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THE CONCEPTION OF THE BOTTLE FOR CARBONATED DRINKS

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SUMMARY

In the domain of the course "Research Assignment For Exchange Students", it was proposed to me the realization of a work throughout the semester. This work is based on the assimilation of knowledge about polymers and composite materials of polymeric matrix from the chemical part to its mechanical behaviour, transformation processes and applications.

The choice of this project was due to its practical character, given its use in everyday life. We found particularly interesting to study a bottle, whose project study represents much more than the mere bottling of a liquid, but also the pressure storage, taking into account that it is a fizzy drink.

CONTENTS

ACKNOWLEDGEMENTS

We would like to thank Professor Antonio M. Mateo García, who made himself available to be my tutor in the curricular unit "Research Assignment For Exchange Students" who accompanied me throughout the semester, always showing great interest and availability during the development of this work.

LIST OF FIGURES

Figure 20: Bottle recycled from plastic collected from the sea 37

Figure 21: Effect of the percentage of fibres incorporated in the cement matrix 38

LIST OF TABLES

INTRODUCTION AND OBJECTIVES

The objective of this work is based on the assimilation of knowledge of polymers: the chemical part, their mechanical behaviour, transformation processes and applications.

The choice of this project was due to its practical character, given its day-to-day use. We found it particularly interesting to study not only the bottling of a liquid, but also the pressure storage, due to the fact that it is a carbonated drink. The study of this project follows a logical sequence and is divided into multiple steps:

- ✓ Chemical analysis of the material;
    - Consideration of the requirements demanded in this industry;
    - Justification of the advantages inherent in the use of polymeric materials;
    - Selection of the most suitable plastic to meet the requirements required in the bottling of this soft drink within the wide range of existing polymers;
    - Analysis of the synthesis process of the polymer in question;
- ✓ Mechanical behaviour and properties of the selected polymer;
- ✓ Bottle manufacturing process;
    - Deepening and analysis in a practical perspective of the knowledge acquired in the theoretical-practical lessons about the processes of polymer processing;
- ✓ Recycling and sustainability of the material in use;
    - Study of the environmental impact;
    - Awareness of the approach to this issue when studying any material is a topic considered indispensable nowadays.

With the realisation of this work, it is also fostered the development of our ability to search, process and manage the information/data collected.

MARKET REQUIREMENTS

Packaging is essential in the food industry. It allows drinks and food to be transported safely, so that they can reach consumers with the same quality that they present in the production lines.

There is no doubt that there is a different packaging for each use, but the priority has always been to reduce the weight of packaging, maintaining the design and quality, in order to obtain the highest possible efficiency and the lowest environmental impact.

This is the type of packaging that allows a better ratio between the amount of drink and the weight of the material.

The entire design of this bottle includes the parallel analysis of particularities related to functional and commercial character, and also aesthetics cannot be neglected, due to the fact that it is a product for sale. In this way, it is given a list of requirements to take into account while choosing the material for bottling this product:

➢ Waterproof ➢ Allow pressure storage ➢ Rigid ➢ Barrier against odors ➢ Lightweight ➢ Present some thermal insulation (low thermal capacity)	**FUNCIONAL**
➢ Recyclable ➢ Appealing design ➢ Transparent	**ESTÉTICO**
➢ Affordable price	**COMERCIAL**

DESIGN OF THE BOTTLE

It is of great importance in the design of the bottle not only to be appealing to the consumer, having an eye-catching label, but also its functional character, as mentioned above.

A special feature of the carbonated drinks bottles is their rounded shape. This preferred physiognomy is due to the fact that it allows the bottle to be under tension and does not deform so easily.

As for the size of Coca-Cola bottles, the thickness of the side walls varies between 3 and 4mm. These bottles can also have volumes from 250 to 2000ml, the most popular being the 330mL and 500mL bottles.

The design of the base is a very common and complex aspect of plastic bottles. The petal-shaped rounded bottom is a widely used solution worldwide as it not only supports the weight of the fluid, but also keeps the bottle stable and undeformable when filled.

Figure 1 shows the possible dimensional variables of the petal base of these bottles. The higher the "height" of the petal, the wider the "valley" and the shorter the length of the "foot", the lower is the probability of the bottle cracking, namely in the "valleys", because it is the place where the applied tension is higher independently of its volume and weight supported.

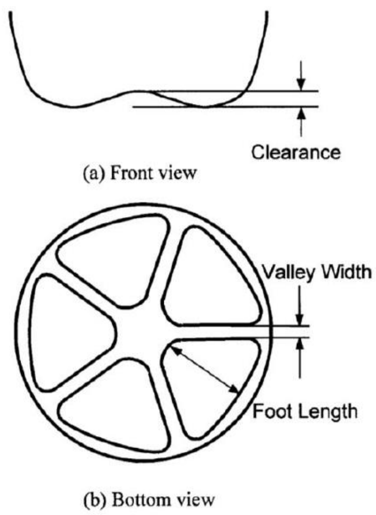

Figure 1: Detail of the petal-shaped base

As for the neck design, this is influenced by the handling requirements and the incorporation of the regular-sized caps. Different neck finishes may have different weights. The body of the bottle was the focus in the manipulation of the design for weight reduction, as the neck and base design cannot be changed much for the reasons given.

The figure below shows the pressure distribution generated by Coca-Cola being a fizzy drink along the bottle.

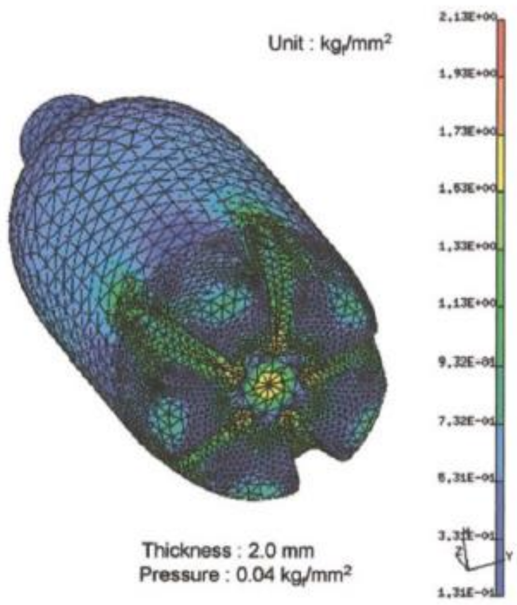

Figure 2: Stress distribution in a soft drink bottle

However, it is important to emphasise the major inconvenience associated with this format. Its circular profile generates the occupation of more space than a possible model with more rectangular lines. Although this aspect may seem negligible, it is important when it comes to storage, especially for transport. This stage incorporates a significant part of the costs associated with the stages prior to the sale of the product. Bearing this in mind, there is every interest in making this issue profitable for both distribution and storage of the packages. Taking into account all the percentage of free space between bottles due to the format adopted, besides the reduction of costs, also the reduction of the environmental impact would be achieved with the filling of this aspect.

