

PRODUCTION OF CARBON FIBER AND POLYPROPYLENE TAPES TRANSFORMED BY HEAT COMPRESSION MOULDING

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JURY

Presidente

Orientador

Coorientador

Arguente

Resumo

Nas últimas décadas, a produção e o consumo de plástico aumentaram consideravelmente, bem como os resíduos que se originam ao longo da produção, tratamento e consumo deste. Por isso, neste projeto, surge a necessidade de se poder investigar materiais plásticos que também sejam ecológicos.

Este projeto define as bases teóricas e metodológicas para a criação de um termoplástico reforçado que atenda aos requisitos atuais. Crie uma placa feita de polipropileno e fibra de carbono. O desafio é conseguir juntar um termoplástico como material de matriz, que, quando impregnado com outras fibras, sua alta viscosidade dificulta o processo, tendo como reforço a fibra longa de carbono, que, por sua vez, possui alta densidade que também o torna o processo de impregnação dificulta, mas proporciona melhor desempenho mecânico.

Para a realização da placa o projeto foi dividido em três partes. Primeiramente, a impregnação por fusão do termoplástico, ou seja, a criação da primeira fase do composto. Usando calor e pressão, derreta o polipropileno e impregne-o com as fibras de carbono, resultando em uma longa fita. Em segundo lugar, através da técnica de mistura das tiras cortadas da fita, crie camadas do material dando um formato quadrado para obter a placa. Em terceiro e último lugar, na máquina de moldagem por compressão térmica, utilizando calor e pressão, junte todas as camadas na mesma, podendo formar o corpo final, denominado compósito.

A intenção é poder criar um material que combine as propriedades de ambos os elementos, aproveitando as melhorias mecânicas que pode oferecer em relação a outros materiais. Além disso, quando a fibra de carbono é misturada com uma resina termoplástica, esse composto pode ser reformado e reciclado. Por isso, vale a pena investigar esse tipo de composto para o futuro.

Abstract

In the last decades, the production and consumption of plastic have increased considerably, as well as the waste that originates throughout the production, treatment and consumption of this. That is why, in this project, the need arises to be able to investigate plastic materials that are also ecological.

This project defines the theoretical and methodological bases for the creation of a reinforced thermoplastic material that meets current requirements. Create a plate made of polypropylene and carbon fiber. The challenge is to be able to join a thermoplastic material as a matrix material, which, when impregnated with other fibers, its high viscosity makes the process difficult, with long carbon fiber as reinforcement, which, in turn, has high density that also makes the impregnation process difficult, but it provides better mechanical performance.

For the realization of the plate the project has been divided into three parts. First, the melt impregnation of the thermoplastic, that is, the creation of the first phase of the compound. Using heat and pressure, melt the polypropylene and impregnate it with the carbon fibers, resulting in a long tape. Second, through the technique of mixing the strips cut from the tape, create layers of the material giving a square shape in order to get the plate. Third and last, in the heat compression moulding machine, using heat and pressure, join all the layers in the same one, being able to create the final body, called composite.

The intention is to be able to create a material that combines the properties of both elements, using to its advantage the mechanical improvements that it can offer compared to other materials. Plus, when carbon fiber is mixed with a thermoplastic resin, this compound can be reformed and recycled. For that reasons, it is worth investigating this type of compound for the future.

Resumen

En las últimas décadas, la producción y consumo de plástico han aumentado considerablemente, así como también lo han hecho los residuos que se origina a lo largo de la producción, tratamiento y consumo de este. Es por ello, que en el presente proyecto surge la necesidad de poder investigar en materiales plásticos que a la vez sean ecológico.

En este proyecto se definen las bases teóricas y metodológicas para la creación de un material termoplástico reforzado que cumpla con los requisitos actuales. Se deberá crear una placa compuesta de polipropileno y fibra de carbono. El reto está en poder unir un material termoplástico como material matriz, que, a la hora de impregnarse con otras fibras, su alta viscosidad hace difícil el proceso, con larga fibra de carbono como refuerzo, que, a su vez, al tener una alta densidad también dificulta el proceso de impregnación pero que aporta mejores prestaciones mecánicas.

Para la realización de la placa se ha dividido el proyecto en tres partes. Primero, la impregnación por fusión del termoplástico, es decir, la creación de la primera fase del compuesto. Mediante calor y presión, fundir el polipropileno e impregnarlo con las fibras de carbono, resultando en una larga cinta. Segundo, mediante la técnica de mezcla de las tiras cortadas de la cinta, crear capas del material dando una forma cuadrada a modo de poder conseguir la placa. Tercero y último, en el horno de consolidación, mediante calor y presión, juntar todas las capas en una misma pudiendo crear el cuerpo final, denominado material compuesto.

La intención es poder crear un material que combine las propiedades de ambos elementos, utilizar a su favor las mejoras mecánicas que puede ofrecer frente a otros materiales. Añadiendo, que cuando la fibra de carbono se mezcla con un plástico termoestable, este compuesto puede ser reciclado. Es por ello que vale la pena poder investigar en el futuro de este tipo de compuestos.

Special Thanks

First of all, I would like to thank my parents for always being there, for always giving me all the necessary help and dedication that a son can ask for.

Secondly, I would like to thank my professor Púria Esfandiari, for posing this issue with me and making me discover the world of composite materials that has allowed me to learn about this field and raise awareness of a current problem that is global, and that has aroused interest in me for the future.

