BACHELOR FINAL PROJECT

Degree in Mechanical Engineering

DESIGN AND MANUFACTURING OF A RACEWAY POND REACTOR THROUGH FFF PROCESS

Memòria i Annexos

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RESUM

El present treball pretén estudiar el disseny i la fabricació d'un "Raceway Pond Reactor" (RPR) mitjançant la tecnologia FFF (Fused Filament Fabriation), una de les tecnologies que engloba la fabricació aditiva (AM), més conuguda com a impressió 3D.

Per tal de fer possible aquest estudi, s'han hagut de dissenyar i fabricar (mitjançant impressió 3D) petits models a escala del disseny original del RPR, de manera que sigui possible realitzar assajos preliminars. El fet de reduïr les dimensions del model original del RPR, ha permès reproduïr diversos prototips, els quals han estat estudiats per tal d'investigar els diferents materials proposats i els paràmetres d'impressió més adequats per a la fabricació.

En un inici, s'han considerat tres possibles materials, els quals són molt comuns en impressió 3D: Acrylonitrile butadiene styrene (ABS), Timberfill i Polylactic acid (PLA). Els rajos ultraviolats del sol han provocat que l'ABS sigui el primer material descartat, degut a la seva baixa resistència radiativa. D'altra banda, el Timberfill ha hagut de ser estudiat i comparat amb el PLA (mitjançant els models a escala del RPR) per a poder elegir, finalment, el material amb millor comportament mecànic i químic: el PLA.

RESUMEN

El presente proyecto pretende estudiar el diseño y la fabricación de un "Raceway Pond Reactor" (RPR) mediante la tecnología FFF (Fused Filament Fabrication), una de las tecnologías englobadas por la fabricación aditiva (AM), comúnmente conocida como impresión 3D.

Para la posible realización del estudio en cuestión, se ha debido de diseñar y diseñar (mediante la impresión 3D) pequeños modelos a escala del diseño original del RPR, de manera que se posibilite la realización de ensayos preliminares. El hecho de reducir las dimensiones del RPR, ha permitido reproducir varios prototipos los cuales han sido objeto de estudio para la investigación de los diferentes posibles materiales y de los parámetros de impresión más adecuados.

En un inicio, se han considerado tres posibles materiales, los tres muy comunes y usados en impresión 3D: Acrylonitrile butadiene styrene (ABS), Timberfill y Polylactic acid (PLA). Los rayos solares ultraviolados han perjudicado al ABS, hecho que ha permitido rechazar al ABS como materia prima del RPR. Por otra parte, el Timberfill ha tenido que ser estudiado y comparado con el comportamiento del PLA (usando los modelos a escala del RPR) para poder elegir el material con mejor comportamiento químico y mecánico: el PLA.

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ABSTRACT

This project intends to study the design and fabrication of a Raceway Pond Reactor (RPR) through Fused Filament Fabrication (FFF) process, one of the additive manufacturing (AM) technology, more commonly known as 3D printing.

For being able to realize this work, small scale of the practical dimensions the RPR has been designed and manufactured to execute preliminary tests. This reduction of dimensions has allowed to reproduce various prototypes, which has been studied in order to investigate the best material and the effect of various manufacturing parameters in the mechanical behaviour.

In principle three most common materials have been considered: Acrylonitrile butadiene styrene (ABS), Timberfill and Polylactic acid (PLA). Due to the low resistance against the UV radiation ABS was eliminated in the first step. However, Timberfill was rejected after the study and comparison of its chemical and mechanical behaviour against PLA. Consequently, the most adequate material accepted for this project is PLA.

ACKNOWLEDGEMENTS

The development of this project has been a challenging task that would not have been possible without all the help and support received from all people who has shown interest in this work.

Firstly, I would like to thank Mr. Travieso, for giving me the opportunity of being part of this project. As a future mechanical engineer, I am grateful for the election of this work which I could have got into design field, as I could also have gone deeper in areas such as 3D printing.

Big thanks to Mr. Damous, for being the person who has guided me in all this process. Since the very first day Mr. Damous has been always at hand for any requirement I have had. Thanks for all the time spent on me.

Finally, I do not want to forget to appreciate all the support received from my people, especially my family, who has shown a great confidence in me all these years. They never stop trusting me.

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GLOSSARY

- **ABS:** Acrylonitrile Butadiene Styrene
- **AM:** Additive manufacturing
- **CAD:** Computer-aided Design
- **FDM:** Fused Deposition Material
- **FEA:** Finite Elements Analysis
- **FEM:** Finite Elements Method
- **FFF:** Fused Filament Fabrication
- **LOM:** Laminated Object Manufacturing
- **PLA:** Polylactic Acid
- **RPR:** Raceway Pond Reactor
- **SGC:** Solid Ground Curing
- **SLA:** Stereolithography
- **SLS:** Selective Laser Sintering
- **TOC:** Total Organic Carbon
- **TPs:** Transformation Products
- **UV:** Ultraviolet

ÍNDEX

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CHAPTER 1. Introduction

This project deals with the manufacturing of a Raceway Pond Reactor, starting to design and continuing with fabrication using different printing conditions through FFF technology to achieve a functional sample from the mechanical and chemical point of view.

1.1. Motivation

Recently, additive manufacturing has experienced an increase of its usage. It can be said that a great number of companies have interest in this new manufacturing method. Characteristics such as the lower environmental impact, freedom of design or low-cost production are some few examples of the advantages it has over the traditional techniques.

In one side, as the capabilities of the AM have increased into our society, this project is a great opportunity as a future engineer to demonstrate the skills learned during these years in the degree and to continue learning. In the other side, this project has some main work areas that I am really interested in. The design or the manufacturing methods are some examples of them.

1.2. Objective

As mentioned above, the main objective of this project is the fabrication of RPR through FFF process based on a previous design. So, the different objectives of this work are presented below:

1. To select the most adequate material based on its capabilities
2. To study the effect of different printing parameters
3. Mechanical properties of PLA in the RPR
4. Chemical properties of selected material
5. Select the dimensions of RPR
6. Study the mechanical strength through Finite elements Method (FEM)

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1.3. Structure and content of the project

This work is divided into various parts, with the main objective of stablish a well-structured document. This part is the introductive one, which the overall goals of the project and motivations have been defined.

State of the art is the second chapter, which includes a general explanation of Additive Manufacturing (AM) technology and a definition of Fused Filament Fabrication (FFF) process in detail including printing parameters, used in this project. In addition, there are also presented the principal polymers that are candidates for being the raw material of the Raceway Pond Reactor (RPR). Subsequently, the possible behaviours of materials are presented that can be taken into account from the mechanical and chemical point of view.

The third chapter is the one responsible for the methodology used in this work and the results obtained. In methodology section, order of process and the problems solved in order to obtain valuable results, are described. Finally, in the results part, is showed the final resolution after a comparison between the applicable materials are indicated.

In the conclusion chapter, the objectives of the work and the scientific contributions achieved as a result of the research are explained.

CHAPTER 2. STATE OF THE ART

2.1. Additive Manufacturing

Additive Manufacturing (AM) is a construction technique where a three-dimensional object is created through the build-up of thin layers of a base material. Some recent advances have resulted in the commercialization and popularization of what is commonly known as 3D printing (3DP). Terry Wohlers (industry consultant specialized in AM), tells us in the *History of Additive Manufacturing*[1] "The first attempt to create solid objects using photopolymers using a laser took place in the late 1960s at Battelle Memorial Institute. The experiment involved intersecting two laser beams of differing wave length in the middle of a vat of resin, attempting to polymerize (solidify) the material at the point of intersection." Anyways, it was only an attempt.

Development of additive manufacturing, as a new technology, began ten years later in the late 1970s with the grant of a patent to Wyn Kelly Swainson for a process where a three-dimensional object is created through the build-up of photopolymer material [2]. A computer-controlled laser is used to solidify a liquid puddle of plastic monomer [3]. This method is in continued use today and has become known as the Laser Sintering process. One of the main disadvantages of this process, which slowed the technologies main-stream acceptance and popularity, is cost, as very expensive laser equipment is required in each printer.

We had to wait until 1987 to see the first 3D printer placed on the market. It was a stereolithography (SLA) machine from 3D Systems [1]. Four years later, in 1991, three AM technologies were already commercialized. Then, on the part of the companies, it started a rush for developing these new techniques: including fused deposition modelling (FDM), solid ground curing (SGC) and laminated object manufacturing (LOM).

Nowadays, additive manufacturing (AM) is becoming an essential tool for so many businesses, which consist of some different technologies, most commonly known as 3D printing. Every of these methods works on a different way of the other, so this is one of the reasons of getting different results, as it can be the election of the materials.

These techniques have a common process to take forward their purpose. Firstly, is needed a 3D design created by a CAD (Computer-aided design) tool. Then, this CAD model is sliced horizontally (usually with the help of the same CAD software), creating thin layers used by another software that is going to read and prepare the parameters to print the object sequentially by sections, one on top of the other, to form a 3D object.

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In contrast, traditional subtractive manufacturing process uses the removal of material from a stock piece of base substrate to create a component. Computer controlled subtractive processes include single and multi-axis CNC machines, lathes, laser and water jet cutting tables. While a variety of three-dimensional shapes can be created through subtractive process the technology suffers from the drawback as material is removed at all locations where the tool patch insects the component. Certain hollow and shell components cannot be made through subtractive means. For an additive process a deposition path can be generated such that the extruder does not pass through the same point in space more than once and thus hollows and shells are easily created.

The most commonly AM technologies are: stereolithography (SLA), selective laser sintering (SLS) and fused filament fabrication (FFF).

2.2. Fused Filament Fabrication (FFF)

FFF technology is the most common used technology in 3D printing. This AM technology is easy to use, and the cost of production and equipment is very low. This is one of the reasons why lots of industries are establishing such a technology in their production departments. Also, individual persons have seen its advantages of building some pieces they need on their own.

The printing process consists on a filament of material that is extruded through a heated nozzle, fusing the material and depositing it onto a build plate. This melted filament is meant to cool and solidify to form the first layer of the CAD model. The next steps are almost the same, the process is repeated but this time the nozzle must put the fused filament onto the last layer printed. After that sequence is finished, and the printed model has been correctly cooled, it is time to make the finishing touches, such as refine the material, painting or joining the pieces. This last step is necessary for those objects whose dimensions are bigger than the limits allowed by the printer. It is solved by dividing the CAD model in different parts to be able to print them one by one, and then join all pieces to create the definitive object/product.

As FFF is an available technology, there have been lots of innovations last years. Nowadays there are a large number of FFF printers in the market. For instance, some companies have developed printers that are able to work using two or more different materials. For the same reason, they are able to print with different colours at the time. This is possible due to the installation of more than only one roller of building material (Figure 1).
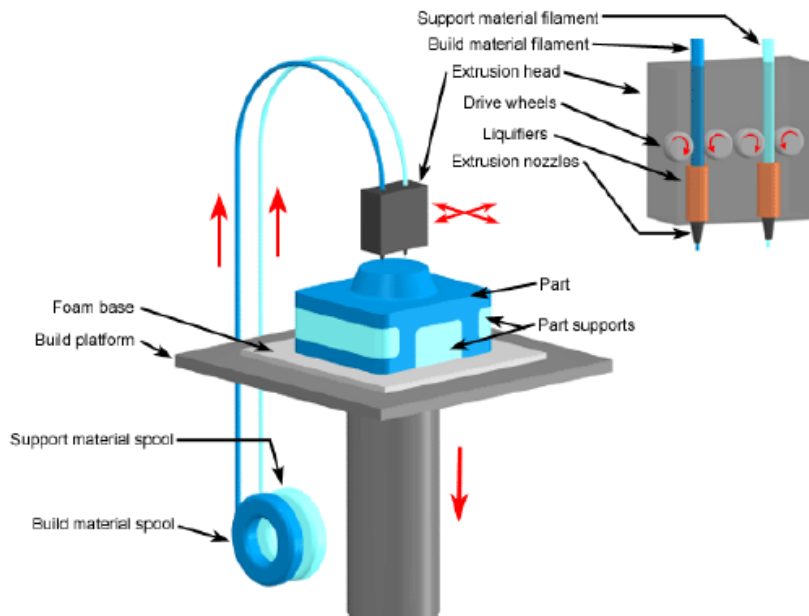
Figure 1. FFF process scheme [4]