Another major weakness related to the format currently used is related to the frequent loss of control while dropping the drink. This has been found in studies that involved close observation of the wide range of consumers aged between 15 and 55, men and women while using the bottle. That is, the gradual transfer of weight from the base to the opening of the bottle when it is half full causes instability of the bottle and extra force in its handling. On the other hand, in the case of larger volume bottles, their curvature is completely unsuitable for the hand size of women and children.

For these reasons, in a survey we considered the following prototype (Figure 3) very appealing to delegate to consumers full confidence when using it.

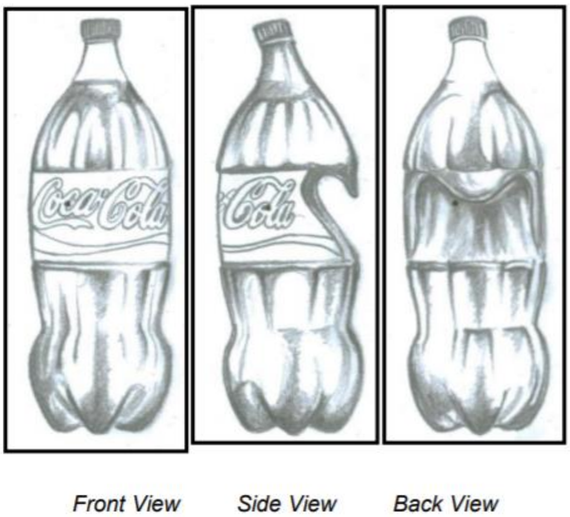

Figure 3: Large bottle prototype

This suggestion does not distort the iconic features that are central to maintaining and incorporates an innovative philosophy that appeals to potential buyers of the product, as its creativity and unusual aesthetics. Nevertheless, this possible bottle would increase the value of the brand, although the manufacturing of the bottle would be more expensive. However, the issue associated with the percentage of free space when packaging the bottles would be aggravated.

The manufacturing cost of a plastic bottle varies according to the area where it is produced, since the raw material is a derivative of petroleum and is exposed to fluctuations in the price of petroleum and energy in each region. That said, in the european market, the average cost of a plastic bottle is 3.2 cents.

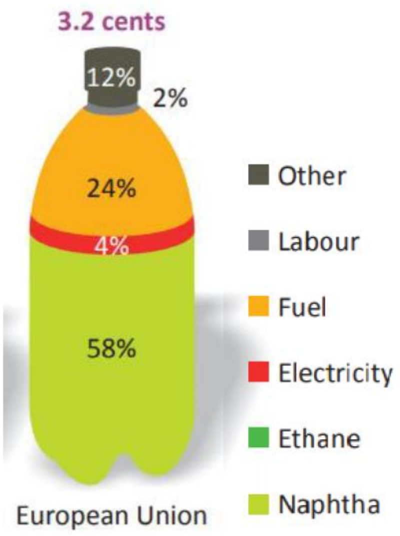

Figure 4: Cost of a 330 ml bottle in the European Union and breakdown of cost by area (Labour, Fuel, Electricity, Ethane, Naphtha, and others)

In summary, the major advantages of this prototype would be:

- The eye-catching design for consumers.
- It would encourage more reuse due to its aesthetics and usefulness.
- It would eliminate the need to use 2 hands to handle it.

CHOICE OF MATERIAL

Over the years, the bottling of the soft drinks have been the target of some improvements both in the format of the packaging and in the material used for it. So, in this section, the advantages and disadvantages associated with each material used are analysed.

Figure 5: Evolution of the Coca-Cola bottle

Ceramic Materials

Just a few years ago, **glass** was the main material for making soft drink bottles. However, this material presents not only advantages but also disadvantages. The excellent aesthetic and mechanical properties of glass, such as its shiny appearance, low permeability to CO_2 , chemical inertness (allows to better preserve the smell, taste, and properties of the drinks) and also its high rigidity (allows reuse of the bottle) are fundamental characteristics of glass that will shape the final product. As for the disadvantages, the brittleness of the glass, which can cause problems in the production of the bottle, as well as during handling and transportation, is the main drawback, together with the cost associated to manufacturing and reuse.

Metallic Materials

In this group, the most suitable solution is aluminium, because of its low density and permeability to CO2. Its opacity contributes by protecting the drink from UV rays (important in the storage and transport stages) and has the benefit of being easily recyclable. On the other hand, it is important to know that it is impossible to reuse the packaging due to plastic deformation at low stresses and, also, because of the influence of metal ions when in contact with the drinks (this problem is not very relevant since all cans have a polymeric coating).

Polymeric Materials

The target material for the bottle in this study is in this group, so all the topics associated with its production will be studied in detail. In the next chapter, the focus is on the reason that led to the evolution until this material became the most used. In this sense, the main benefits are the low price, the low melting temperature, the easy handling and the good chemical and mechanical properties. On the other hand, it is also crucial to take into consideration the low weight of this material comparing to the previous ones, which leads to a lower expenditure and ecological footprint associated with transport.

In the graph shown below, it's possible to see the good relationship between the density (intended to be low) and the mechanical property related to the stiffness/rigidity of the material, the Young's Modulus (ideally with a high value and constant for each material).