Glossary

ACRONYM LIST

PP	Polypropylene
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PE	Polyethylene
-----------	--------------

CF	Carbon Fiber
-----------	--------------

GF	Glass Fiber
-----------	-------------

SFRT	Short Fiber Reinforcement Thermoplastic
-------------	---

LFRT	Long Fiber Reinforcement Thermoplastic
-------------	--

CFRT	Continuous Fiber Reinforcement Thermoplastic
-------------	--

BPA	Bis Phenol A
------------	--------------

MFR	Melt flow rate
------------	----------------

MFI	Melt flow index
------------	-----------------

PAN	Polyacrylonitrile
------------	-------------------

UNIT LIST

Pa	Pascal
-----------	--------

MPa	Mega Pascal
------------	-------------

GPa	Giga Pascal
------------	-------------

N	Newton
----------	--------

g	Grams
----------	-------

m	Metres
----------	--------

ton

ton

°C

Celsius degrees

Figure list

Illustration 1. Polypropylene Monomer _____	8
Illustration 2. Polypropylene polymer after chain growth _____	8
Illustration 3. Powder Polypropylene _____	9
Illustration 4. Polyolefins monomer _____	9
Illustration 5. Atactic vs Isotactic PP (via thermoplastics and thermoplastic composites) _____	10
Illustration 6. Continuous carbon fibers _____	12
Illustration 7. Equipment employed to produce pre-impregnated matrix _____	15
Illustration 8. Processing window of the PP polymer (extract from Produção de pre-impregnados de matriz termoplástica e fibras de carbono by Púria Esfandiari) _____	16
Illustration 9. Heat moulded compression process _____	17
Illustration 10. ICORENE 4014 Polypropylene _____	19
Illustration 11. SIGRAFIL carbon fibers _____	20
Illustration 12. Equipment used _____	21
Illustration 13. Melting machine _____	22
Illustration 14. Melting machine (bottom part) and pressure roller _____	22
Illustration 15. Relays and Thermocontrolers _____	23
Illustration 16. Last module to produce tape _____	23
Illustration 17. Heat moulding machine _____	24
Illustration 18. Flexural test equipment _____	24
Illustration 19. Calcination equipment _____	25
Illustration 20. Pre-impregnated matrix _____	26

Illustration 21. Pre-impregnated stripes _____	26
Illustration 22. Build of the woven _____	27
Illustration 23. Criss-crossed woven _____	27
Illustration 24. Woven entering Heat mould compression machine _____	28
Illustration 25. Composite plate obtained _____	29
Illustration 26. Composite stripes for flexural test _____	29
Illustration 27. TGA analysis for PP (via Researchgate) _____	30
Illustration 28. Calcination phases _____	30
Illustration 29. Method A, three point test _____	32
Illustration 30. Flexural test _____	33
Illustration 31. Stress-Strain cure, parallel axis _____	37
Illustration 32. Stress-Strain curve, opposite axis _____	37

Table list

Table 1. ICORENE 4014 properties _____	19
Table 2. Propertis of TORAYCA carbon fibers _____	20
Table 3. Heat mould compression phases _____	28
Table 4. Calcination results _____	35
Table 5. Flaxural test _____	36
Table 6. Deviation of secimens _____	38
Table 7. Comparison of Elastic Modules _____	39

Índex

JURY I

RESUMO	III
ABSTRACT	IV
RESUMEN	V
SPECIAL THANKS	VI
GLOSSARY	VIII
FIGURE LIST	X
TABLE LIST	XII
1. INTRODUCTION	3
1.1. Objectives	4
2. COMPOSITES	6
2.1. Thermosets vs Thermoplastics	6
2.1.1. Thermoplastic composites.....	6
2.1.2. Thermosets composites.....	7
2.2. Polypropylene	8
2.2.1. Polyolefins.....	9
2.2.2. History	10
2.2.3. Chemical and Physical properties.....	10
2.2.4. Mechanical properties	11
2.2.5. Thermal and Electrical properties.....	11
2.3. Carbon Fiber	11
2.3.1. History	13
2.3.2. Structure and properties.....	13
2.3.3. Applications.....	13
2.3.4. Synthesis	14
2.4. Thermoplastic matrix impregnation	14
2.4.1. Production of pre-impregnated matrixes.....	14
2.4.2. Transformation of pre-impregnated matrixes	16
3. EXPERIMENTAL PART	19

3.1. Materials	19
3.2. Equipment involved	21
3.2.1. Tape manufacturing equipment	21
3.2.2. Composite equipment.....	23
3.2.3. Testing equipment.....	24
3.3. Process	25
3.3.1. Set Up	25
3.3.2. Tape Production	26
3.3.3. Heated Compression Moulding	27
3.3.4. Polishing and cutting	29
3.4. Polymer mass.....	30
3.5. Flexural Test	32
4. EXPERIMENTAL RESULTS. _____	35
4.1. Heat compression moulding.....	35
4.2. Calcination test.....	35
4.3. Flexural test.....	36
4.3.1. Theoretical vs Experimental Modules.....	38
CONCLUSIONS _____	43
BIBLIOGRAPHY _____	47
ANNEX _____	51
A1. Flexural test results.....	51
A2. Technical Sheets.....	64

Introduction

1. Introduction

Since the XX period, when the sintering of plastic began it rapidly became one of the bests hits for human commodities. Its capabilities, lightweight, being adaptable to many shapes, but among them, the production costs were the key factor to stimulate its global use. Once it was mastered the production of it, discoveries and techniques were carried on for the search of more powerful plastics. The result ended up with composites.