2.2.1. Parameters

The manufacturing parameters of the objects manufactured through FFF technology have an important weight on how these pieces behave mechanically. This is because the printers depose the material in a directional manner, that affects the anisotropic behaviour. The most important printing parameters to consider are: the layer high, the Nozzle Diameter, the Orientation, the Fill Density or the infill pattern; albeit there are others of less importance like the Printing Velocity.
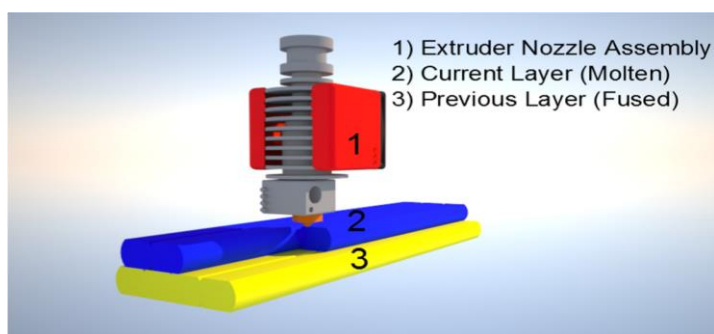

Figure 2: Layers extruded in FFF [5]

Layer high is one of the most influent parameters in the mechanical behaviour. While printing is happening, the difference of temperature between layers is substantial, thus producing a weak union due to the distortion. As the high of layer increase, less layers will be needed to manufacture the same

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dimension. This causes an increment of the tensile resistance (22% between 0.3 mm and 0.2 mm) and a decrease of the distortion. Also, the elastic modulus is altered, but only with 6% between 0.4 mm and 0.2 mm of layer high. [6] In addition, layer high has the most significant impact on fatigue life for PLA so as the layer high increases, longest will be the fatigue life due to its number of cycles. [7]
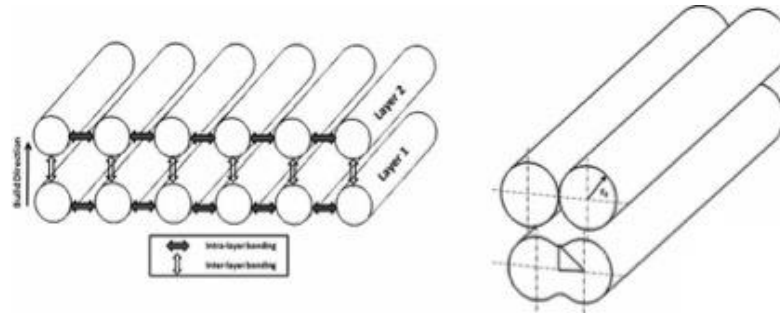

Figure 3: Clarifying layer height

The nozzle diameter is also an influent parameter which determines the width of the filament extruded. The size of the diameter, combined with the orientation, has a great effect in the tensile resistance. The filament size is also relevant to infill strategies, fill patterns such as (rectilinear, honeycomb, Hilbert curve, triangular, etc.) shown in (Figure 4: Some of the existing fill patterns (Figure 4), and fill density. This last parameter defines the solidity of the manufactured piece by a percentage (Figure 5).
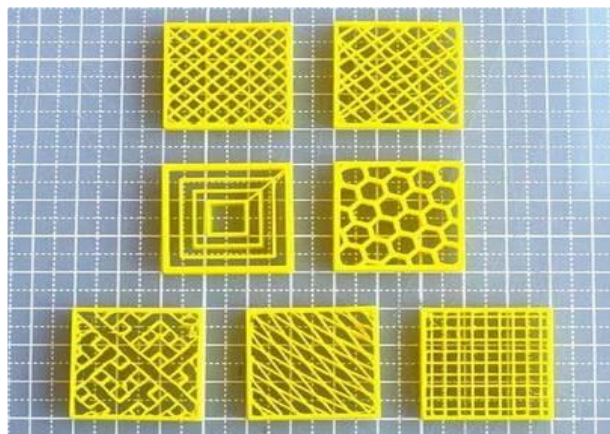

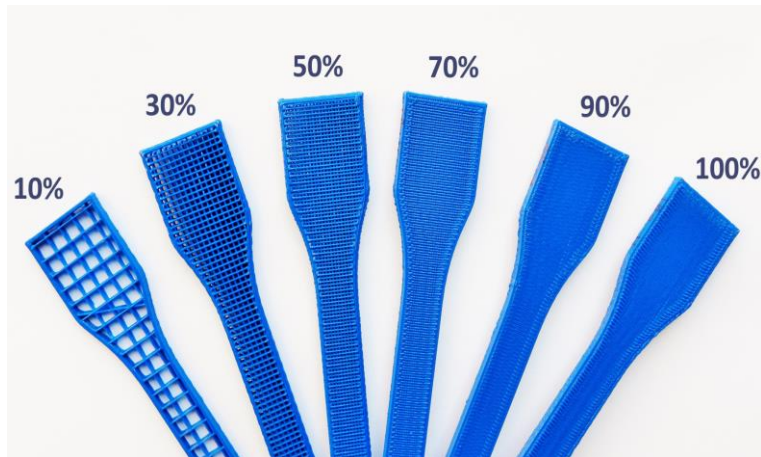*Figure 4: Some of the existing fill patterns*

Figure 5: Visual representation of the percentage of fill density

The orientation or the manufacturing direction determines how the layers are deposited in relation to the origin in the FFF machines (Figure 6).This orientation of layers has a very important influence on the mechanical behaviour, especially on ruptures by compression or traction loads.
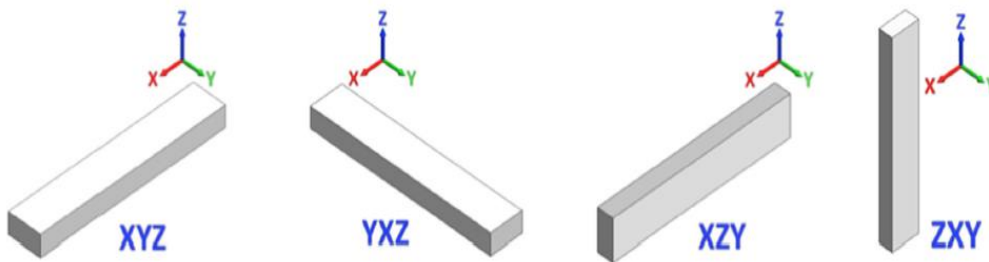

Figure 6: Orientation according to origin of FFF printers [8]

Another important parameter is the feed rate (printing speed). On one hand, increasing linear velocity also leads to an increase in the volumetric printing speed. Thus, when printing speed is increased, the resistance to extrusion also increases, which, obviously, will adversely affect the part mass. On the other hand, the higher the printing speed, the sooner the next layer is printed and the less the sublayer cools before the new layer is deposited. In this sense, increasing the printing speed can have a similar effect to decreasing cooling intensity and, thus, it will contribute to an increase in the cohesive strength between the layers. [9] In consequence, it should be necessary to achieve an appropriate between both extremes for being able to reach the better result.

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2.3. Raceway Pond Reactor

Water scarcity and its problem makes wastewater treatment an effective way to address water shortage issue. According to UN-Water 2015, It is estimated that 44% of global freshwater withdrawals has been consumed, mainly by agriculture, and the rest of 56% in the form of municipal and industrial effluent and agricultural drainage water has been released into the environment as wastewater. On average, 70% of the wastewater in developed countries is treated, while that ratio drops to 38% in upper middle-income countries and to 28% in developing countries [10]. Consequently, it is predicted that over 80% of wastewater without sufficient treatment should be taken into account as a potential water resource globally [11].

For efficient water reuse, the traditional treatment methods such as secondary biodegradation cannot appreciably remove many of water contaminants of emerging concern [12]. On the other hand, micro pollutants, their potential accumulation, and the undesired effects of very low concentrations, pose a serious challenge in regard of closing water loops [13]. In recent years, advanced oxidation processes (AOPs) using hydroxyl radicals and other oxidative radical species are being extensively studied as a solution for the removal of organic compounds from various waste streams. However, large scale applications of these highly effective technologies in water and wastewater treatment are still very limited due to cost and inadequate information about the resultant water quality. One of the most successful AOPs in terms of effective micro pollutants degradation is the Photo-Fenton process [14] Nevertheless, the application of AOPs at commercial scale is limited due to high cost. Using solar light is an effective way to reduce the operating costs in the case of the photo-Fenton process [15]. In this regard, several systems such as thin Film Fixed Bed Reactor (TFFBR), Double Skin Sheet Reactor (DSSR), shallow pond configurations and flat-plate reactors have been studied for micro pollutant removal [15].

In terms of designing photo reactors simpler and less costly, raceway pond reactors (RPRs) have been widely used as extensive photo reactors in microalgae mass culture [16]. The main advantages of raceway pond reactors are low power requirements for pumping water ($4W.m^{-3}$), varying liquid depth, adaptability to yearly seasons their flexibility, easy scale-up and solar irradiance variation [17]. Likewise, the advantage of RPRs such as Effective, extensive and low-cost (per surface unit) photo reactors may spread the use of the photo-Fenton process as tertiary treatment [15]. Current advances in chemical engineering are often linked to the concept of process intensification, which aims to manufacture chemical products in a more sustainable and efficient way. One focus area is to introduce innovative principles in the equipment design leading to improvements in process efficiency. In this regard, using 3D printing and computational modelling is increasing as digital tools for the design and fabrication of reactors and cost reduction [18]. On the other hand, there is a wide range of 3D printing materials with

their own features, strengths and weaknesses for improving the thermal properties and durability life of the solar reactors. Regardless of specific goal, it is hard to choose the most suitable material. Most of the commercial 3D printing devices are used with ABS (Acrylonitrile Butadiene Styrene) or PLA (Polylactic acid) thermoplastic materials because of their capability to use. Other material options include polycarbonate, polyamide, high-impact polystyrene, polyetherimide, polyoxymethylene, polyphenylsulfone and others [19]. Recently, further work has studied Timberfill that is made of biodegradable material based on wood. This material exhibits similar mechanical features as ABS or PLA and models printed with this material have a genuine appearance of wood.

In this work, the low cost and practical design of the raceway ponds was studied through 3D printing based on the three materials including PLA, ABS, and Timberfill from both chemical and mechanical point of views.

In resume, [20] Raceway ponds Reactors (RPRs) are an efficient technology to remove micropollutants by photo-Fenton. This system consists of a rectangular basin where the water flow is maintained by a paddlewheel system, which allows large volumes of water to be treated.
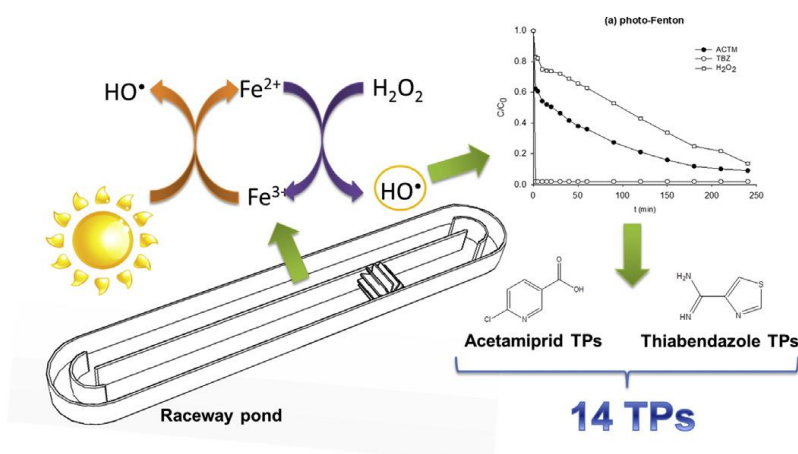

Figure 7. RPR scheme [21]

2.4. Materials

Nowadays, we have a great variety of materials that could be used in additive manufacturing. Some of these materials can be identified amongst thermoplastics, photopolymers, metal powder or inkjet powder. However, the most used materials in these technologies are thermoplastics, even more in FFF process due to its properties. These polymers have an important presence in the market, and they have a great user accessibility. But there are lots of polymeric materials available and every one of

them have different qualities and behaviours, so it is necessary to have a previous knowledge about them to be able to choose the right one for every manufactured piece.

Some of the polymers available from machine manufacturers are Acrylonitrile Butadiene Styrene (ABS), Polylactide Acid (PLA), Timberfill, polycarbonate (PC), Nylon, Polyether Ether Ketone (PEEK) or Polyetherimide (PEI). But in this work, only the first three materials (ABS, timberfill and PLA) has been considered.