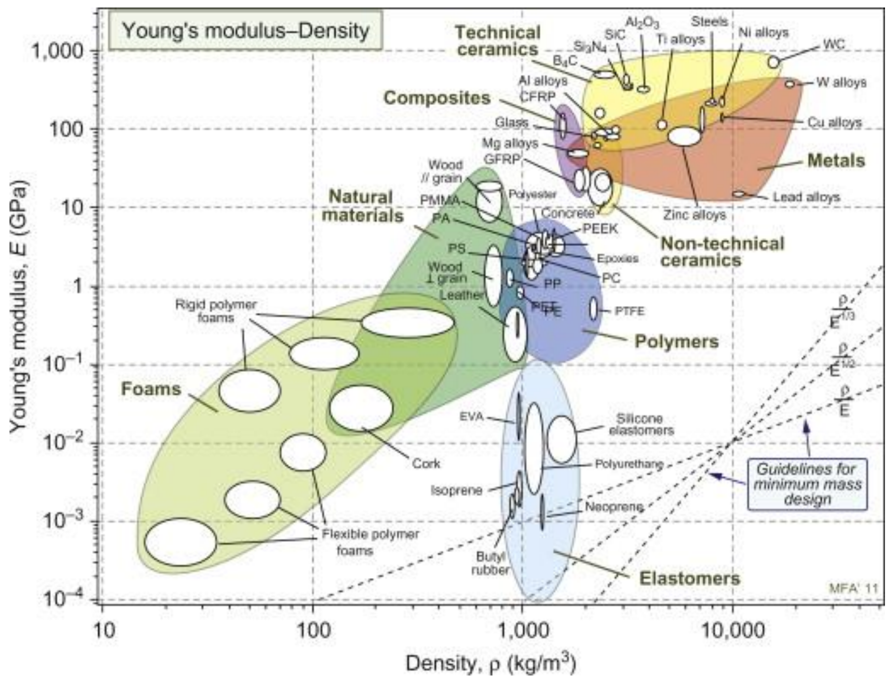

Figure 6: Young's Modulus as a function of density

CHOICE OF POLYMER

Elastomers

They may have natural or synthetic origin and have a high degree of elasticity (when subjected to a stress, even if it is small, they deform significantly but not permanently). They have great flexibility and molecular cohesion is guaranteed by crosslinking, whose number determines the rigidity of the material. The remaining synthetic polymers can be classified as thermosetting or thermoplastics, depending on their ability to be melted and solidified repeatedly with or without significant loss of its fundamental properties.

Thermosetting

They assume their definitive form when processed, that is, when subjected to a single thermal cycle, and cannot be subjected to further heating without deterioration of their properties. The final product is hard and does not melt with the increase in temperature. They are insoluble, infusive, and also more resistant to heat, compared to thermoplastics.

Thermoplastic

They support several thermal cycles (can be melted and re-solidify several times) and some of them can be dissolved in several solvents. They can be partially crystalline, or totally amorphous, and also easily recyclable. After doing a research about which of the polymers would be viable to be used in the manufacture of Coca-Cola bottles, it can be concluded that thermoplastic polymers are the ones that have better properties. Now follow the different thermoplastic polymers to be analysed.

- **Polypropylene or PP** is a partially crystalline thermoplastic, with good resistance, low density, and transparency (which makes it less appealing from an aesthetic point of view). It is widely used for production of moulded plastics due to the excellent combination of its properties. It has a high rigidity and higher temperature resistance compared to other plastics, which allows continuous applications with temperatures above 100ºC. Due to its low cost and good properties, it is often used in the manufacture of bottle caps and detergent packaging.

- **Polystyrene** is a versatile plastic used to manufacture a wide variety of consumer products. Since it is a hard and solid plastic, it is used frequently in products that require transparency, such as food packaging and laboratory equipment. It is a highly fertile amorphous polymer with good dimensional stability and low chemical resistance. Despite its low mechanical strength, it has excellent properties for certain applications, namely rigid household items, brushes, packaging for cosmetics and CD covers.
- **Polyethylene or PE** is a partially crystalline, flexible and highly resistant thermoplastic obtained through the polymerization of ethylene. There are five types of Polyethylene, each having unique properties and being all of them recyclable. High density polyethylene although not very suitable for the production of soft drink bottles, is a material often used as a raw material for bottle caps.
- **Polycarbonate or PC** is a linear polyester of high transparency, high strength impact and good insulating properties. However, it has a very high cost compared to other thermoplastic polymers. Very common applications of this polymer are compact discs (CDs and DVDs), covers, lenses for glasses and finishing parts in the automotive industry.
- **Polyvinyl Chloride or PVC** is, within this group of polymers, the most used throughout the world, after polyethylene. It is defined by its high chemical resistance, its good insulating properties, and the fact that it is impermeable to gases and liquids. It is specially used in the manufacture of tubes, linings, gloves, windows, boots, etc.
- **Polyethylene terephthalate or PET** is a transparent thermoplastic polyester, chemically inert, with high wear resistance and with high impermeability. It is mainly used in the production of preforms, which are then blown into the shape of bottles.

Both **PET** and **PVC** meet the proposed requirements, however, the most appropriate solution is PET, due to its low production cost and its behaviour against the UV rays.

POLYETHYLENE TEREPHTHALATE (PET)

PET is one of the most diffused thermoplastic polymers available on the market. It has the advantage of being not only easily re-processed at high temperatures but also easily recyclable, which is why almost the entire bottle production industry uses this specific polymer.

Now that it is established that PET is crucial in the packaging industry, the reasons for its importance should be defined and also the reason why it is known as the "king of the bottled drinks end-segment". PET is:

- Colourless and can be transparent (if amorphous) or translucent (if semi-crystalline), which allows people to see what's inside the bottle.
- Lightweight: Comparing the weight of a 1L PET bottle designed for containing water and a 750 mL wine bottle made by glass (respectively, ca. 25 g. and ca. 360 g weight).
- Thermoplastics, robust, semi-rigid to rigid, mechanically resistant to impact, and stretchable during processing.
- Gas-barrier properties against moisture and CO_2
- Extremely inert compared to the other plastics, and free from plasticizers

And can also be:

- Blended with other polymers (e.g., with PC, PP, PP copolymers, and PBT) or surface modified (through physical and chemical treatments), to improve specific properties.
- Copolymerized

The ratio between the amounts of crystalline and amorphous phase of the material is a central property in defining its use. PET is an inherently semi-crystalline material, i.e. varying amounts of its chains can be organised into crystals or remain amorphous, similar to glass. Another important characteristic of this polymer is its low density compared to glass, which facilitates transport, generating a reduction in costs.

Density	**1290 - 2,74x10 [Kg/m3]**
Melting Point	255 -265 [ºC]
Max Working Temperature	66,9 – 86,9 [ºC]
Min Working Temperature	-123 - -72,2 [ºC]
Tensile Strength	56,5 – 62,3 [MPA]
Young's Modulus	1700 [MPA]
Water absorption	0,5 [%]
Heat Capacity	0,138 – 1,151 [W/m.ºC]
Viscosity	0,7 – 1 [dL/g]

Table 1: Properties of PET

PET SYNTHESIS PROCESSES

The industrial production of PET can be carried out in two or three stages, depending on its application: prepolymerization (I), polycondensation (II) and solid state polymerization (III).

Prepolymerization

In the first process, the bis terephthalate oligomer is produced. This polyester can be manufactured by two distinct processes, direct esterification or transesterification, and the main difference between both lies in the monomer with the group ester. Direct esterification is achieved by reacting terephthalic acid (TPA) with ethylene glycol (EG), while transesterification is the replacement of the terephthalic acid monomer with the dimethylene terephthalate ester (DMT).