A composite can be defined as a material that has at least two elements in its constitution, and permits to obtain better capabilities in a way where neither of the elements could achieve on their own. With different physical and chemical properties when they are combined, they create a material that is specialized to do a certain job, for instance, to become stronger, lighter, or resistant to electricity. The reason for their use over traditional materials is because they improve the properties of their base materials and are applicable in many situations.

For the past years, the vast majority of plastic composites have used thermosets as raw material due to their easier conformability since it has a lower viscosity which makes the impregnation easier.

Thermosets are a lightweight material and can have a long life. Since the discovering of them, it has been one of the most used materials on earth as mentioned before, but on the other side, one of the cons is, its recyclability, non-existent. Thermosets take ages to decompose and many times before that end up in the ocean where it kills much marine life or on earth polluting the environment.

On the other hand, with the new techniques carried out, thermoplastics composites became a possible solution, adding the recycling factor that was key triggering to know more about them. In many aspects improving the mechanical capacities of thermosets such as resistance or damage tolerance, too.

Thermoplastic composites had gained a considerable amount of production for injection parts but the fibers were short so the resistance was good but not best, as the long-continuous fibers, according to the new studies, could add to. The utilization of long continuous fibers implies greater technological advances since it requires much more temperature and pressure, and since the thermoplastics have a higher viscosity makes it even harder, then again it needs better technology to compete with the rest of the plastic composites.

The main difference is that when thermosets once get conformed can't go back to their initial form, so the recyclability it's almost nonexistent but the thermoplastics can be conformed again and again. This project will try to develop a thermoplastic composite.

1.1. Objectives

The main goal is to try to create reinforced thermoplastics plates from polypropylene (PP) with high TEX carbon fiber (CF), see how they can cope. Then, it will be mechanical tested and see if it's a good enough composite.

This work will try to give continuity to the studies already made by professor Púria Esfandiari around the thermoplastics composites.

To be able to produce at larger scales composite first it's important to study the production techniques, if the impregnation between both materials is good enough, and as the final key point, tests of its mechanical capabilities are good too, then the project could have success.

The principal objectives of this work will be:

1. Production of CF/PP tapes
2. Weaving technique
3. Production of the composite by heat compression moulding
4. Mechanical testing

Composites

2. Composites

A composite is a combination of at least two different materials, both of each being different materials and having different mechanical properties. A composite has two parts, the reinforcement part whose role is to support the efforts, and it is given by the more strength and resistant element. The second part, is called matrix, its purpose is to distribute all the efforts that are supported by the reinforcement part, normally it's a polymer.

The polymer used as a matrix can be a thermoset or a thermoplastic. Thermosets are known for having a low viscosity which enables a better impregnation with the fibers. The thermoplastics have a much higher viscosity which complicates the impregnation but can be molten and re-shaped.

The thermoset matrixes gained much visibility on industrial processes. But since thermoplastics can offer better mechanical properties, such as more tenacity, ductility, have shorter processing cycles and recyclability, in the last century began the efforts to discover new technologies that could make the impregnation of the polymer into the fibers much more effective.

2.1. Thermosets vs Thermoplastics

Following its chemical structure, plastics can be separated between 3 different groups, thermoplastics, thermosets, and elastomers. The two most important groups are thermoplastics and thermosets.

2.1.1. Thermoplastic composites

Thermoplastics in the form of composites are most commonly reinforced with short fibers, meaning, the resin is formed into shapes that rely solely on the short, discontinuous fibers from which they are comprised to keep on their structure.

- **Advantages of thermoplastic composites:**

Thermoplastic composites may offer better advantages for some manufacturing applications. The first advantage is the increased capability to resist an impact compared to the thermosets. The difference can be as much as 10 times the impact resistance.

The second advantage is their ability to become conformed again thanks to its malleability. Thermoplastics are solid at room temperature, but when heated at melting point and pressured

into a reinforcing fiber they become liquid and impregnation occurs. However, it isn't a chemical reaction that results in a permanent, no reversible change. This is what allows thermoplastic composites to be re-formed and re-shaped.

For example, you could heat a thermoplastic bar and shape it into another completely different object. Once cooled, the newly created figure would remain, whereas thermosets can't be done. This property shows tremendous promise for the future of recycling thermoplastic composite products when their original use ends.

- **Disadvantages of thermoplastic composites:**

While it can be made malleable through the application of heat, it is harder to impregnate with other reinforcing fibers rather than thermosets. To do that, pressure and heat have to come together. The polymer has to be heated to its melting point and pressure has to be applied to mix it with the fibers, and then cool it down, all while keeping the pressure.

Special tooling, technique, and equipment must be used, many of which are expensive. The process is much more complex and expensive than traditional thermoset composite manufacturing.

2.1.2. Thermosets composites

Curing a thermoset resin means transforming it into a plastic. The raw uncured resin molecules are cross-linked (the process of bonding two polymer chains by covalent bonds) or with a catalyst, going from a liquid phase into a solid one, through most of the times with an exothermic chemical reaction. As a result of this change, polymer chains create extremely strong bonds. Thermosetting resins are popular because uncured and at room temperature, they're in a liquid state, which allows for convenient impregnation of reinforcing fibers such as fiberglass, carbon fiber, or Kevlar.