2.4.1.   Acrylonitrile Butadiene Styrene (ABS)

Acrylonitrile Butadiene Styrene (ABS) is a common thermoplastic polymer typically used for injection moulding applications. This engineering plastic is popular due to its low production cost and the ease with the material is machined by plastic manufacturers. [22]

It must be said which are the main properties and where are found. Its rigidity, chemical attack and the excellent high and low temperature performance are provided by the Acrylonitrile. Other properties such the tenacity to temperature or its impact resistance are associated to Butadiene. Finally, the mechanical strength, rigidity, gloss and hardness are Styrene's responsibility. These properties are possible through the initial creation process. "By polymerizing styrene and acrylonitrile in the presence of polybutadiene, chemical "chains" attract each other and bind together to make ABS stronger". So, this material has its hardness, gloss, toughness and resistance properties more developed than without this combination of materials (only pure polystyrene).

Therefore, ABS is a very strong material, widely used in the automotive industry and in products such as LEGO bricks, small kitchen appliances, keyboard keycaps, or musical instruments. There is attached the technical information indicated in (Figure 8).

Physical properties	Typical Value	Test Method	Test Condition
Material density	1,04 g/cm³	ISO 1183	23 ˚C
Melt volume index	29 cm³/10 min	ISO 1133	220 ˚C, 10 kg
Diameter tolerance	± 0,05 mm		
Weight	750 g of filament (+ 250 g spool)		

Mechanical properties	Typical Value	Test Method	Test Condition
Tensile strength	39 MPa	ISO 527	at yield, 50 mm/min
	32 MPa	ISO 527	at break, 50 mm/min
Elongation at break	20 %	ISO 527	50 mm/min
Flexural strength	60 MPa	ISO 178	2 mm/min
Flexural modulus	1900 MPa	ISO 178	2 mm/min
Izod impact strength	24 kJ/m²	ISO 180-1A	23 ˚C, notched
	10 kJ/m²	ISO 180-1A	-30 ˚C, notched
Charpy impact strength	25 kJ/m²	ISO 179	23 ˚C, notched
	11 kJ/m²	ISO 179	-30 ˚C, notched

Thermal properties	Typical Value	Test Method	Test Condition
Heat deflection temperature	81 ˚C	ISO 75-A	1,8 MPa
Vicat softening temperature	103 ˚C	ISO 306	50 ˚C/h, 1 kg
	96 ˚C	ISO 306	50 ˚C/h, 5 kg
Coefficient of linear thermal expansion	$9,0 \times 10^{-5}$	ISO 11359	

Printing properties	Typical Value	Test Method	Test Condition
Print temperature	220-240 ˚C		
Hot pad	80-100 ˚C		

Figure 8: technical datasheet of ABS material

2.4.2. Timberfill

It is made of biodegradable material based on wood. The material exhibits similar mechanical features as ABS or PLA and models printed with this material have a genuine appearance of wood.

Wood filaments combine a PLA base material with cork, wood dust, or other derivates, giving the models a real wooden look and feel. The technical information is provided in (Figure 9) by the manufacturer.

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Physical properties	Typical Value	Test Method	Test Condition
Material density	1,26 g/cm³		20 ˚C
Melt volume index	25 cm³/10 min	ISO 1133	190 ˚C, 2,16 kg
Diameter tolerance	± 0,10 mm		
Weight	750 g of filament (+ 250 g spool)		

Mechanical properties	Typical Value	Test Method	Test Condition
Tensile strength	39 MPa	ISO 527	at break, 5 mm/min
Elongation at break	2 %	ISO 527	5 mm/min
Tensile modulus	3200 MPa	ISO 527	1 mm/min
Charpy impact strength	22 kJ/m²	ISO 179/1eU	23 ˚C, unnotched
Hardness	77 Shore D	ISO 7619	

Thermal properties	Typical Value	Test Method	Test Condition
Melting temperature	145-160 ˚C		
Heat distortion temperature	48 ˚C	ISO 75	method B, 0,45 MPa

Printing properties	Typical Value	Test Method	Test Condition
Print temperature	170-185 ˚C		
Hot pad	40-50 ˚C		

Figure 9: Technical datasheet of Timberfill material

2.4.3. Polylactic Acid (PLA)

Polylactic Acid (PLA) is a thermoplastic polymer but with a great characteristic, it is derived from a renewable resource. Instead of other plastics derived from oil or natural gas (fossil resources that will run out), PLA is derived from corn starch, wheat, potatoes or sugar cane, resources that are renewed every year and hence biodegradable. For this reason and also because it is not expensive at all, Polylactic Acid is one of the most used materials in FFF technology.

This material can be used in 3D printers easily. It allows a high quality of printing even in tricky details and an excellent lamination of the printed object. The main properties of PLA are variable depending on the colours, but some technical information is attached based on manufacturer datasheet (Figure 10).

Physical properties	Typical Value	Test Method	Test Condition
Material density	1,24 g/cm³	ASTM D792	
Melt flow index	6 g/10 min	ASTM D1238	210 °C, 2,16 kg
Diameter tolerance	± 0,05 mm		
Weight	750 g of filament (+ 250 g spool)		

Mechanical properties	Typical Value	Test Method	Test Condition
Tensile strength	53 MPa	ASTM D882	
Elongation at break	6 %	ASTM D882	
Tensile modulus	3600 MPa	ASTM D882	
Flexural strength	83 MPa	ASTM D790	
Flexural modulus	3800 MPa	ASTM D790	
Izod impact strength	16 J/m	ASTM D256	23 °C, notched

Thermal properties	Typical Value	Test Method	Test Condition
Glass transition temperature	55-60 °C	ASTM D3418	
Heat distortion temperature	55 °C	ASTM E2092	0,45 MPa

Printing properties	Typical Value	Test Method	Test Condition
Print temperature	190-210 °C		
Hot pad	40-50 °C		

Figure 10: Technical datasheet of PLA material

2.5. Mechanical behaviour

This chapter tries to define the impact of different factors, such as the temperature or the chemical nature, on the polymers properties, and how the material structure is affected in the final result. The principal issue in AM technologies is that most of the materials used are polymers, which is why it is difficult to classify their mechanical behaviour field. But it must be said that in this work the problem is widely reduced because FFF technology only uses thermoplastics polymers, and the wide range of polymers drops significantly. However, the mechanical properties can differ greatly from other polymers of the same type.

The parts printed through Fused Filament Fabrication (FFF) technology, show a non-isotropic mechanical behaviour. This means that their properties are not the same, they change depending on their fibre direction. The union between layers and the union between threads of the same layers, are the principal factors that affect the behaviour of the printing parts.

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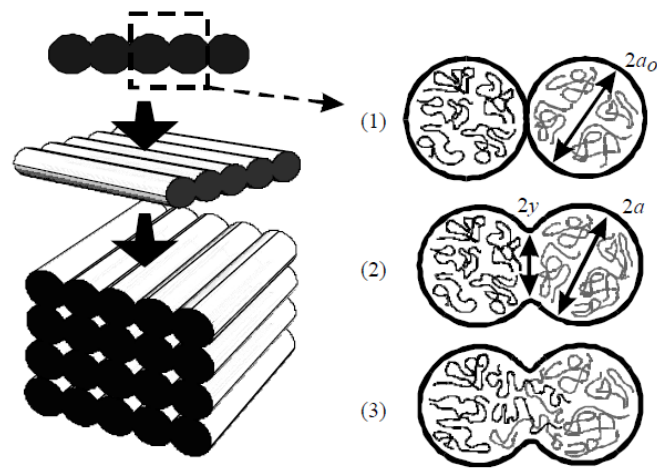BARCELONATECH
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Figure 11. Bond formation process between two filaments: (1) surface contacting; (2) neck growth; (3) molecular diffusion at interface and randomization [23]

The union forces are the ones that formed a rigid structure and depending on how much contact between threads there is, the mechanical behaviour of the piece (in a structural view) will be different. Thus, the most influential parameters are those which can affect these union forces. For instance, the layer high controls the accumulation of layers in the Z axis direction; the fill pattern controls the contact between threads; and the nozzle diameter is a parameter that has the power to control both: the unions between layers but also the unions between threads.

In FFF technology, the layers are printed over the fabrication platform, one layer on top of the other, following the parameters and instructions established with the help of a specific software that has done the slicer's divisions. In this work, *Simplify 3D* has been the software used, a fantastic tool that has a wide range of possibilities to modify parameters or define the best trajectories. However, there is not any software that has the capacity to indicate the mechanical behaviour of a printed part, they only give us the tools to modify it, with our knowledge about the field.

But not all the unions have the same importance. According to some previously done studies, it has been verified that the union between layers is weaker than the union between threads of a same layer. This occurs because of the temperature. When the printer is extruding a layer, the contact between the threads of the same slice is well formed thanks to the similitude of the temperatures, it has not had enough time to cool. On the other hand, when a new layer is about to be extruded, the previous layer is not as hot as it should be to create a solid union, because it has had time to cool down.

In resume, the mechanical properties of the pieces printed by FFF technology are influenced by the thread's union force, and the most resistance unions are the ones between threads of the same layer. For this reason, it is important to orientate the printing object in a perpendicular manufacturing

direction to the one of the forces that are acting on it. This is meant to be more resistant, because the threads aligned in the same direction of the force will act as support fibres.

2.5.1. Tensile and flexural strength

The mechanical properties of lactic acid-based polymers can be varied to a large extent ranging from soft and elastic plastics to stiff and high strength materials. Semicrystalline PLA is preferred over the amorphous polymer when higher mechanical properties are desired. Semicrystalline PLA has an approximate tensile modulus of 3 GPa, tensile strength of 50–70 MPa, flexural modulus of 5 GPa, flexural strength of 100 MPa, and an elongation at break of about 4%.

In materials engineering, the resistance to deformation (Yield Strength) and the resistance to traction (Tensile Strength) are two properties that can be used to characterize a material. The difference between the Yield Strength and the Tensile Strength is that the resistance to deformation is the minimal under which a material deforms plastically (permanently), while that the resistance to traction describes the maximum tension that a material can suffer before breaking, meaning when the opposition that the molecules of the material make isn't enough and the material breaks.

2.6. Selected printing condition

Firstly, when it is decided to print some piece, we must choose the most adequate printing parameters, depending on which result we have planned for the object that is about to be fabricated. So, in order to begin testing with RPR samples (with a reduced scale), the printing parameters adopted to begin with, are the following (Table 1).

- Temperature of the extruder: it is the melting temperature of the material (filament). The recommendation of the manufacturer is working between 190 ºC and 210 °C; we have used the average: **200 ° C.**
- Bed temperature: it is the temperature of the table where the part is deposited while printing; we have used **60 ° C.**
- Perimeters: they are the number of threads you want to deposit in the outline; we have used **2 perimeters.**
- Solid layer Shell: they are the amount of top and bottom layers that make a special infill to make satisfactory contour; we have used **2 layers**.
- Fill pattern: it is the pattern of drawing of filling each layer that uses the machine; we have used **rectilinear.**
- Layer height: it is the distance between layers or the z axis displacement in order to start a new layer; we have used **0.3 mm.**

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- Nozzle diameter: it is the thickness of the thread; we have used **0.4 mm.**
- Fill density: it is percentage of filler that will use the infill; we have used **75%.**
- Velocity (feed rate): it is the speed of manufacture both the perimeter and the fill; we have used 30 **mm / s, (or 1800 mm/min).**
    - It must be said that while the first layer of the object is being printed, the feed rate is not working as always; the velocity is reduced to a 90% of its selected value, in order to ensure a better start.

Layer high	0.3 mm
Nozzle diameter	0.4 mm
Number of Perimeters	2
Solid Layer Shell	2 layers
Fill density	75%
Fill pattern	Rectilinear
Temperature of the extruder	200 ºC
Bed temperature	60 ºC
Feed rate (velocity)	30 mm/s

Table 1. Printing conditions

CHAPTER 3. METHODOLOGY

As mentioned above, this project has considered three raw materials with a great capability of its use in FFF technology. These materials are ABS, Timberfill and PLA, polymers that apart from being very used in FFF, they are quite affordable. The methodology used in this work in order to obtain a good design, with the rightful material, and the best printing conditions is the following.

3.1. Selection of materials

Once the three possible materials have been presented, it is necessary to select the most adequate for the project. This material should be chemically strong because of its durability. Raceway Pond Reactors are usually installed at the exterior, so they must support the UV rays of the sun. Also, they are in permanent contact with water and its micropollutants. Furthermore, the material selected must be strong enough to resist the pressure and weight of the water, so the mechanical behaviour is another aspect that should be considered.

In order to see the material that resist better against the UV radiation, some pieces of each material have been tested. In this step, PLA and Timberfill were shown reasonable characteristics to continue, but ABS was rejected due to its weakness against the UV radiation. For this reason, ABS must be removed as a possible candidate. So, to do the subsequent analyses of raw materials, PLA and Timberfill are left to make the final decision.