- *Direct esterification Reaction*

Direct esterification is a heterogeneous and autocatalytic reaction, with H20 release. Due to its autocatalytic character, catalysts are dispensed and the reaction molar ratio of TPA: EG and temperature range are 1:1,5-3 and 240-260ºC, respectively. The use of a lower monomer ratio and a higher temperature, compared to the transesterification method, is essential to achieve excellent solubility of the TPA monomer in EG.

- *Transesterification Reaction*

In transesterification the reactor is loaded with DMT: EG and catalysts at a temperature between 170-210ºC. During the reaction, the releaser methanol is collected in a receiver, allowing to estimate the extent of the reaction. When the distillation of methanol ceases, the reaction is considered to have been completed and BHET is obtained with a degree of polymerization between 25 and 30. For a long period, this process was preferred due to the ease of obtaining the DMT monomer that presented a higher degree of purity.

Polycondensation

In this method, BHET is gradually heated to 280ºC after its synthesis in the prepolymerization step. During heating, the internal pressure of the reactor is reduced to values below 1.3 x 102 Pa and, consequently, the degree of polymerization is increased to 100. The total reaction time (2 preliminary steps) can vary from 5 to 10 hours and EG is obtained as a by-product.

This step is final for some PET products such as clothing fibers in which mechanical properties are not the most important characteristic.

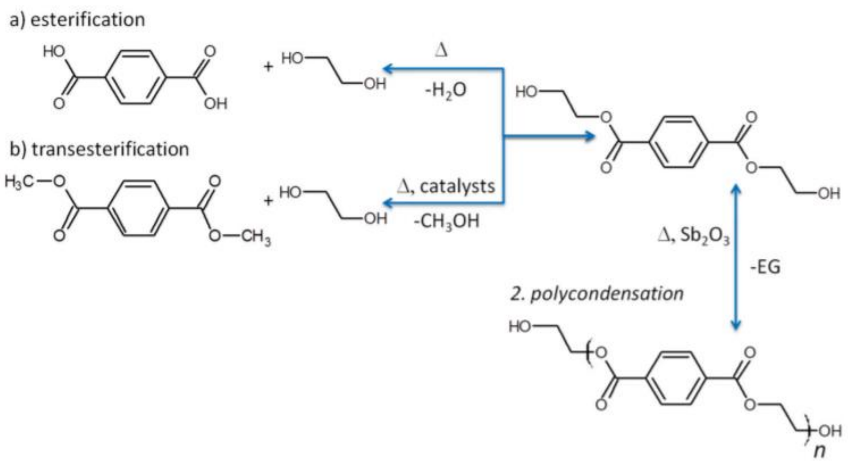

Figure 7: The PET synthesis process

Solid-state polymerization

The polycondensation or solid-state polymerization (SSP) is used to obtain products of high molar mass, such as soft drink bottles, carried out at 220-230ºC for a period between 10 and 30 hours.

The most important aspect of SSP is to increase the degree of crystallinity of the material in a short period of time under high vacuum or with an inert atmosphere system under agitation, avoiding the sintering process. Particle adhesion improves not only improves the mechanical properties of the polymer but also increases the degree of crystallinity.

In the end of the PET production process, this polymer comes in the form of crystalline pellets that will then serve to feed the injection moulds.

BOTTLE MANUFACTURING PROCESSES

There are two procedures that can be used when manufacturing PET bottles, namely injection and blow moulding and extrusion and blow moulding. In both of them, there is a previous stage of raw material preparation, in which the PET pellets are heated to a temperature of approximately 150-170ºC, in order to become softer and more flexible.

Injection and Blow Moulding

This method is adopted when we pretend to manufacture small bottles in large quantities, given its dimensional and geometric versatility and the high quality achieved. This process is one of the soft drink bottle production processes that requires a preform.

After the preform is produced it is transported to another mould, which will give the final shape of the bottle, as it is shown in the picture.

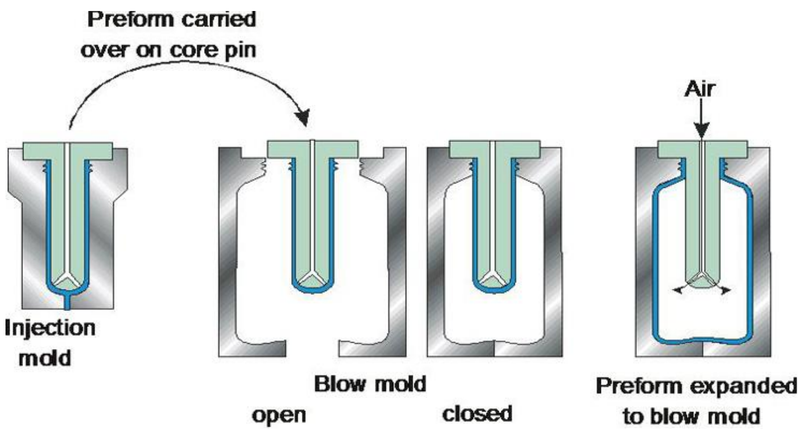

Figure 8: Blow moulding process stages

It is very important after blowing to cool the bottle before opening the mould, which can be done by an optimal balance in the mould closing gap tolerance. If the mould closing gap tolerance is too big, at the end of the process there can be burrs which after polishing are still visible, besides the extra cost in the polymer.

The setting of the mould closing gap not only influences the cooling of the bottle, but also whether or not air escapes when the material stretches against the walls.

As far as the characteristics of this process are concerned, this is a very interesting process as it produces cheaper parts than the extrusion and blow moulding process, as it is shown in the table below:

	Relative price per unit (EUR)	Production cadence (units/hr)
Injection and Blow Moulding	13.3-25.3	100-2500
Extrusion and Blow Moulding	15.0-29.5	10-250

Table 2: Comparative analysis of production costs of the blowing process with the extrusion and blowing process

However, this process does not allow the manufacture of parts with complex shapes, which means that this process is not performed in the production of bottles with a capacity above 5L or simply a part with a more refined geometry. It is also possible to produce bottles with larger cap openings using this process.

Due to the use of the preform, this process involves no waste of material and also leads to better control of the final part weight and wall thickness compared to the extrusion and blow moulding process.

However, this soft drink bottle manufacturing process has a higher tool cost than extrusion and blow moulding and is therefore only used for high volume production.

Extrusion and Blow Moulding

Unlike the injection and blow moulding process which is generally used in the manufacture of small volume bottles, this process is used in the manufacture of larger volume bottles.

It starts with the extrusion of a hollow polymer tube, through a machine. The mould encapsulates the tube at the ends and the top is cut to form the opening where the compressed air will be applied. In this process, this mould is already the one that will give the final shape to the piece. Compressed air is applied through the free end and will force the plastic to take the shape of the mould. The mould opens and the piece is transported to another machine which cuts the excess material from the bottle at both ends, thus obtaining the final piece.