- **Advantages of thermoset resins**

Advantages of thermoset resins are excellent resistance to solvents and corrosives, resistance to heat and high temperature, high fatigue strength, tailored elasticity, excellent adhesion, excellent finishing qualities for polishing and painting.

- **Disadvantages of thermoset resins**

A thermosetting resin, once catalysed, cannot be re-shaped or reversed, meaning that once a thermoset composite is created, its shape cannot be changed again. Because of this, the recycling of thermoset composites is extremely difficult. Thermoset resin itself is not recyclable.

What ultimately determines which material is best suited to any given application comes down to a number of factors that may include some or all mentioned after: purposes of the composite, durability, mechanical properties as resistance to impact or flexibility, expense of manufacture, and recyclability.

2.2. Polypropylene

Polypropylene (PP), also known as polypropene, is a thermoplastic synthetic resin built up by the polymerization of propylene. It is produced via chain-growth polymerization from the monomer propylene $[CH_2=CHCH_3]_n$ or $[C_3H_6]_n$, at low temperatures and pressures using Ziegler-Natta catalysts like $TiCl_3$ or $TiCl_4$, along with an aluminium based co-catalyst.

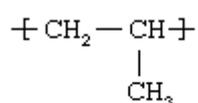


Illustration 1. Polypropylene Monomer

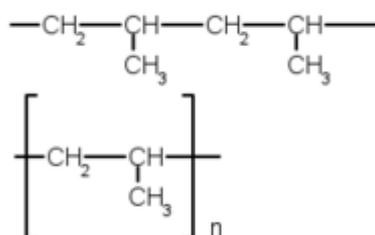


Illustration 2. Polypropylene polymer after chain growth

Polypropylene is a gaseous compound and belongs to the group of polyolefins, a class of hydrocarbons whose molecules contain a single pair of carbon atoms linked by a double bond. Obtained by the thermal cracking of ethane, propane, butane, and the naphtha fraction of petroleum. It is partially crystalline and non-polar. It is a white, mechanically rugged material and has a high chemical resistance. Its melting point is approximately 170 °C. It is slightly more prone to oxidation than other polymers unless appropriate stabilizers and antioxidants are added.



Illustration 3. Powder Polypropylene

It is moulded or extruded into plastic products in which toughness, flexibility, lightweight, and heat resistance are required. It is also spun into fibers for employment in industrial and household textiles. Used in a wide variety of applications like home furnishings, indoor or outdoor carpets, automotive compounds such as battery cases as well as industrial uses like rope and cordage, disposable nonwoven fabrics, reinforcement constructions, or road paving among many others. Also, it can be blow-moulded into bottles for food, shampoos, and other household liquids, since its melting point is high enough for daily uses such as dishwashing machines and it doesn't contain Bis Phenol-A, BPA. BPA is not a safe option for food packaging since this chemical has been shown to leach into food products. It has been linked to various health issues.

Polypropylene is reasonably economical. Polypropylene is the second-most widely produced plastic, after polyethylene.

2.2.1. Polyolefins

Many polymers are derived from the olefins, a family of hydrocarbon compounds—that is, compounds containing hydrogen (H) and carbon (C)—which are produced from the refining of petroleum and natural gas. An olefin contains one double bond between two carbon atoms. The general chemical formula can be represented as $\text{CH}_2=\text{CHR}$, with R representing any of several possible atoms or groups of atoms. As the repeating unit of a polymer, the compound has the following chemical structure:

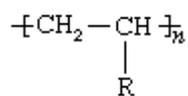


Illustration 4. Polyolefins monomer

When R in the above structure represents a methyl group (CH₃), the polymer obtained is polypropylene.

2.2.2. History

Isotactic polypropylene was discovered in 1954 by Italian chemist Giulio Natta and his assistant Paolo Chini, working in association with the Montecatini company. They employed catalysts of a type recently invented by the German chemist Karl Ziegler for synthesizing polyethylene. Since the early 1980s, production and consumption have increased significantly, owing to the invention of more efficient catalyst systems. The most recent technique is Metallocene catalysis polymerization, is growing fast to produce a consistent PP with uniform molecular distribution, resulting in enhanced toughness, impact and puncture strengths among other properties.

2.2.3. Chemical and Physical properties

The properties of polypropylene depend on the molecular weight and molecular weight distribution, crystallinity, type and proportion of comonomer (if used), and the isotacticity (to characterize where the substituent locates in a molecular backbone). In isotactic polypropylene all substituents are located on the same side, for example, the methyl groups are oriented on one side of the carbon backbone. This arrangement creates a greater degree of crystallinity and results in a stiffer material that is more resistant to creep than atactic (irregular positioning of the substituents) polypropylene.