This decision between the two candidates, must be validated by the chemical group, that realizes tests on the materials. Thus, to obtain more reliable data, a design of small-scaled RPR is done (Annex A).

3.2. Sample manufacture

First of all, it has been decided to test the materials and see how they work. For being able to do this test, it has been designed a small model of the RPR. Thus, if some problems appear, new samples can be printed, in order to change characteristics or printing parameters, without wasting a significant amount of raw material. Also, the samples printed from this small-scale model can be easily manipulated.

Only two materials have been used for printing the samples: PLA and Timberfill. ABS has been eliminated because of the bad behaviour it has in front of the UV radiation. It should be mentioned that Timberfill samples have been manufactured using a PYRAMID 3D Studio printer (Figure 12). This

machine is very easy to use, and it can be assembled and installed by their users. So, it is an easy device to obtain 3D pieces.
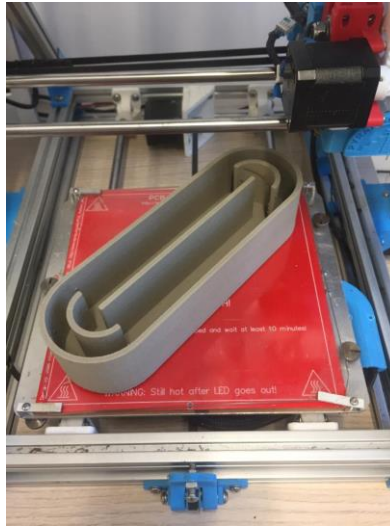
Figure 12. Timberfill sample, printed by Pyramid 3D printer

On the other hand, PLA samples have been created by a Sigma printer (Figure 13) (BCN3D company). Sigma printer presents better and most accurate results, because it is a robust machine designed for professional results.
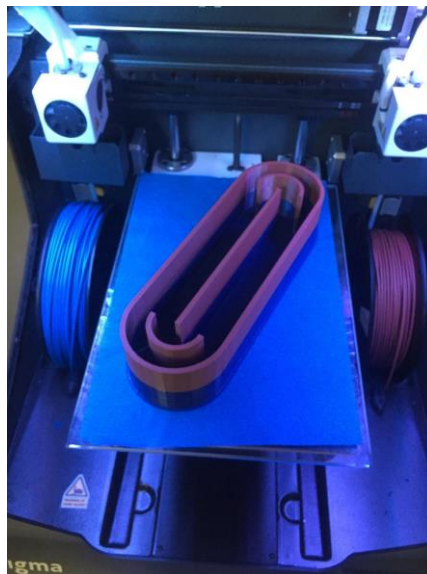
Figure 13. PLA sample, printed by Sigma printer.

First samples have been done with the parameters explained before in Chapter 2.6 (p.24). These are previous parameters to see how the scaled RPR responds in the working conditions.

The first attempt to test the samples, has not been as successfully as it has been expected. Right at the start, when the water was into the raceway ponds for some time, it started to appear some leakage. That was a signal that something had not been done correctly. The leakage presented in both printed samples, was a clear indicator that it should have been some printing issue.

Consequentially, the printing conditions of the samples have had to change in order to achieve a better and more solid result without leakage. The modified parameters with the software help, are the following (Table 2. Printing conditions to avoid leakage.).

- Perimeters: in order to obtain a better insulation, the number of perimeters must increase to avoid leakage. It is changed from 2 to **3 perimeters.**
- Solid layer Shell: as same as the perimeters, the number of external layers must be increased in order to avoid leakage. It is changed from 2 to **3 layers.**
- Layer height: in order to obtain a better result against the leakage, it is needed less distance between layers. There will be more material and the union between layers will be stronger. It is changed from 0,3 mm. to **0,2 mm**.
- Nozzle diameter: to avoid the leakage, the nozzle diameter must be increased. There will be more material and the union between threads will be more robust. It is changed from 0,4 mm. to **0,6 mm**.
- Velocity: it has been reduced a little bit, with the objective of obtain a better printing process. It is changed from 30 mm/s. to **25 mm/s.**

Layer high	0.2 mm
Nozzle diameter	0.6 mm
Number of Perimeters	3
Solid Layer Shell	3 layers
Fill density	75%
Fill pattern	Rectilinear
Temperature of the extruder	200 ºC
Bed temperature	60 ºC
Feed rate (velocity)	25 mm/s

Table 2. Printing conditions to avoid leakage.

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After printing new samples with these modifications in the manufacturing conditions, none a simple sign of leakage has appeared in them. Therefore, to realize the tests in them, in order to select the rightful material, is possible.

## 3.3. Finite Elements Method (FEM)

The Finite Elements Method is a numerical method, which its overall goal is to solve structural problems of engineering. In the earlies 1960s, engineers started to use this method for approximate solutions of problems in their areas of study. The principal advantage of this method is that can solve problems with complicated geometries, loadings, and restraints, where the traditional analytical methods cannot resolve. Also, this tool can handle a wide variety of engineering problems (solid mechanics, fluids, dynamics, heat problems, electrostatic problems, …).

However, FEM analysis has a general closed-form solution, where only approximate solutions are obtained. For this reason, it is very important to not make any mistake when using it, because a little mistake can be fatal for the solution.

3.3.1. Pre-process

To analyse a CAD model through Finite Elements Method (FEM), it is necessary to select the type of analysis it is desired to make. For instance, in this project it is desired to know which thickness should have the RPR, so the analysis type should be a structural static study. Also, selection of the material and the definition of their properties are required. Finally, the user must define the boundary conditions of the problem to solve. For instance, in a mechanical solid problem, the user must define the subjections for the piece and the loads that affects the model.

Then, this numerical method cuts a structure into several elements, making lots of individual pieces of the structure, and reconnects these elements with nodes, as if they were pins or drops of glue that hold elements together. This process of cutting the structure is named "meshing", because all the connected elements form structure like a mesh.
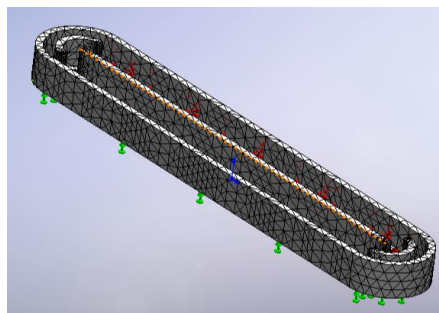
Figure 14. Mesh of RPR

All in all, it is necessary to mention that the creation of a mesh is a critical process which any mistake can alter the result. For this reason, this pre-process part is the most important for the user to be sure of not committing any error. The size and geometry of the elements are the principal factors that affect the process.

3.3.2. Process and postprocess

The solving process of FEM is carried by a computer. The specialized software is responsible to follow an algorithm in order to return the results that have been asked. But these results aren't definitive, they must be compared with others and discussed with the finality to obtain the right ones.

A common strategy that most of users adopt in FEM is to solve the same problem with different types of meshes. That permits to compare the number of nodes calculated with the result, obtaining a reliable one when the numbers of nodes do not influence the result. Furthermore, that is very useful to avoid unnecessary solving time by increasing the number of elements and nodes. In (Figure 15), for more than 1000 elements, the result is already credible. Thus, the refined mesh is inefficient, as it is increasing the time. This little comparison is known as study of convergency.
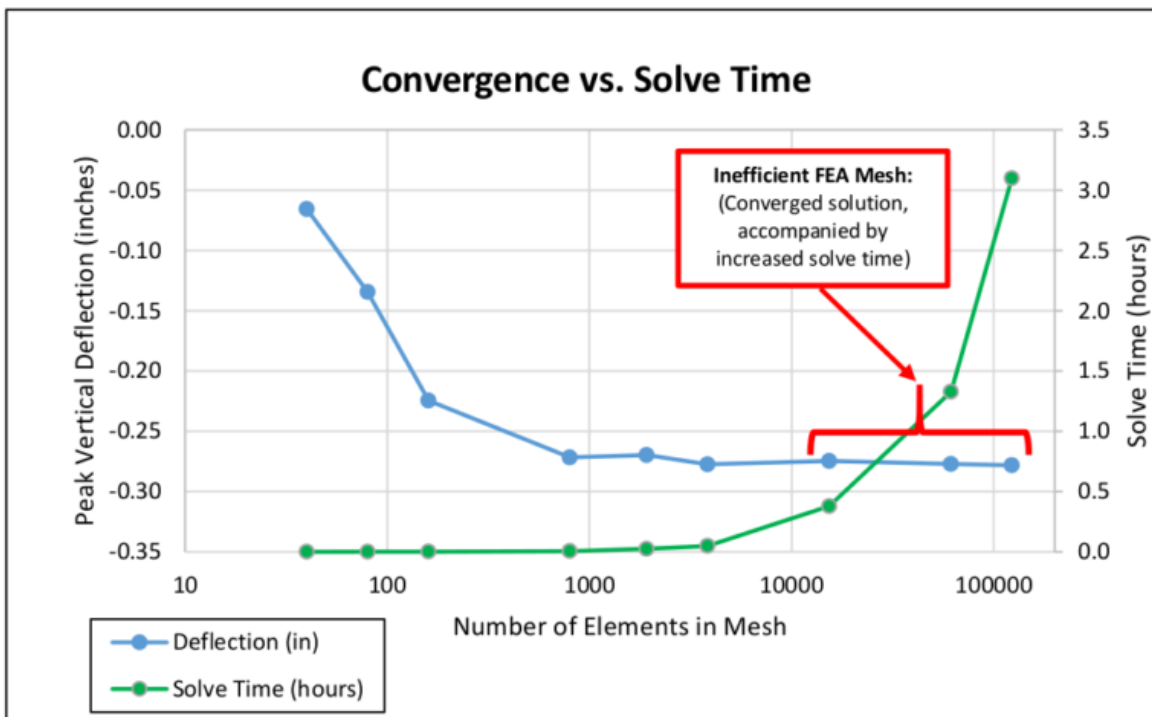
Figure 15. Graphic of converge vs Solve time.

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CHAPTER 4. RESULTS

4.1. Sample tests. Printing conditions modified

Both candidates, PLA and Timberfill, have been tested by the chemical group, with the small-scaled samples printed for the occasion. PLA (polylactic acid) and Timberfill were evaluated in terms of chemical resistance to photo-Fenton reactants. First, these raw materials were exposed to H_2O_2 solutions at pH=3±0.2 under sunlight to simulate photo-Fenton environment. TOC analysis showed that PLA did not alter the concentration of TOC of the solution in the presence of H_2O_2 and iron. Furthermore, printed PLA and Timberfill lab-scale raceway ponds were examined under similar conditions and also 30±0.5 mg·L-1 of caffeine as a contaminant. Through different assays in the PLA pond, TOC was not raised during operation, and no organic matter contaminated the solution from its container. However, in the case of Timberfill, the TOC of solution increased that represented the material destruction. This work shows the promising capability of PLA to be used as photo-Fenton reactor.
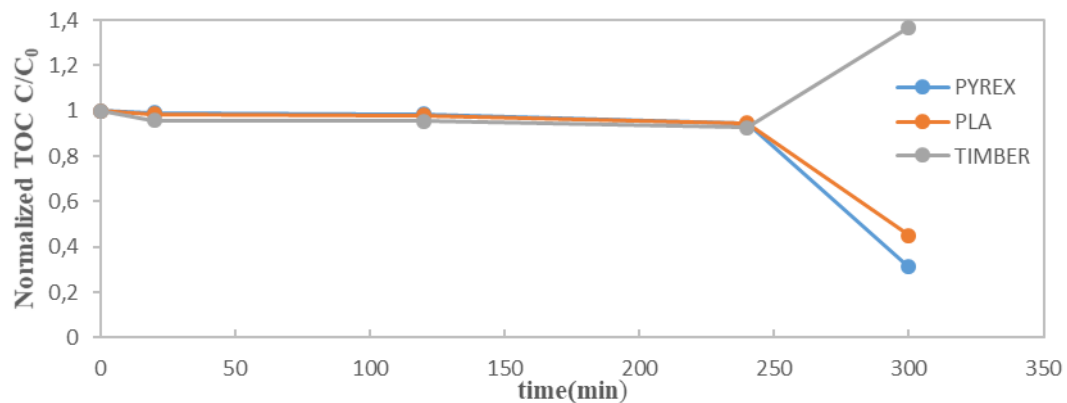
Figure 16. TOC analysis comparison.

