plastic recyclates is relatively unimportant.
    c. Homogeneity of the inlet plastic recyclates is a critical aspect when considering reprocessing.
    d. The combination of several layers of recycled and new plastic materials is not a feasible alternative to increase the quality of the end material.
4. Which one of the following processes would you recommend for recycled materials containing paper and metal contaminants?
    a. Intrusion moulding
    b. Transfer moulding

  c. None of the above
  d. Sinter moulding

5. Choose the wrong statement:
   a. Addition of antioxidants (e.g. hindered phenols) is useful to delay oxidation of polyolefins.
   b. UV absorbers, quenchers and radical traps can be used to increase light stability of recycled materials.
   c. The intended application is not a relevant factor when considering the additivation of a material with stabilizers.
   d. Polyvinyl chloride is specially affected by heat degradation, thus requiring the use of stabilizers.

6. Choose the correct statement:
   a. Polyolefins such as PE and PP are generally not compatible with other thermoplastic materials.
   b. If two materials are immiscible there is no way of combining them in a single material.
   c. Polyolefins such as PE and PP are generally compatible with almost any other thermoplastic material.
   d. All thermoplastic polymers are compatible and can be combined in a mixed polymer.
7. Which one is not a relevant aspect when considering the production of consumer goods from plastic recyclates?
   a. The purity of the inlet materials.
   b. The previous uses of the material.
   c. The thermal and mechanical stresses undergone previously.
   d. None of the above. All of them are relevant aspects to be considered.
8. Float-and-sink separation is...
   a. a useful technique to separate polymers of similar density (e.g. PET and PVC).
   b. a method for removing contaminants from a polymer (contaminants sink and the polymer floats).
   c. a technique of separating organic debris from scrap materials.
   d. often used to separate polyolefins with different density.
9. Select the correct statement:
   a. Quality control of recyclate materials only concerns long-term properties.
   b. Quality control of recyclate materials concerns both short-term and long-term properties.
   c. Quality control of recyclate materials is not required as it is for virgin materials.
   d. Quality control of recyclate materials only concerns short-term properties.
10. Which one of these options is not a reclamation strategy?
   a. Landfill
   b. Reuse

c. Mechanical recycling
d. Feedstock recycling

Co-funded by the Erasmus+ Programme of the European Union

Co-funded by the Erasmus+ Programme of the European Union