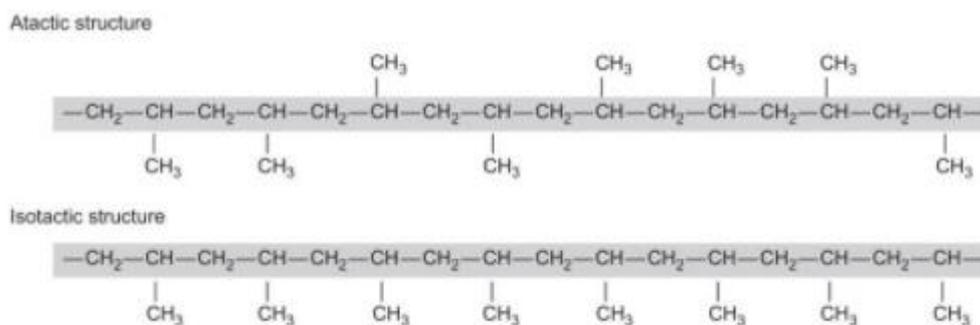


Illustration 5. Atactic vs Isotactic PP (via thermoplastics and thermoplastic composites)

The tacticity reflects on the polymer's physical properties. An isotactic structure leads to a white semi-crystalline polymer. The higher percentage on the polymer chain of isotacticity, the greater crystallinity will have. Also, better rigidity, young modulus, and hardness. Polypropylene can be made translucent, though, many times is opaque or colored using pigments. Atactic PP, on the other side, has an amorphous structure resulting in no crystallization and implies lower mechanical properties.

The melt flow rate (MFR) or melt flow index (MFI) is a parameter used to measure the viscosity of the polymer. When having a high index of MFR indicates how easily will the polymer flow when processing,

for instance, when filling a mould. Thus, this helps to know how good will be the physical properties, polymers with higher rate will have stronger mechanical properties and lower rates ones on MFR table will decrease its properties.

2.2.4. Mechanical properties

The mechanical properties are generally fair with high elongations at break but have much more limited strains at yield. Modules and hardness are higher than PE (Polyethylene).

The density of polypropylene is between 0.895 and 0.92 g/cm³, being the lowest one for amorphous PP and the highest for crystalline isotactic PP. Therefore, PP is the commodity plastic with the lowest density. As with density, the same occurs with Young's modulus of PP, which is between 1300 and 1800 N/mm². Polypropylene is normally tough and flexible, this allows polypropylene to be used as an engineering plastic.

Polypropylene has a good resistance to fatigue, when a thin section of moulded polypropylene is flexed repeatedly, its molecular structure changes so it is capable of withstanding much additional flexing without failing.

2.2.5. Thermal and Electrical properties

As many factors are combined different polypropylenes can vary its melting point, but perfectly isotactic PP melts at 171°C. When being under 0°C PP becomes brittle. The thermal expansion of PP is very large.

PP's are good insulators even in wet environments, with high dielectric resistivity and rigidity and low loss factors.

2.3. Carbon Fiber

Carbon fibers are the strongest fibers known but aren't that used due to their high cost of manufacture. Having spectacular mechanical properties (high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance, and low thermal expansion) the elevated cost makes the use only in specific applications such as navy, aerospace, civil engineering, military, and motorsports, alongside with other competition sports. They are relatively expensive when compared with similar fibers, such as fiberglass or plastic fibers. Depending on the process, they can be 15 times the cost of glass fibers.

Carbon fibers are about 5 to 12 micrometers in diameter and composed mostly of carbon atoms. Several thousand carbon fibers are bundled together to form a tow, which may be used by itself or woven into a fabric.



Illustration 6. Continuous carbon fibers

To produce a carbon fiber, the carbon atoms are bonded together in crystals that are aligned parallel through the long axis of the fiber as the crystal alignment gives the fiber a high strength-to-volume ratio, meaning it's capable of withstanding much stress for its area. However, CF is sensitive to impact and abrasion.

Carbon fibers are usually combined with other materials to form a composite. When combined with a melted plastic resin, it forms carbon-fiber-reinforced polymer which has a very high strength-to-weight ratio and is extremely rigid although depending on the polymer used somewhat brittle.

Carbon fibers can be obtained by two different methods:

- Former fiber wigs of polyacrylonitrile (PAN). This type of fibers have good resistance and can be easily attached to the composite matrix.
- Fragments left from petroleum, conveniently treated (PITCH). These fibers have higher Young modulus.

The above mentioned fibers can be classified into three types:

- Type I; elevated Young modulus, they have a good carbon-carbon alignment, oriented alongside the fiber axis.
- Type II; intermediate Young modulus, obtained through PAN.
- Type III; low Young modulus, obtained through isotropic pitch (mechanical properties don't change depending on the studied direction of the body).

2.3.1. History

In 1860, Joseph Swan produced the first carbon fibers to be used in lightbulbs. Later on, Thomas Edison burn cotton threads and bamboo slivers at high temperatures to obtain carbonized fiber filaments used in one of the first incandescent lights fed by electricity.

A century later (1960) from its first discovery, a process in Japan by Dr. Shindo was developed with Polyacrylonitrile (PAN) as a raw polymer material, being a success at that time because it could have up to 55% in mass weight of carbon. The same year, in the US, Dr. Millington developed a completely different process using rayon (regenerated cellulose) that could get up to 99% of carbon fiber, milestone was reached since these new fibers had sufficient elastic module and tensile strength to be mixed with other materials, such as plastics, creating the carbon-reinforced composites having high strength to weight ratio properties and for high temperatures applications.

2.3.2. Structure and properties

The atomic structure of carbon fiber is similar to graphite structure, sheets of carbon atoms arranged in hexagonal polygons, the difference is in the distances between layers.

Depending on which substance is made from (precursor), carbon fiber may be turbostratic or graphitic, or both structures resulting in a kind of hybrid. Turbostratic CF layers are haphazardly folded or crumpled together. Turbostratic CF comes from polyacrylonitrile (PAN). Whereas, graphitic CF comes from mesophase PITCH (phase between liquid and solid) when being treatment heated over 2200°C. Turbostratic carbon fibers have a higher tensile modulus (maximum stress accepted) and graphitic carbon fibers have higher Young modules implying better stiffness, tenacity, and high thermal conductivity.