4.2. Dimensions of the RPR

In order to obtain a final design of the RPR studied in this work, some previous dimensions were given by the chemical group. These dimensions (Figure 17) were the large, the weight and the maximum capacity in litters of the real scale RPR. Anyways it should be said that these dimensions are not a must, they are a guide to follow and can be changed if necessary.
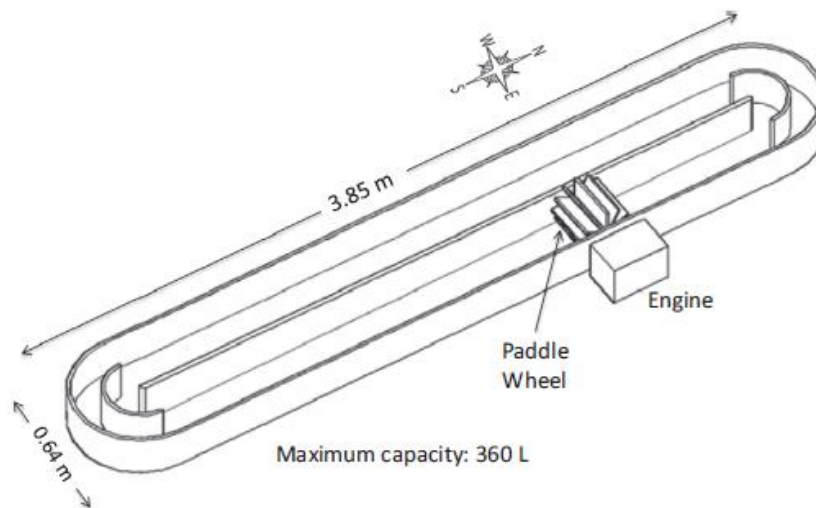
Figure 17. Previous dimensions of RPR [21]

Following the indications, it has been decided to maintain the volume of water with the help of a constant height. For this reason, the thickness of internal walls must be also constant in order to maintain the surface of the base. Likewise, the external wall is going to adopt different thickness, thus the maximum strength can be calculated for every value of thickness.

In order to obtain a final thickness (the missing dimension), some possible values have been provided. With these values, various static analysis has been done through Finite Elements Method (FEM).

4.2.1.   Procedure and equations

For being able to calculate the height needed in order to obtain an approximately capacity of 360 litters in the RPR, the equation of the volume has been used.

$$V = S \cdot (H - t) \;\; \rightarrow \;\; H = \frac{V}{S} + t \quad (1)$$

- *V = Volume of water*
- *S = Surface of the base*
- *H = height of RPR*
- *t = Thickness of base (same as internal walls)*

The volume of water is the maximum capacity RPR is due to have, 360 litters. Furthermore, for the inside wall thickness 40 mm has been selected, as same as the base (see Figure 18). So, the only unknown variable of the equation is the surface. In order to calculate it, the surface have been divided into four different areas (Figure 19). These four surfaces which form the total surface, are calculated:

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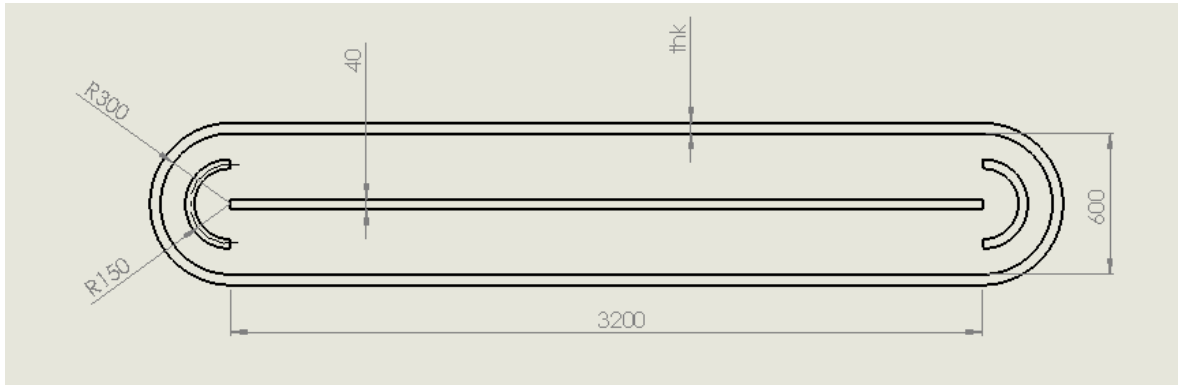
Figure 18. Dimensions
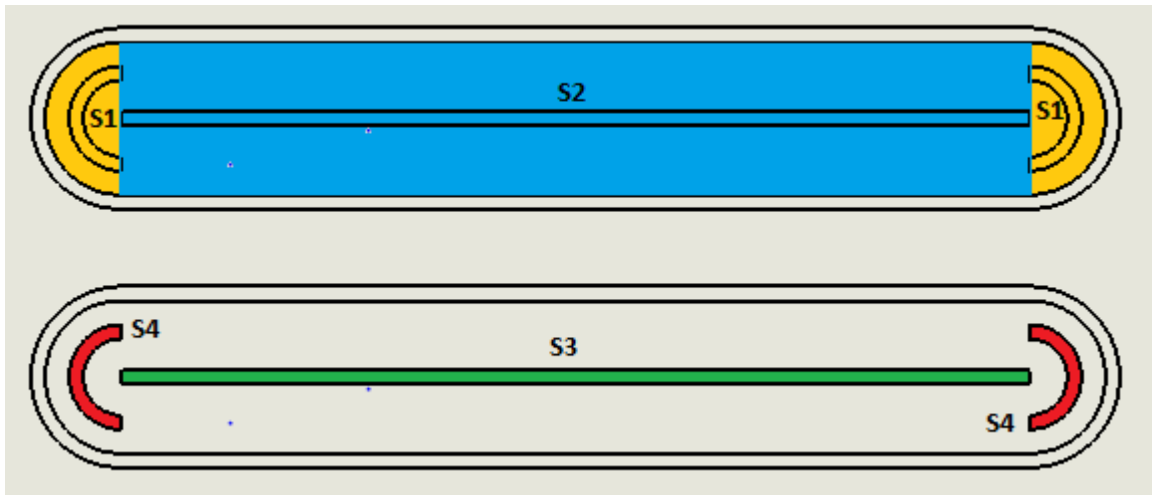
Figure 19. Division of the surface (4 areas)

$$S_1 = \frac{\pi \cdot R^2}{2} = \frac{\pi \cdot 300^2}{2} = 141.371,67 \ mm^2 \quad (2)$$

$$S_2 = 3200 \cdot 600 = 1.920.000 \ mm^2 \quad (3)$$

$$S_3 = 3200 \cdot 40 = 128.000 \ mm^2 \quad (4)$$

$$S_4 = \frac{\pi \cdot \left(\frac{R}{2} + \frac{40}{2}\right)^2}{2} - \frac{\pi \cdot \left(\frac{R}{2} - \frac{40}{2}\right)^2}{2} = \frac{\pi \cdot \left(\frac{340}{2}\right)^2}{2} - \frac{\pi \cdot \left(\frac{260}{2}\right)^2}{2} = 18.849,55 \ mm^2 \quad (5)$$

$$Total \ Surface \ \rightarrow \ S = 2 \cdot S_1 + S_2 - S_3 - 2 \cdot S_4 = 2.037.044,227 \ mm^2 \quad (6)$$

With the sum of these surfaces (eq. 6), the height needed for the RPR can be calculated, using the first equation (eq. 1):

$$H = \frac{V}{S} + t = \frac{360 \cdot 10^6 \ dm^3}{2,037 \cdot 10^6} + 40 = 216,727 \ mm \ \approx 220 \ mm \ (7)$$

33

4.3. FEM results

The best configuration of dimensions should be chosen in order to obtain a good mechanical behaviour. The raw material selected (polylactic acid), must support all loads without any risk of fracture, break or any similar failures.

Due to the geometry of the RPR, various static analysis has been made using the Finite Elements Method (FEM). Simulation, SolidWorks' complement, has been used in order to run the FEM analysis. This tool presents enough technical services that permits to calculate the stress that should support such a geometry.

The first FEM static analysis has been done for a hypothetical thickness of 40 millimetres, and with a rounding of 20 millimetres joining the walls with the basis. This rounding has been introduced because of the concentration of tensions that it could appear at some edges (see drawing at Annex 1). The smoothest the piece is, the better the result. But before running a simulation, bounding conditions should be defined.

First, the basis of RPR, part that is in contact with the ground, must be fixed because the software needs some subjections to solve the analysis through this method. Then, the principal loads should be also inputted. In this case, water has an approximate weight of 3600 N, because of the RPR capacity (it is known that water has a density of 1 g/cm^3, thus if there is a capacity of 360 litters, RPR must support a weight of 360 kg). In addition, water causes a hydrostatic pressure that affects all vertical walls of RPR. But this pressure is not constant, it increases as deeper we go ("y" variable).

$$Pressure = \rho \cdot g \cdot h = 1000 \cdot 9{,}81 \cdot h$$

$$P = 9810 \cdot y \quad (8)$$

Thereupon, it is time to create a mesh that permits to calculate the maximum strength that the piece should support. For the correct selection of the element's size (for the mesh) and its structure, a study of convergency is required. The process consists of running the simulation with a determinate size of mesh, with the purpose of reducing this size until reaching the goal of obtain the same result every time the mesh is improved.

In the following table (Table 3), a study of convergency has been done. It is calculated with 40 millimetres of thickness for the walls.

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Thickness	Num. of nodes (with Rounding)	Von-Misses (with Rounding)	Sec. Factor	MAX Strength (MPa)
	39099	3,04E+07	1,5	45,7
	94160	3,81E+07	1,5	57,2
40	101438	4,30E+07	1,5	64,4
	147127	3,88E+07	1,5	58,2
	186820	3,84E+07	1,5	57,5
	214939	3,84E+07	1,5	57,5
45	196950	2,89E+07	1,5	43,3
50	208107	2,21E+07	1,5	33,1

Table 3. FEM Results. Convergency done for 40 mm of thickness

The quality of the mesh is a direct function of the number of nodes that are used in it. It is shown (Table 3) that at the order of 140.000 nodes, the mesh is returning a coherent result. In order to visualize this, a graphic of convergency, showing the von Misses strength as the value to equilibrate, has been done (Figure 20).
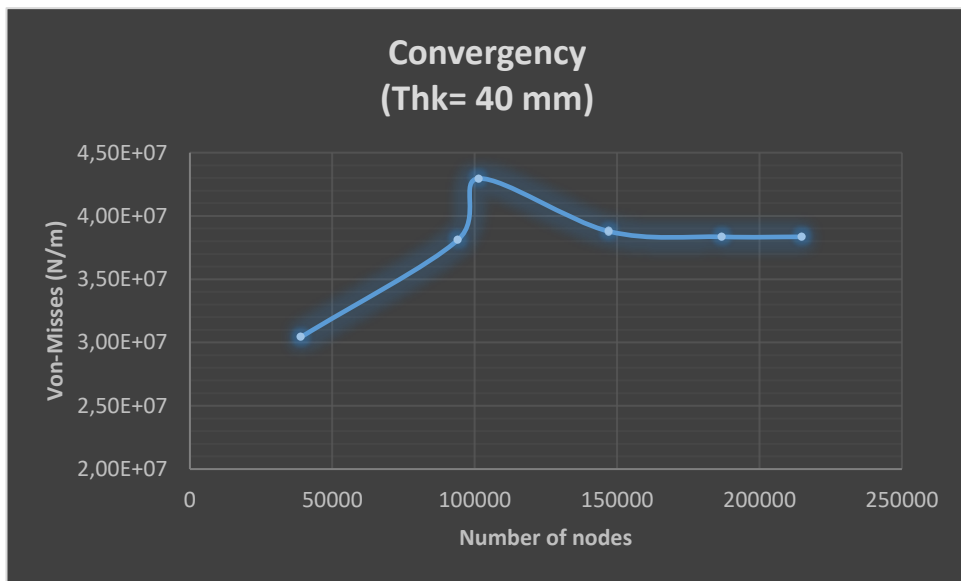
Figure 20. Graphic of convergence

This graphic permit to adopt the correct meshing conditions for the rest of the simulations. For instance, in this work has been done various studies, each one for every value of thickness adopted, and all of them have been meshed with the same conditions. These conditions are the ones has returned more than 150.000 number of nodes in the convergency study:

- Maximum size of element: 35 mm
- Minimum size of element: 7 mm

4.3.1. Thickness selection

The overall goal of selecting a thickness, is to guarantee the minimum possible value, in order to waste the less material as possible, but with the security of being an enough value that could resist all the loads explained above.