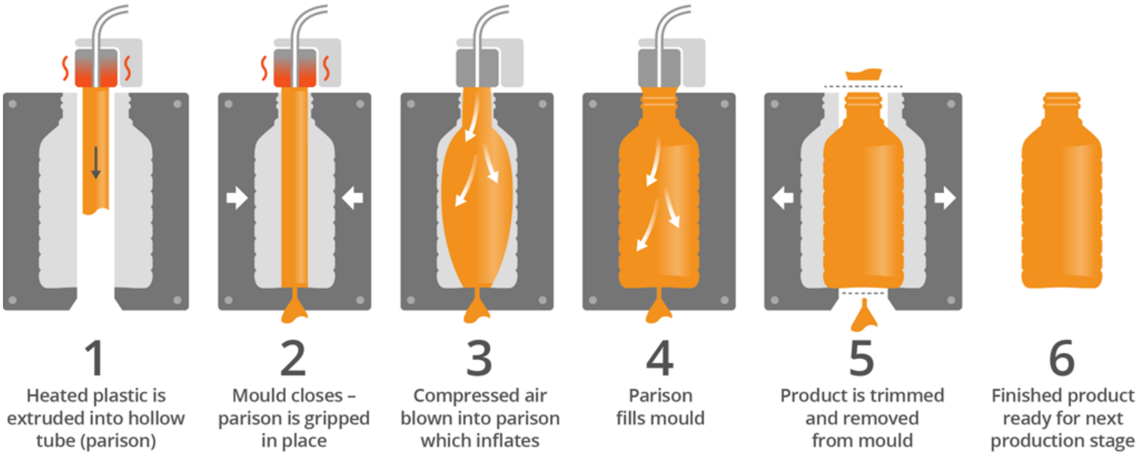

Figure 9: Blow moulding stages of the extrusion and blow moulding process

This method, as can also be seen, leads to a great waste of material. Therefore, the question of material recycling is also relevant here, a subject that will be addressed in the section "Recycling".

This method and the method previously seen have very equivalent tooling and machinery costs, because although the injection and blow moulding method needs one more mould to execute the preform production, the extrusion and blow moulding method needs a machine that performs the extrusion of the polymer, extrusion that slows down the speed of part production.

Preform

Preforms are the result of the first processing of PET after it has been formed into pellets. These pieces are the elements to be shaped during the subsequent stages that will result in the final soft drink bottle and which keep some of its characteristics, such as weight and neck.

Figure 10: PET preform

Preforms are obtained through an injection moulding process in which PET pellets are heated to a temperature that allows the material to change state and exhibit a fluid behaviour compatible with use in injection. The most common temperature in these situations is around 265ºC. The heating is done through resistances that are arranged parallel to the worm screw that feeds the mould with the melted thermoplastic.

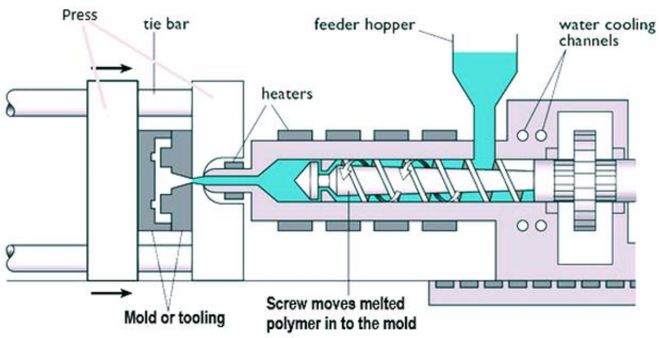

Figure 11: Schematic diagram of a plastic injection moulding machine

After the mould cavity is completely filled, the mould releases itself and expels the solidified preforms from the mould cavity. In order to solidify them in a fast way, the moulds have interior channels for the circulation of cold water that will cool the mould and consequently the preform. In order to get a return on the high investment made in the mould, the injection moulding machines work in large uninterrupted production cycles and each mould allows a high number of preforms to be moulded in each cycle.

In the following image it is possible to verify that a production cycle with the presented mould allows the formation of 48 preforms. Each mould is made up of two parts: one side of the mould with the cavity in which the material will be injected and another cavity which contains the cores which allow the inner cavity of the core to be created..

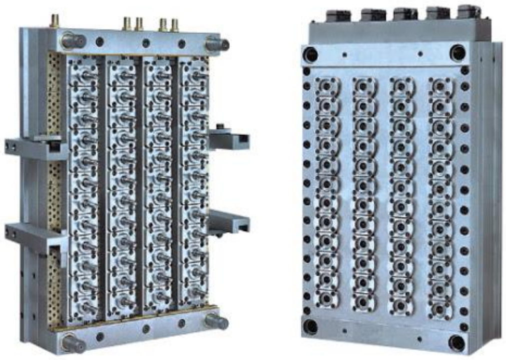

Figure 12: Preform mould for PET bottles

Obtaining preforms by injection moulding processes requires controlled parameters, as do all products obtained by injection, however, as the preform is a semi-product these parameters must be controlled with increased precision.

The typical problems associated with the injection of preforms are divided into two groups, depending on the area where the defects occur: Lateral area or neck area.

In the lateral area of the preform, the defects most likely to occur are air bubble trapping, the appearance of black spots and material lines with other properties.

In the neck area, the most common defects are the unfinished filling of the thread, and deformations on cooling.

STUDY OF CREEP RESISTENCE

Plastics are viscoelastic materials that manifest themselves under prolonged pressure stresses, a phenomenon known as creep.

Coca-Cola bottles are typical shelf objects, they can be resting for months on their base, subject only to their own weight, the weight of the drink and the pressure forces applied by the gas. Therefore, it is important to analyse the capacity of a PET bottle to resist creep, i.e. how long can such a bottle be left standing without creep deformation being such that it deforms the material to the point that the drained gas undermines the product - the concept of shelf-life.

Creep deformation, by disturbing the organization of the molecules, will generate micro-cracks in the structure, which will cause the gas to drain faster and faster. It is essential to study creep in packaging because, in addition to affecting the retention of CO_2, it also affects the appearance of the packaging and the fixing of the labels. The table is taken from an article which carried out an experiment to pressurise 2L PET bottles of different mass. Pressurisation was initially carried out at 3.5 atmospheres and over a period of about 2.5 months, the internal pressure in the bottle and its lateral perimeter were measured. The greatest stresses are applied to the lateral walls of the bottle, which are therefore the most susceptible to deformation, and it is therefore important to record a measurement of this (the perimeter around in this case).