The properties vary depending on the process, but among them are: high tensile strength, high young modulus, high creep resistance, high fatigue resistance, high dielectric conductivity, high thermal conductivity, lower density than GF (glass fiber), low coefficient of friction and low thermal expansion. On the other hand, the drawbacks are low impact strength, low abrasion resistance and high cost of manufacture.

2.3.3. Applications

For its extraordinary properties but its high cost, composites are where carbon fiber is mostly used since it will have the good mechanical properties inhered from the CF but won't have much CF weight ratio. Also, CF can be mixed with non-polymer materials such as metallic ones or more carbon indeed but has seen limited success due to suffering from corrosion. Aeronautics, aerospace, military or motorsports are where CF is seen the most.

2.3.4. Synthesis

Each carbon filament is produced from a polymer like polyacrylonitrile (PAN), rayon, or mesophase PITCH. For synthetic polymers such as PAN or rayon, first, it is spun into filaments, using chemical and mechanical processes trying to align the molecules into the axis direction to achieve the outstanding properties of CF. After that, filaments are heated to expel non-carbon atoms from themselves (carbonization), leaving the already made carbon fibers. Further treatment may be applied to gain or enhance its capabilities depending on its purposes.

2.4. Thermoplastic matrix impregnation

There exist three types of thermoplastic matrixes, short fiber reinforced thermoplastic (SFRT), long fiber reinforced thermoplastic (LFRT), and continuous fiber-reinforced thermoplastic (CFRT).

The short fibers come in granule, however, since it is short they tend to degrade faster. The long fibers have a length larger than 6 mm. And, the continuous ones, can be divided into two groups according to their flexibility:

- Pre-impregnated flexibility with partial impregnation, characterized by not having the whole fibers impregnated.
- Pre-impregnated semi rigid with total impregnation, less flexibility but whole fiber body impregnated.

2.4.1. Production of pre-impregnated matrixes

Different techniques have been developed for the impregnation of thermoplastic matrixes as new and continuous studies develop the current state of art. The impregnation is a critical process where if the conditioning factors are not okay, the polymer matrix will not properly enhance a good adhesion to the fiber.

Many factors can affect the process (length of the fibers, pressure, polymer viscosity, geometric disposition of the fibers, the thickness of fibers, etc.) thanks to *Darcy Law* it's possible to estimate the impregnation speed in order to produce a proper reinforced pre-impregnated composite:

$$u_p = \frac{dx}{dt} = \frac{K * dP}{\eta * dx} \quad (\text{Ec. 2.1})$$

Where:

- u_p is the polymer flow speed, (m/s)
- K , impermeability of the fibers, (m²).
- η , viscosity of the polymer, (Pa*s).
- $\frac{dP}{dx}$, Pressure gradient.

Integrating the speed, it is possible to know the time impregnation, considering the pressure is uniform and does not vary in the time.

$$t_{imp} = \frac{\eta * D_p^2}{2K * P} \quad (\text{Ec. 2.2})$$

According to Darcy Law, to produce a good tape, as seen in the equation (Ec. 3.2), the impregnation distance (D_p) should be as short as possible, since the value is squared and makes the process in terms of time much more longer, hence, making it more expensive.

2.4.1.1. Melt Impregnation by mixture of polymer powder with reinforced fiber

The first step in manufacturing is impregnation. During this step, dry powder polymer (polymeric thermoplastic matrix) will be impregnated to the reinforced fibers. By heating the polypropylene until its melting point and pressure added, the polymer will stick to the fibers.

Impregnation is accomplished when surrounding it with the matrix and forcing it to penetrate the fibers. Due to its porous structure, the fibers will get impregnated. Thanks to Darcy's Law it can be estimated the time process. The final product is called pre-impregnated material.

Some advantages of this method are absence of solvent adders. Due to its simple manufacturing it is quite more economically viable than many processes.



Illustration 7. Equipment employed to produce pre-impregnated matrix

The process in the photo is divided into 5 sequences:

1. Unrolling the reinforced fibers.
2. Making the fibers pass through the melting polymer.
3. Adding PP around the continuous CF and heating it to stick it to the fibers.
4. Pressure to consolidate the polymer.
5. Cool down the tape and final rolling.

2.4.2. Transformation of pre-impregnated matrixes

Once conformed the tape, it will come down to the final transformation, where the product will have the physical geometry to achieve the final mechanical requirements. To transform it implies many factors such as pressure, temperature, and time to do the transformation, also, the equipment involved has to be carefully chosen. The rheological factors of the thermoplastic matrix have to be considered, too.