As presented before in the technical datasheet of PLA material (Figure 10), the yield strength of this material reaches a value of 53 MPa. This means that the simulations done by FEM must give a lower value of von Mises.

$$53 \; MPa = \sigma_{tensile} \geq \sigma_{max. \; von \; Mises} \quad (9)$$

Thickness	$\sigma_{max. \; von \; Mises}$	$\sigma_{max.} \cdot$ Security factor	Validation
40 mm	38,4 MPa	57,5 MPa	NO
45 mm	28,86 MPa	43,3 MPa	YES
50 mm	22,1 MPa	33,1 MPa	YES

Table 4. Selection of thickness

As it can be observed, the FEM simulations give lower values than the tensile strength of the PLA. However, it does not happen the same if a security factor of 1,5 is applied in those results. As it is shown in Table 4, the minimum thickness that can be adopted is 45 millimetres.

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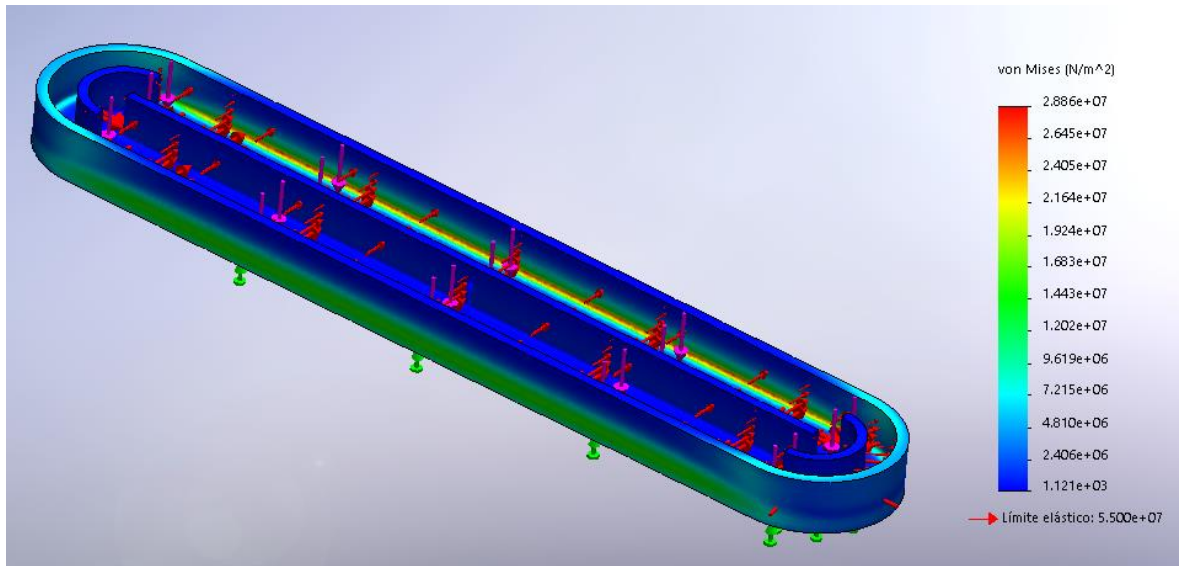
Figure 21. Tensions von Misses
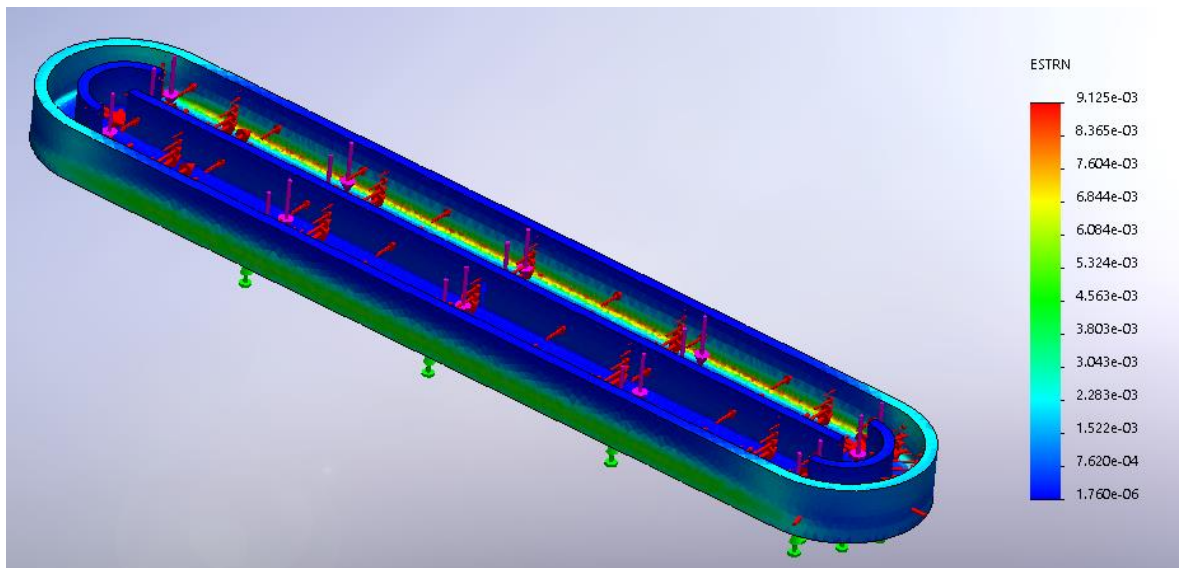
Figure 22. Unitary deformations

Environmental Impact Analysis

During the development of this project, the environmental impact has not been very remarkable. As it has been seen, the 3D printing through FFF is done by machines that does not waste a considerable amount of energy.

Furthermore, the principal materials used (PLA and Timberfill), are materials derived from a renewable resource. On the one hand, instead of other plastics derived from oil or natural gas (fossil resources that will run out), PLA is derived from corn starch, wheat, potatoes or sugar cane, resources that are renewed every year and hence biodegradable. On the other hand, Timberfill is made of biodegradable material based on wood that combine a PLA base material with cork, wood dust, or other derivates.

In conclusion, except for the 3D printing and the experimental tests, the rest of this work is done by informatic tools. For this reason, the real environmental impact is not considerable.

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Conclusions

Now, once the project is finished, it can be confirmed that the objectives presented in the first chapter have been accomplished. Furthermore, it has been deduced some conclusions on the way to achieve the main objectives. These are presented below.

Printing conditions

1. Depending on the printing conditions of the samples, their functions have been affected. Firstly, it has been seen that with the initial parameters adopted none a sample have worked correctly. Two first samples printed with different materials (PLA and Timberfill), have been useful to see the leakage presented in both pieces.
2. Incrementing the number of perimeters and the solid layer shell has helped to obtain samples with their external layers more consistent, in order to avoid another possible leakage.
3. Increasing the nozzle diameter and decreasing the layer height, have been the right decisions to avoid leakage. These modifications have permitted better and stronger unions between layers.
4. Also, the velocity (feed rate) has been modified. The reduction of its value has permitted a better deposition of the melted material.

Selection of raw material

1. ABS is not good for UV radiation, its weakness against the radiation has been fatal. It has been the principal reason of why it has been rejected at the first step.
2. Timberfill sample under the photo-Fenton test (exposed to H2O2 solution and under the sunlight) has been chemically affected. The material destruction has been represented by the increment of Total Organic Carbon (TOC) concentration.
3. PLA, otherwise, has not been affected. Its TOC concentration has behaved very similar as a glass pond (pyrex).
4. The raw material selected (Polylactic acid) has been astoundingly remarkable. It is ideal for this project due to its mechanical behaviour.

Design and Calculation

1. In Finite Elements Method, it is very important to choose the right boundary conditions, in order to obtain an approximate result.

2. A thickness of 45 mm is enough for the PLA pond (real scale) to support all loads. The maximum strength to support is 43,3 MPa, with the security factor already applied. Thus, any thickness upper than 45 millimetres is an adequate value.

3. The selection of the thickness should be the minimum, in order to avoid unnecessary material. We should take consciousness of the importance of reducing the waste of material, not only for the economic part but for the environmental.

Budget

Hardware used	Description	Price item	Amount	Total
	Computer	1.259,00 €	1	2.518,00 €
	PC (Laptop)	795,90 €	1	795,90 €
	Sigma BCN3D	2.475,00 €	1	2.475,00 €
	PYRAMID 3D	520€	1	520 €
			Subtotal	**6.308,90 €**

Software used	Description	Price item	Amount	Total
	Pack Microsoft Office	99,00 €	2	198,00 €
	Simplify 3D	149,00 €	1	149,00 €
	SolidWorks Premium	10.950,00 €	1	5.490,00 €
			Subtotal	**5.837,00 €**

Engineering	Description	Labour Hours	Price Hour	Total
	CAD Design	15	20,00 €	400,00 €
	Material and sample testing	-	- €	200,00 €
	3D printing (SIGMA BCN3D)	38	0,45 €	17,10 €
	3D printing (Pyramid 3D)	32,5	0,45 €	14,63 €
	Chemical study / selection of the material (Annex B)	30	20,00 €	600 €
	FEM simulation	15	20,00 €	300 €
	Writting of the project	710	20,00 €	14.200 €
	Documentation	200	20,00 €	4.000 €
			Subtotal	**19.731,00 €**

Materials	Description	Price	Amount	Total
	PLA	23,90 €	2 rollers	47,80 €
	Timberfill	44,00 €	2 rollers	88,00 €
	ABS	29,95 €	1 roller	29,95 €
	Extruder for 3D printer	11,06 €	3 units	33,18 €
			Subtotal	**165,75 €**

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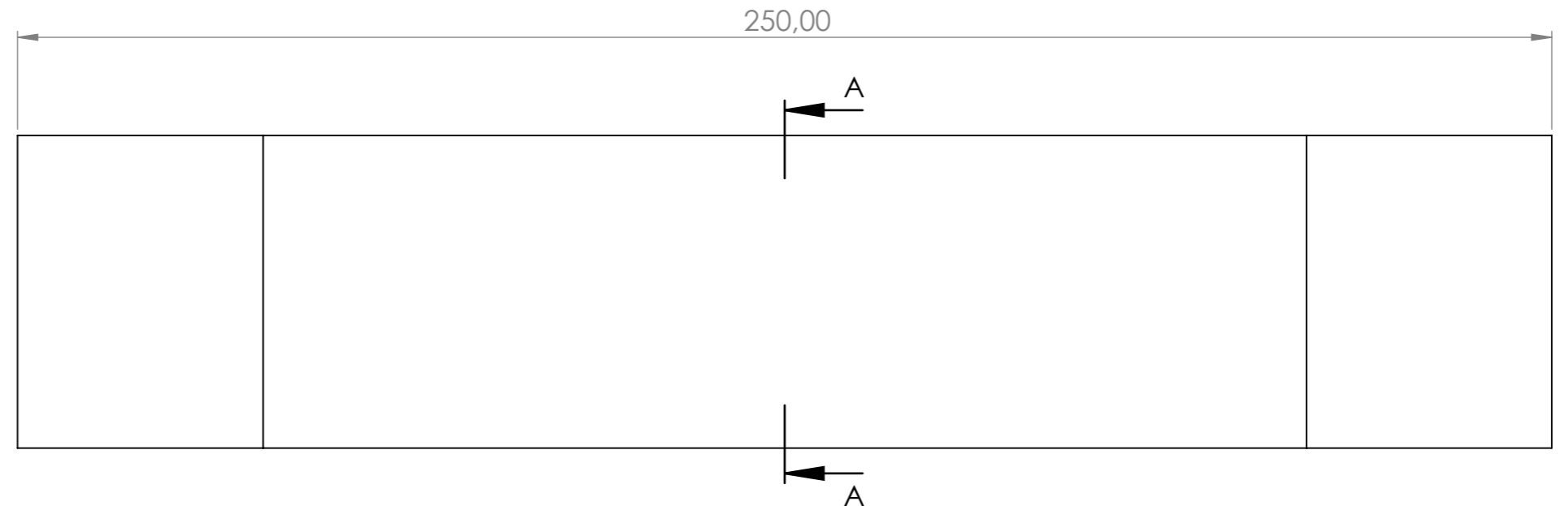
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ANNEX A