Date	40g		41g		42g	
	CO_2	Circumference	CO_2	Circumference	CO_2	Circumference
Day 0	3.5	31cm	3.5	31cm	3.5	31cm
14/10/05	3.1	30.9cm	3.2	30.8cm	3.29	30.8cm
25/10/05	3.19	31.1cm	3.19	30.9cm	3.19	31.0cm
12/11/05	2.84	31.1cm	2.88	30.9cm	2.95	31.0cm
06/12/05	2.72	31.0cm	2.73	30.8cm	2.79	31.0cm
03/01/06	2.54	31.0cm	2.61	30.9cm	2.64	30.8cm

Table 3: Results of the creep test on 3 bottles of 2L

As expected, a progressive depressurization of the package is observed due to the outward flow of CO_2, but it should be noted that this depressurization is, as time goes by, less and less intense, which can be explained by the fact that there are three types of creep: the primary, which in these cases occurs in the first 3-4 days and is when the most abrupt formation occurs, the secondary, where the deformation rate tends to be constant, and the tertiary, which is not relevant in this study because it involves rupture.

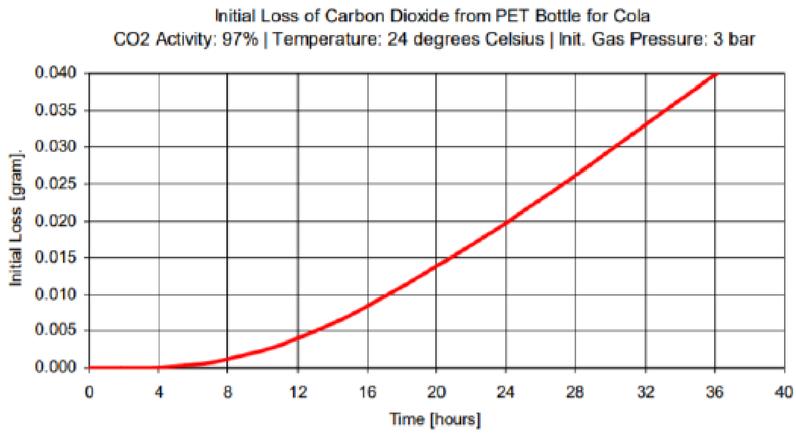

Figure 13: Initial loss of Co2 after filling a PET bottle with Coca-Cola

CO_2 losses are permissible only to a limited extent, and Coca-Cola has specific restrictions, which dictate that gas losses should not exceed approximately 25% in 6 months of shelf life for bottles of more than 1 litre capacity and 5 months for bottles of less than 1 litre capacity.

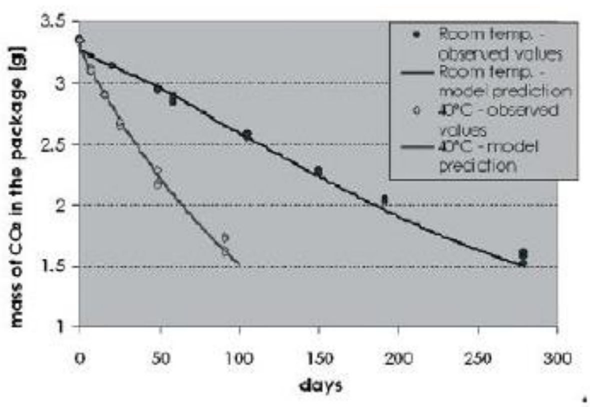

Figure 14: Representative graphic of CO2 flow in a 0,5L bottle for ambient temperature and 40ºC

Another important factor besides the time of application is the temperature to which the material is subjected, as it is a determining factor in the deformation caused by this. Creep deformation increases with the increase of the temperature of exposure, as can be deduced from the figure. In the figure, it is possible to see that, although the condition of 25% of gas loss in 5 or 6 months (150 or 180 days) is not verified, it is clearly visible that the gas loss is much higher in the case of a temperature of 40 degrees. This condition is not problematic because this type of coolant is normally kept in cool places, at the limit, in the refrigerator.

As mentioned above, creep is highly temperature-dependent, but the deformation caused by temperature is not very relevant at low temperatures (which can be found in refrigerators, for example).

RECYCLING

The post-consumer PET recycling industry has emerged in line with environmentalist pressure to reduce waste and with the fact that this polymer has a very low natural breakdown rate, as this plastic is not degradable under normal conditions.

At this stage, we distinguish PET into 3 different categories in order to monitor the contamination level: virgin PET, PET contaminated after use and recycled PET.

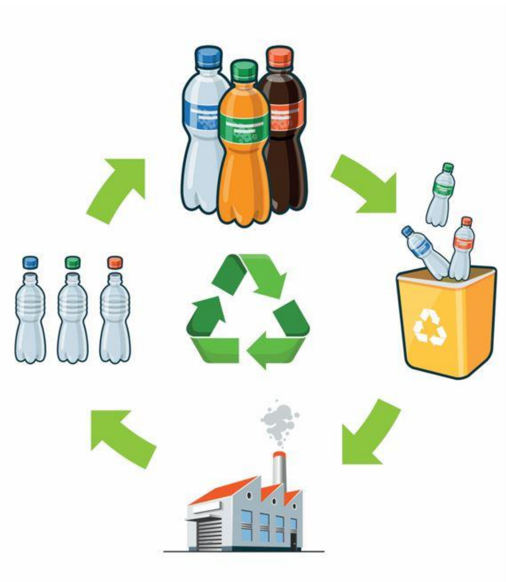

Figure 15: Recycling

Polymer recycling methods are still subject of improvement. This is because the majority of material collected for recycling is almost always deteriorated and contaminated compared to never recycled products. This is the case even though PET is an inert polymer, which results in low absorption of components in the material's first life and simplifies the assessment of the quality of these recycled products when used in the meticulous food industry. Therefore, it is essential to correct these shortcomings during this process in order to achieve the desired minimum requirements. Contamination is the biggest detrimental cause of the desired chemical and mechanical characteristics after recycling. This is where the major obstacle of PET bottle recycling lies, in the use of recycled plastic for food/beverage packaging. Speaking in statistics, 1 in 5 recycled PET bottles is not fit for food use. This explains the utility in many recycled PET products in the market, as container for cosmetics, detergents, oils for mechanical use; fibres; among others. At the end of the recycling process, there are several types of PET which differ in the level of contamination.

Firstly, it is important to remember that plastics are made of monomers and other primary substances, which react chemically, generating a macromolecular structure. To this polymer some additives can be added in order to obtain desired properties, as it has an inert structure. Given the molecular weight of this plastic (about 1,000 g/mol), it cannot be absorbed by the human body, so the health risk is very low. There will only be risk, if incomplete reactions of monomers, primary substances or low molecular weight additives incorporated in the polymeric matrix and these elements pass into the drink due to their close contact.