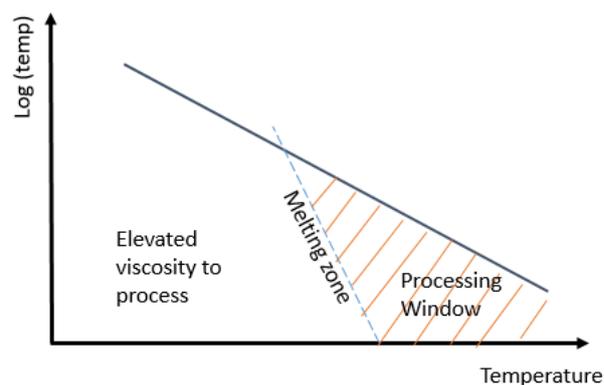


Illustration 8. Processing window of the PP polymer (extract from Produção de pre-impregnados de matriz termoplástica e fibras de carbono by Púria Esfandiari)

As seen in illustration number 7, to be able to do the transformation, the thermoplastic composite should be in the grey lined zone to achieve the transformation into the desired characteristics. Low temperatures won't change the polymer viscosity making it unable to transform, whereas high temperatures will cause degradation. Fast changes tend to cause internal pressure that also will reduce the mechanical properties, so it is very important to be in the correct zone to obtain a proper composite.

For the project, the method chosen was heat moulded compression, as for technical aspects it was easier to use this equipment rather than conforming it by pultrusion.

2.4.2.1. Heat compression moulding

Compression moulding, also known as press moulding, is the most used thermoset and thermoplastic polymer composite manufacturing process. Moulding compression is the process of moulding where a preheated polymer gets conformed in a cavity. Is the final previous step to achieve the composite.

This process is able to produce different parts with different lengths, thickness and forms. The objects it produces are also high in strength, making it attractive for different industries. It is a manufacturing process with high production volume capability, such as the automotive industry.

The pre-impregnated reinforced tape is put into the cavity part of the mould, between two plates of the press. The composite is pre-formed into the shape desired. Pre-forming is a crucial step to improve the performance of the composite.

Then curing process begins, the hydraulic plates apply the heat until the set temperature, when pressure commences, giving the piece the mould shape for the time needed.

Once, arrived at the time, heat stops, and only pressure is applied until the piece is at room temperature, finally, the plates pull away, leaving the resulting form.

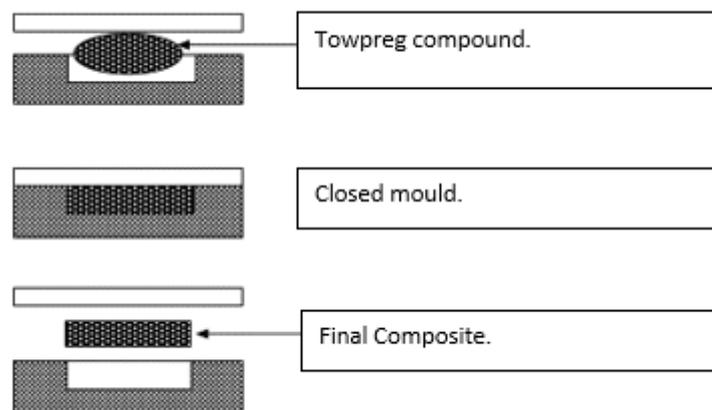


Illustration 9. Heat moulded compression process

Parts of its popularity stems from its use of advanced composites, these materials tend to be stronger, stiffer, lighter, and more resistant to corrosion than metal parts. Another advantage, is the ability to create very complex parts. It also allows for longer fibers than plastic injection moulding, resulting in stronger and stiffer composites. Meanwhile creating complex parts, the time and cost is a priority. This process is really suitable for a wide range of industries.

Experimental Part

3. Experimental part

For this part, all the experimental processes from having both elements separated till it is together in form of a tape and then into the final mixture as composite will be explained.

3.1. Materials

- **Polypropylene**, nowadays being one of the most used thermoplastics in the market presents itself with a lot of good mechanical properties. The polymer employed was ICORENE 4014 and was made for rotational moulding.



Illustration 10. ICORENE 4014 Polypropylene

Table 1. ICORENE 4014 properties

PROPERTIES	UNITS	ICORENE 4014
Density	g/cm ³	0.9
Tensile modulus	GPa	1.15
Tensile strength	MPa	24
Melting temperature	°C	170
Diameter	µm	400

- **Continuous Carbon fibers**, for this work the fibers employed, were from SIGRAFIL a company known for producing a vast extension of different carbon fibers with many purposes, the carbon fibers are known for their extreme lightweight but tremendous good mechanical properties for the area/volume ratio needed. The model used is *C30 T050 TP1 – TEX 3280*.



Illustration 11. SIGRAFIL carbon fibers

Table 2. Propertis of TORAYCA carbon fibers

<i>PROPERTIES</i>	<i>UNITS</i>	<i>C30 T050 TP1</i>
<i>Number of filaments</i>		50k
<i>Fineness of yarn</i>	Tex	3280
<i>Density</i>	g/cm ²	1.80
<i>Single filament diameter</i>	μm	7.0
<i>Tensile strength</i>	GPa	4.0
<i>Tensile modulus</i>	GPa	240
<i>Elongation at break</i>	%	1.70
<i>Filament resistivity</i>	μΩm	15

3.2. Equipment involved

The set up to produce composite was conformed with all the equipment seen on the photo. The set up to produce the pre-impregnated matrix could be divided into 3 different parts or modules.



Illustration 12. Equipment used

3.2.1. Tape manufacturing equipment

The first module contains the bobine with the carbon fibers and a white roller to prevent the initial carbon fibers to mix with the already coming ones with polypropylene on it. The second part is the melting machine to produce the pre-impregnated material, and the last module is another roller to store the tape.

As seen in the photo below, there is the melting machine where on the top part, PP and CF enter as separate elements, and through heat and pressure, it combines into a partially cured tape.