DRAWINGS

SECCIÓN A-A

4,00 4,00

250,00

A

A

170,00

R20,00

4,00

80,00

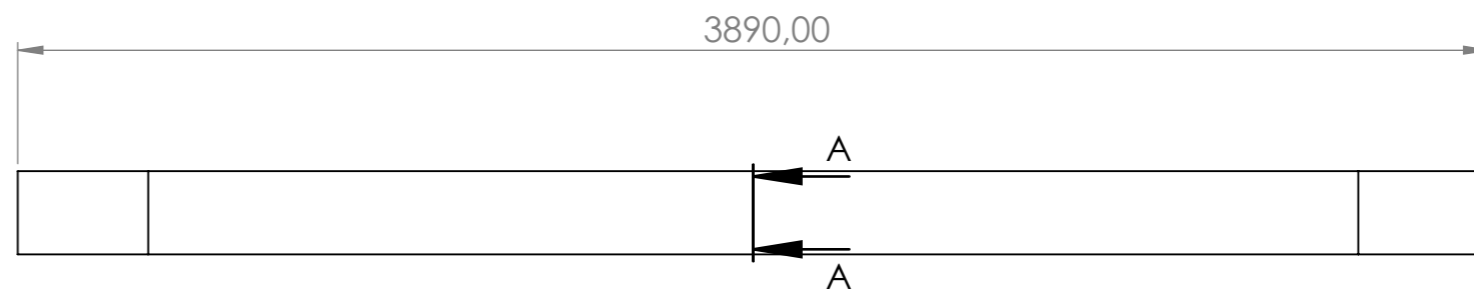4,00

Design and manufacturing of RPR through FFF technology		Peça: SCALED RPR			Plànol nº: nº 1
Revisat: -		Data d'entrega: 02/05/2019			Capacitat: 0,5 L
Dibuixat: PAU FERRER GUASCH		Format: DIN A3	Escala: 1:1		Projecció:
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH UPC Escola d'Enginyeria de Barcelona Est					
		Material: PLA i TIMBERFILL			

45,00 40,00 45,00

220,00

45,00

R20,00

SECCIÓN A-A
ESCALA 1 : 10

3890,00

A
A

3200,00

R175

690,00

45,00

	Peça:	Plànol nº:
Design and manufacturing of RPR through FFF technology	RPR real scale	nº 2
Revisat: —	Data d'entrega: 02/05/2019	Capacitat: 360 L
Dibuixat: PAU FERRER GUASCH	Format: DIN A3	Escala: 1:20	Projecció:

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UPC
Escola d'Enginyeria de Barcelona Est

Material: PLA

ANNEX B

Materials experiments comparisons

B.1. Experiments without UV exposure
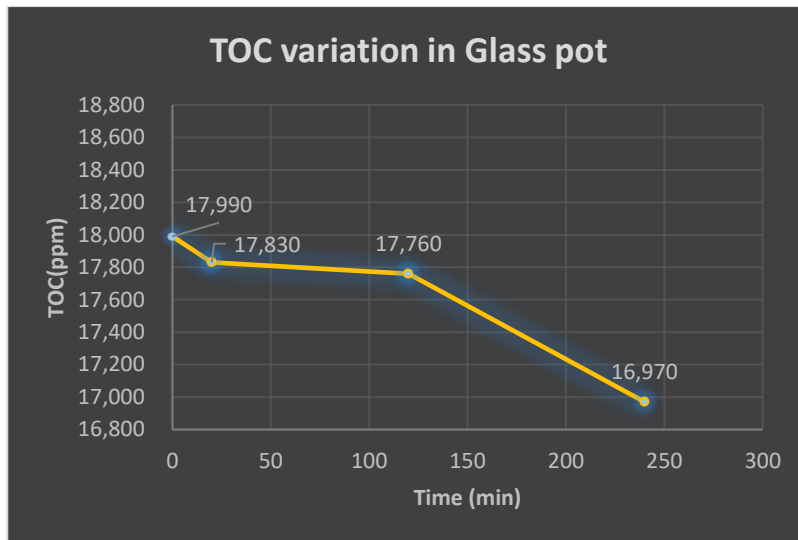
Figure 23. TOC variation in Glass pot
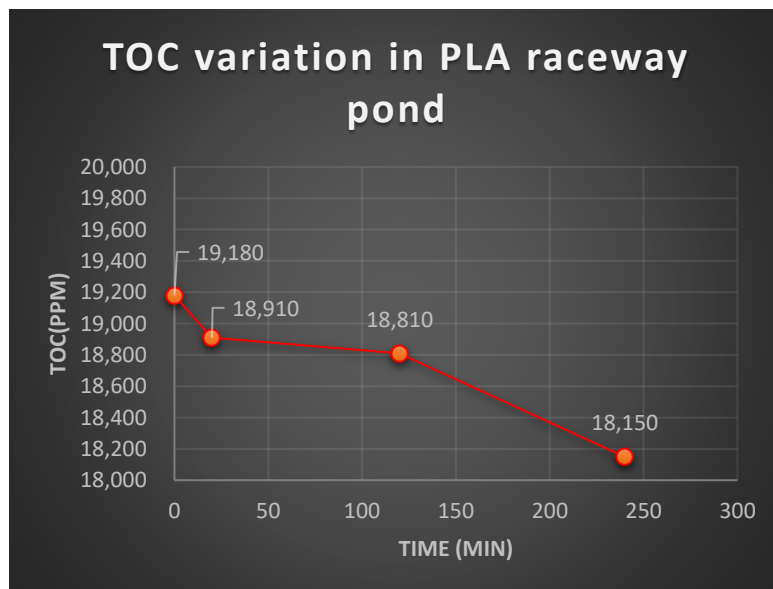
Figure 24. TOC variation in PLA pond
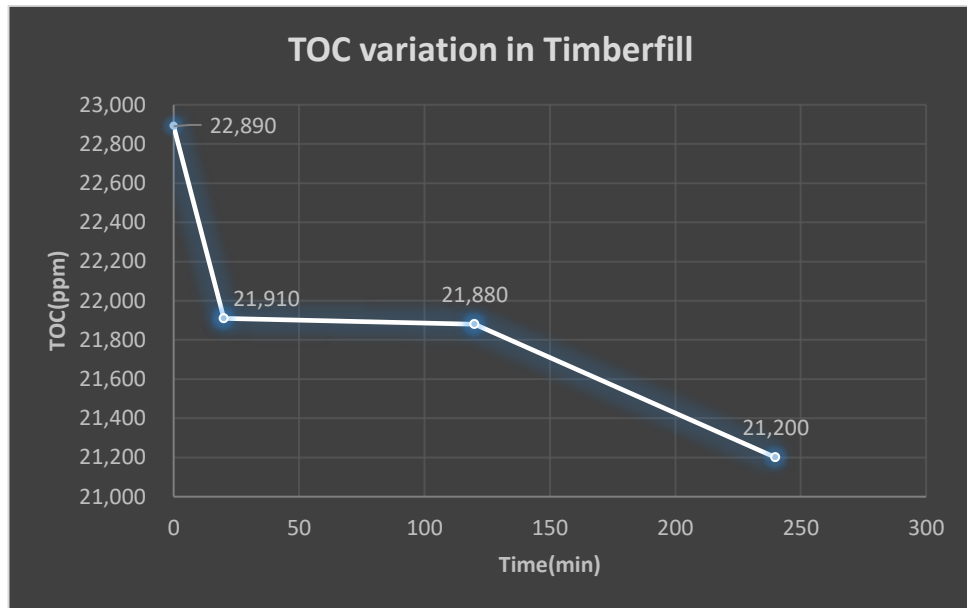
Figure 25. TOC variation in Timberfill pond
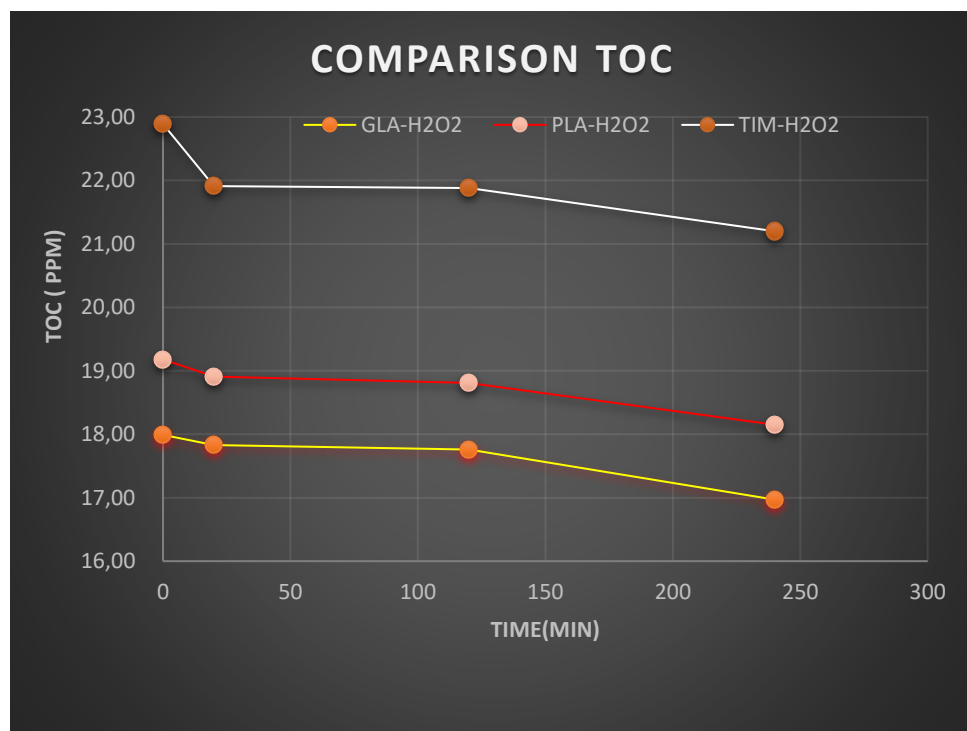
Figure 26. Comparison of TOC. Glass, PLA, Timb.
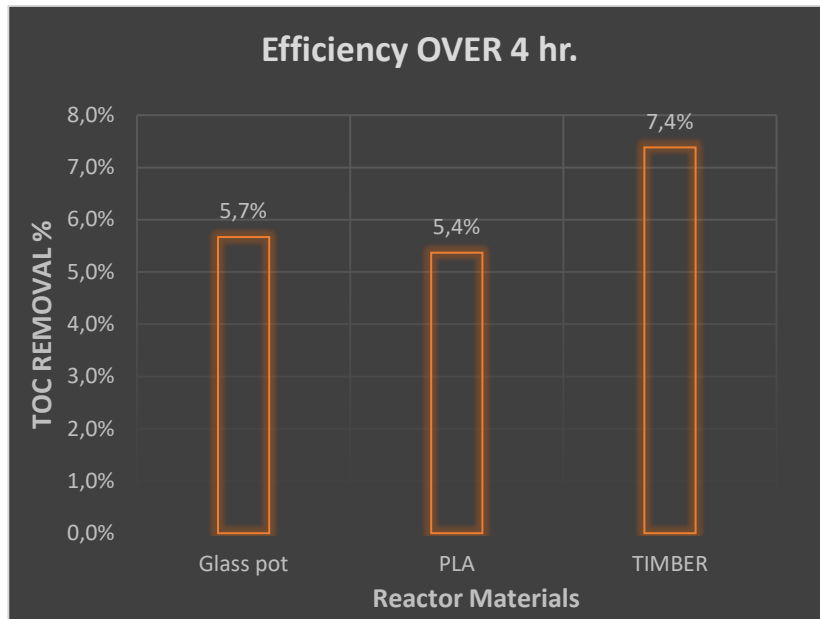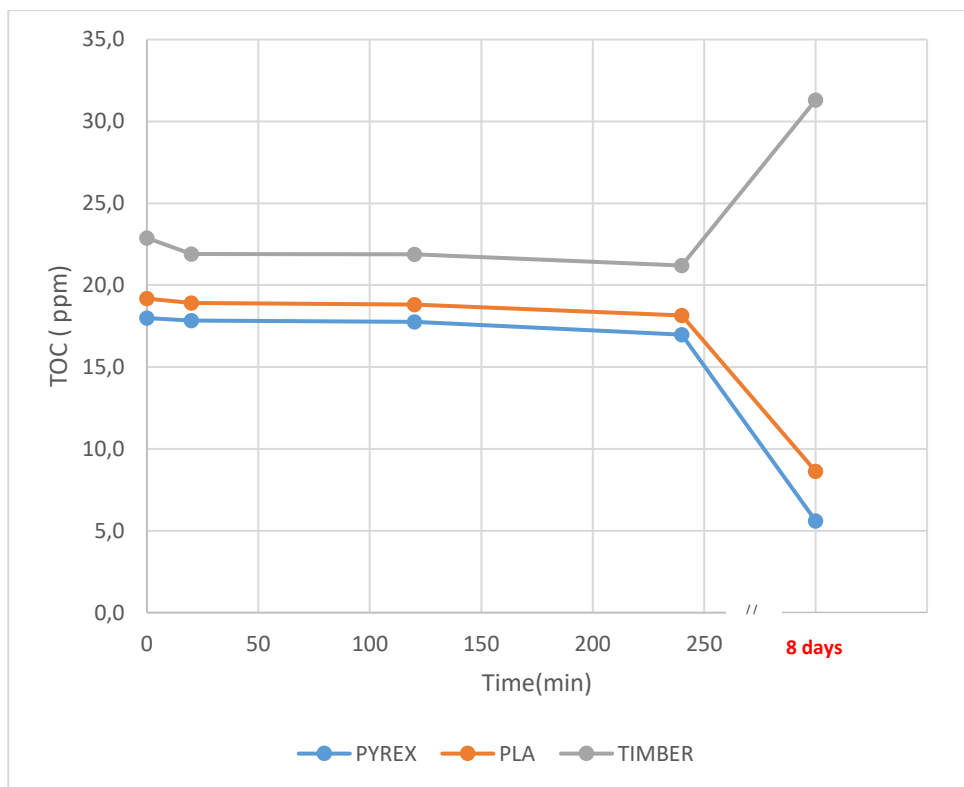
Figure 27. Efficiency over 4 hours