In any case, it is important to note that bottle-to-bottle PET recycling has been showing increasing percentages. This aspect of recycling is associated with the concept of super-clean recycling, which, as it may be guess from the name, involves more intrusive cleaning processes than conventional recycling.

Today, it is possible to find plastic products on the market that have been subjected to this type of recycling at the same price as products in their first life.

In this way, this process begins with a step arising from conventional recycling, which corresponds to the inverse of the polymerisation phase: the process of depolymerisation process.

In conventional recycling processes, cleaning is done with water, which may contain some chemical additives or detergents in low concentrations, under some pressure. As to the lids and labels, whose plastic constituent is not PET, are easily removed, in a previous phase, due to the density differences. The polymers at this stage are not yet suitable to be used in direct contact with food/beverage. In those cases where more than surface washing is required, further and more efficient purification steps are used to achieve PET 'flakes' with similar levels of contamination as virgin PET, once organic substances that had been absorbed by the polymers can be removed. The most common technologies to remove unwanted substances from polymers are the following:

- ✓ High temperature treatments;
- ✓ Vacuum treatments;
- ✓ Surface treatments with resource chemical substances.

Having said that, after the first stage common to all the processes, we are faced with PET "flakes" and it is at this stage that we distinguish 4 different ways of super-clean recycling, which are summarised below in a few topics and with the help of diagrams.

Super-clean recycling process based on "pellets"

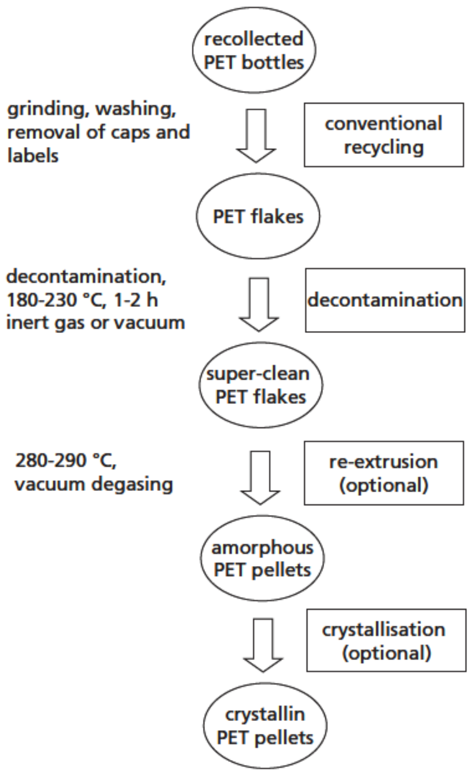

Figure 16: Super-clean recycling process based on "pellets"

In the recycling process described above, the pellets are first obtained by extrusion of the "flakes" and then they are decontaminated. In this type of recycling, the order in which these two processes take place is the other way round.

Given that the impurities are located on the surface of the pellets, the impurities have to move over shorter distances, so that the time taken to decontamination of the pellets is significantly less than in the previous one. On the other hand, a disadvantage lies in the fact that the increase in viscosity during this process is not significant.

The time dedicated to the re-extrusion process varies with the size of the pellets.

Super-clean recycling process based on the depolymerisation of the "flake" surface

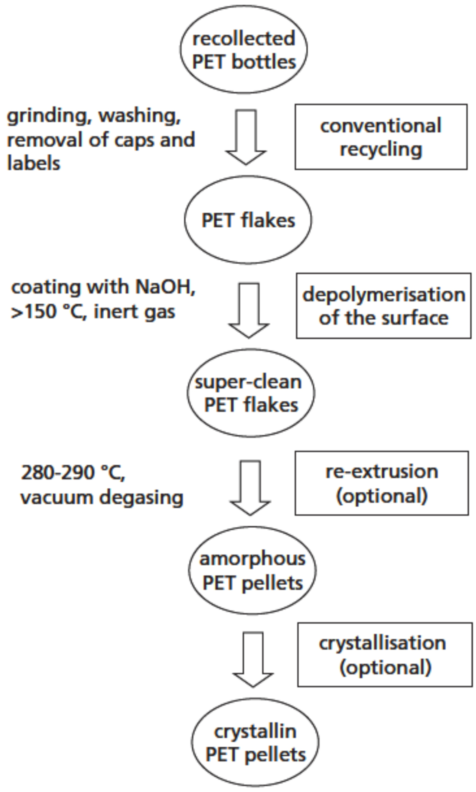

Figure 17: Super-clean recycling process based on "flakes"

Partial depolymerisation of the surface is achieved by hydrolysing the PET polymer with caustic soda. After coating the flake surface with caustic soda and removing the unit, the "flakes" are heated, and the PET polymer reacts on the flake surface. That said, the volatile reaction product ethylene glycol and post consumption contaminants are removed from the flake surface due to the high temperatures applied, while the other reaction product, sodium terephthalate, is removed after the reaction by washing the "flakes" in water and/or by neutralization of the surface.

The amount of time that PET "flakes" stay in these processes depends on the temperature and the thickness of the depolymerised surface, so no general value can be given. Therefore, decontamination processes based on partial depolymerisation processes cannot significantly increase the viscosity of PET polymer during super-clean recycling.

Super-clean recycling process based on partial depolymerisation in oligomers

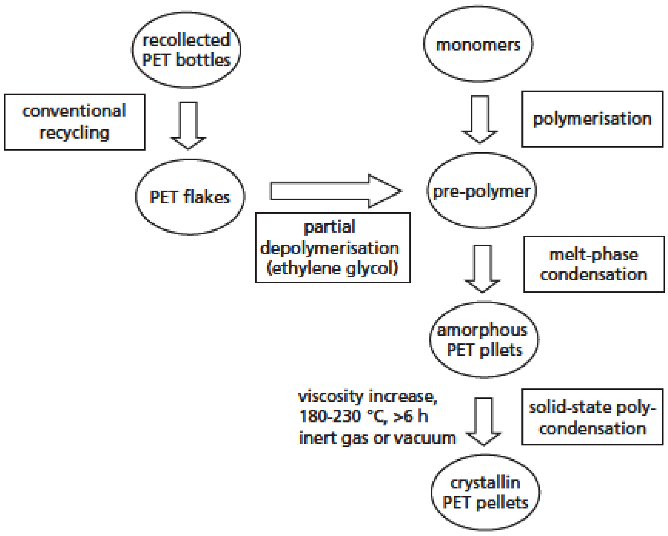

Figure 18: Super-clean recycling process based on depolymerisation of the surface of PET "flakes"

PET 'flakes' can also be recycled by another depolymerisation process, where PET "flakes" are heated together with ethylene glycol. This glycolysis reaction breaks down the ester groups giving rise to a mixture of polyester oligomers. An advantage of this process is that the production lines for virgin PET production lines can be adapted for post-consumer PET with only minor changes. Thus, using these recycling technologies, the borderline between of virgin PET and recycling companies become blurred.