Figure 28. Comparison after 8 days

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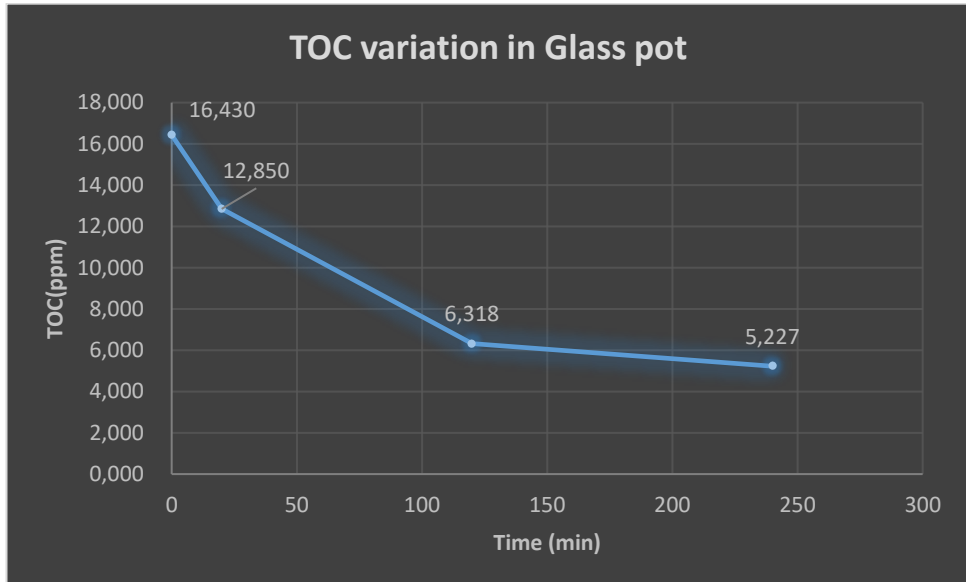BARCELONATECH
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B.2. Experiments with UV exposure

Figure 29. TOC variation in Glass pot. Under UV.
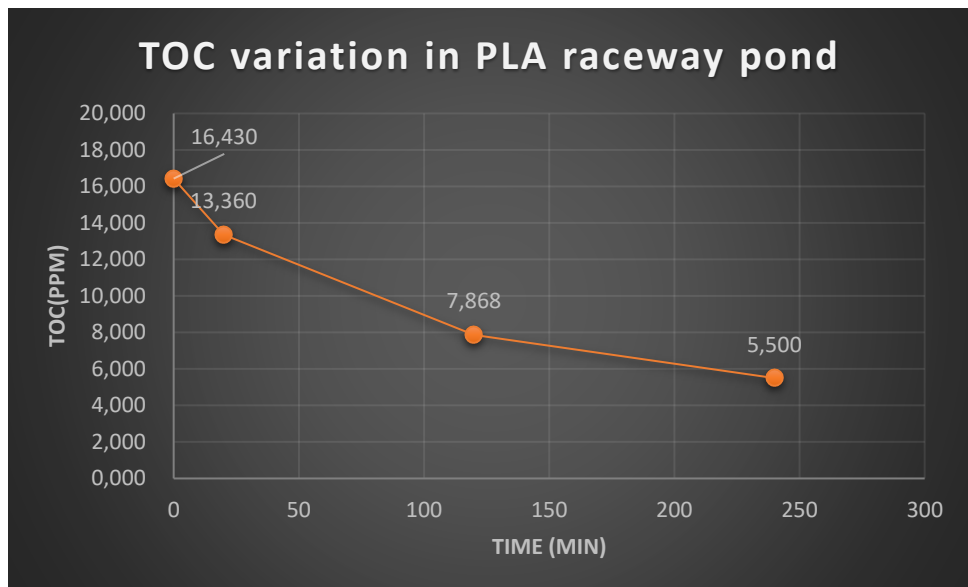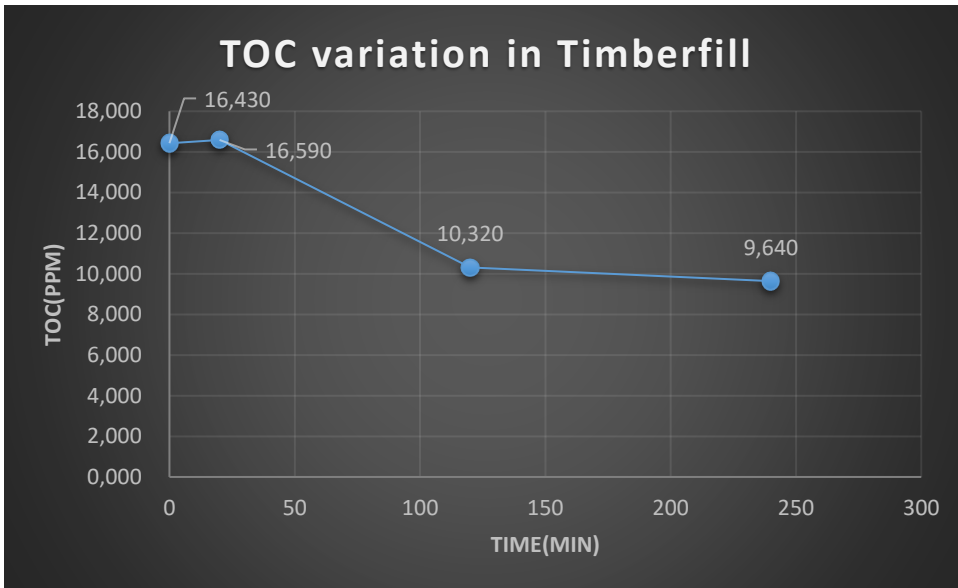

Figure 30. TOC variation in PLA pond. Under UV.

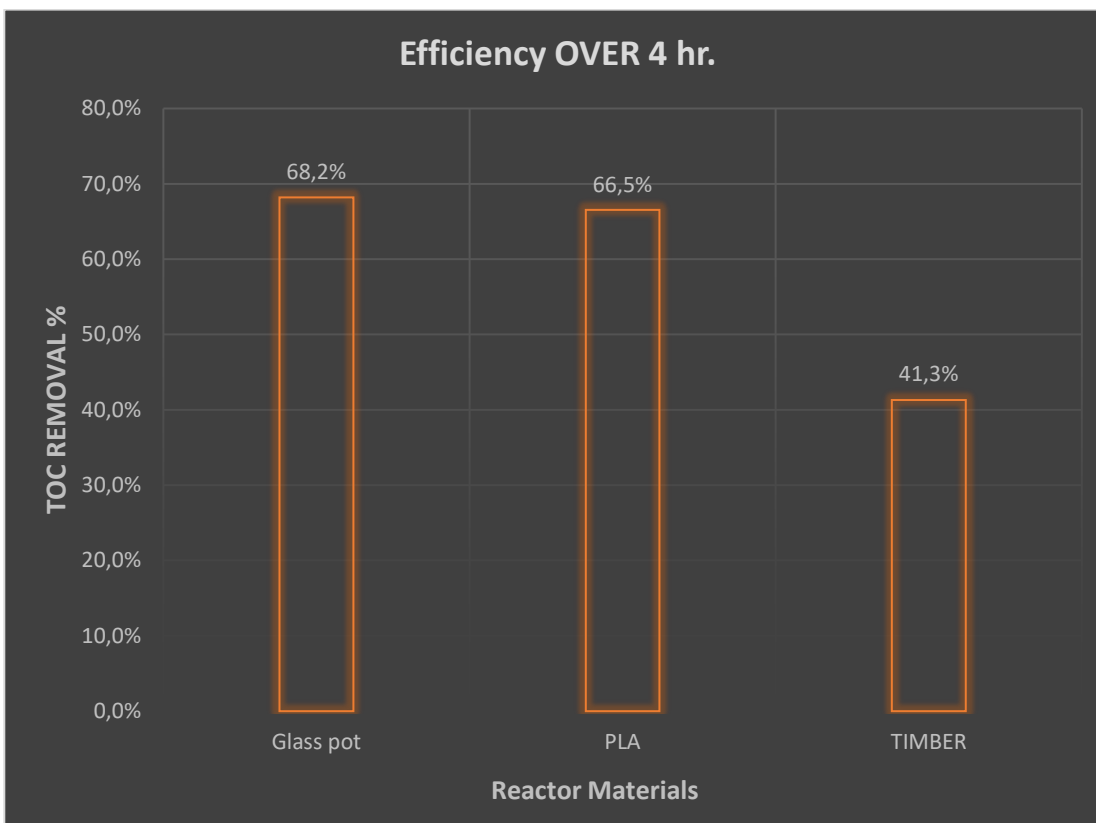*Figure 31. TOC variation in Timberfill pond. Under UV.*

Figure 32. Efficiency over 4 hours. Under UV

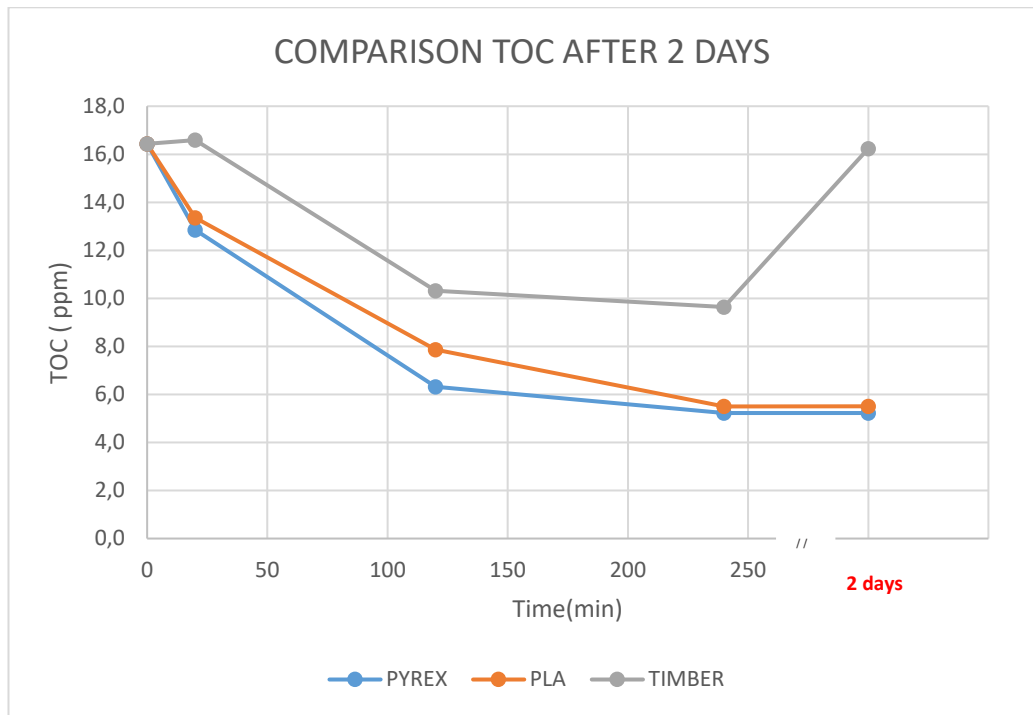UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Figure 33. Comparison TOC after 2 days. Under UV