Mixes of virgin and recycled PET

Some studies were carried out in order to investigate the change in properties of this mix and the optimisation of the percentages of each type of polymer to be included in the composition. This process is made through extrusion and blow moulding, as well as injection and blow moulding.

As already mentioned, after recycling PET, the plastic is in the most degraded state and there is a noticeable decrease in its viscosity. Through studies that tested various ratios of the components of this mixture, it was concluded that the mechanical properties of the virgin material are improved with the addition of recycled PET, increasing crystallinity, stiffness, strength and toughness. However, in the case of large deformations, the material is degraded with significant losses in ductility.

SUSTAINABILITY AND CHALLENGES

The priority of Coca-Cola packaging has always been to reduce weight while maintaining design and quality, to achieve maximum efficiency and minimum environmental impact, particularly when it comes to transporting the packaging, as it is a brand brand marketed all over the world. Over the past few years, Coca-Cola has managed to reduce the weight of almost all its packaging, which has led to fewer resources being used to make resources used to make them and make their transportation more efficient, making a significant reduction in its carbon footprint possible.

PlantBottle

In relation to its commitment to developing sustainable alternatives to traditional packaging, in 2009 Coca-Cola launched the PlantBottle, a bottle containing 30% plant-based materials from a by-product of sugarcane processing, which represents a completely renewable raw material. Its manufacture contributes to the reduction of waste and has a carbon footprint approximately 12% lower than other bottles. Coca-Cola's next challenge, which it is already working on, is to create a PlantBottle 100% made from renewable plant materials.

Figure 19: Plantbottle

Bottle incorporating plastic from the sea

The most recent innovation in the design of bottles was created by this company and is aligned with raising awareness of the problem of marine litter. The Coca-Cola company has launched the world's first bottle made from recycled plastic from beach and seabed cleaning, which are suitable for food use. On this context, it has already been possible to make around 300 bottles made of 25% plastic recovered from the coasts of Portugal and Spain.

This project, apart from its undoubtedly innovative character, implements a revolutionary technique of recycling, taking into account that it transforms a PET plastic that is very degraded and difficult to recycle, into high quality raw material, suitable to be used in the food industry, which implies quite demanding requirements, as we know. In this way, we are moving towards the intended aim of reducing waste on the largest possible scale and, although it represents a small step at this moment, it has the potential to trigger major implications in the future.

Figure 20: Bottle recycled from plastic collected from the sea

Figure 21: Bottle recycled from plastic collected from the sea

Concrete and cement reinforced with PET fibres

Another aspect that we consider relevant to highlight when approaching the recycling and sustainability of PET is the versatility of the ways of using the fibres formed in the recycling, when the state of the polymer does not allow a bottle-to-bottle recycling. That said, a method is presented, in which small, recycled PET fibres are used as structural reinforcement for cement and concrete, as a way to improve the performance of the material and, therefore, of its structure.

Cement is the most widely used construction material worldwide, thanks to its high resistance value to compressive forces, its low cost and its long-estimated lifetime. However, it has some drawbacks such as its low resistance to tensile forces, low ductility, as well as the fact that it easily cracks and its low energy absorption. These disadvantages associated to its use are drastically improved with the use of recycled plastic fibres, which has been proven using several experimental procedures. On the other hand, I would like to point out that with the increase in the percentage of fibres, ductility, and energy absorption capacity decrease. With the addition of these fibres, the formation of visible cracks and shrinkage due to drying.

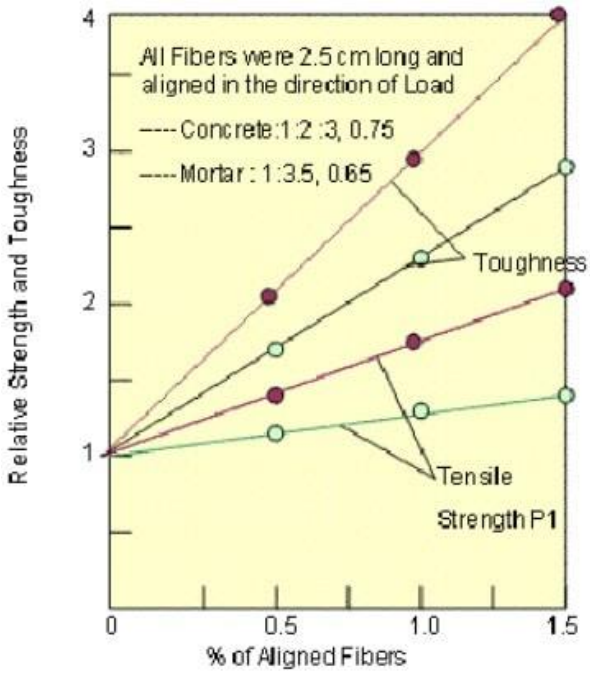

Figure 22: Effect of the percentage of fibres incorporated in the cement matrix

Figure 23: Effect of the percentage of fibres incorporated in the cement matrix

CONCLUSIONS

In recent decades, the bottle-to-bottle recycling capacity has increased significantly, such that today super-clean recycling has already been established worldwide and, especially in Europe, already makes up a reasonable fraction in the economy of this industry. This development has been fostered by stipulated legislations; however, it is not merely for this reason nor the similarity of the cost of this product compared to virgin PET that continues to promote the growth of this type of recycling. A force that greatly influences this growth is driven by the ethics of sustainability, which represents an issue with increasing importance in politics and economics, as well as society's concern with the environmental issue. This is reflected in the increase number of bottles collected each year.

With a view to the competitiveness of this market, it is important to point out that this type of plastic recycling for the same function that the material had in its first life saves over 31 thousand tons of oil and also reduces carbon dioxide emissions by around 70% when compared to the use of virgin PET.

In parallel, all the other uses of recycled PET, outside the bottle-to-bottle concept, such as, for example, the case of concrete and cement reinforced polymer fibres are excellent incentives for further progress in plastics recycling.

On the other hand, with an eye to the future, the issue of the environmental impact environmental impact of the recycling industry. As this term is associated with a clean method, many times, as we are already being "environmentally friendly issues associated with the industrialisation of these procedures are forgotten.

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