Two resistances power the machine (converting electrical energy into heat) therefore the polymer can be heated and melted, lastly, the pressure is done by the geometry of the machine reducing its space where fibers and PP have to flow.



Illustration 13. Melting machine

After leaving the melting machine, pressure must be kept all time, since the pre-impregnated matrix is not yet fully cured and need pressure from preventing the continuous carbon fibers from spreading out and forming the desired tape.



Illustration 14. Melting machine (bottom part) and pressure roller

Two thermocontrollers were installed to control the temperature applied alongside two resistances, to establish a consigned temperature and not let it pass this point, trying to enhance the best combination for the polymer to be melted and stick to the fibers. The thermocontrollers are controlled by two relays (one each).



Illustration 15. Relays and Thermocontrollers

The work by the last module is the same as the first one, the only difference is for storing the pre-impregnated material. Alongside two smaller rollers to keep the pressure on and make the composite flow smoother.

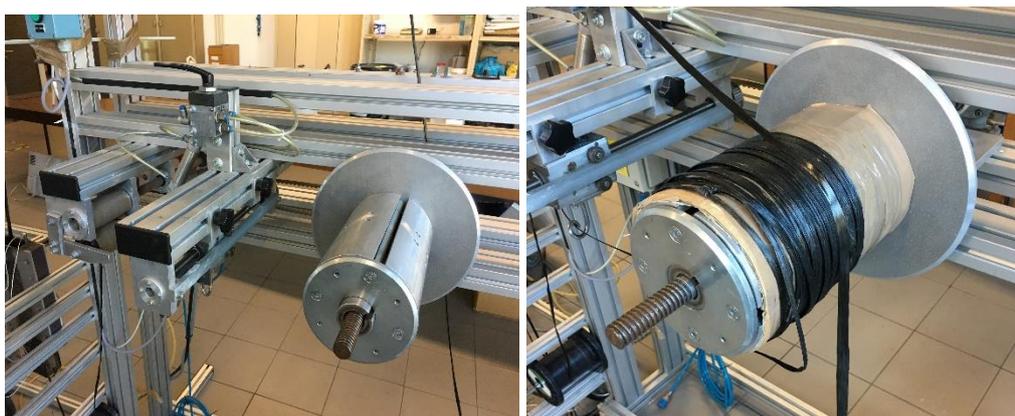


Illustration 16. Last module to produce tape

3.2.2. Composite equipment

The last equipment needed to produce the composite was the heat moulding compression machine from GISLOTICA Mechanical Solutions. Stripes from the bobbins of the tape were compressed and heated to conform to a composite plate.



Illustration 17. Heat moulding machine

3.2.3. Testing equipment

One of the tests realized to the composite was the flexural test, which was realized by SHIMADZU LOAD CELL SPE-100KN. Although to get to the stripes that were tested, extra equipment was used such as cutters and other tools.



Illustration 18. Flexural test equipment

The second test realized was the calcination test. The equipment used for this part was a scale, APX-200 with an error of 0,1 mg which was employed for knowing the mass weight before and after the

calcination test carried by the oven from *NABERTHERM* company. This oven, *LHT08/16*, has a working range from 30 to 3000°C.



Illustration 19. Calcination equipment

3.3. Process

3.3.1. Set Up

To be able to produce some composite tape, first was time to prepare the tape manufacturing machine. From cleaning every part (erasing mainly previous polymer that was stuck in there) to build it up and setting up the best combination possible so heating and polymer losses would be as low as possible. The machine combines two different parts, first, a deposit to introduce the fibers and polymer were will be melted, the second part, the pressure cabin whereby guiding the fibers and making the polymer pass through a small hole get together as a pre-impregnated matrix.

Once done the build-up, was time to introduce the heat resistances to melt the polymer down. Started with three old resistances that barely could be stuck to the machine so in the end it was decided to use two new ones, and would remain as the final configuration.

Now, it was time to power those resistances, so the electrical configuration was made, with the help of two thermal controllers and two relays, one for each resistance, so each of them could have different temperatures.

Last but not least, was to connect the fibers to an automatic pulling machine so the process could be done constantly. Few tweaks had to be made to make the process steadily as sometimes the carbon

fiber wigs weren't rolling as supposed and the pulling machine tried to pull anyway, creating additional stresses resulting in an excess of electricity and blowing up many fuses due to this high picks of current. It was decided to feed manually the extrusion machine to not create this high demands of current.

3.3.2. Tape Production

As seen in the photos before, raw materials section 4.1, when mixing the Polypropylene (PP) and the Carbon Fibers (CF) in the extruder machine it was obtained the pre-impregnated matrix.



Illustration 20. Pre-impregnated matrix

Once obtained the pre-impregnated matrix, the material had to be converted into a composite, since the method chosen was heated moulding compression, it was decided to make stripes of 20 cm large and make a woven, using the crisscrossed technique, and 20x20 cm woven were done.



Illustration 21. Pre-impregnated stripes

Once cut the stripes, preparation of the woven began by setting the first stripes in one direction, the second step was repeating the process but aligning them in a 90° turn, making the fibers pass the second-row fibers one up, one down and repeating the process as much as possible. The four wovens contain approximately 18 pre-impregnated fibers in one direction and 9 in the other direction.



Illustration 22. Build of the woven

Final result of the woven:



Illustration 23. Criss-crossed woven

3.3.3. Heated Compression Moulding

Once done the woven it was time to produce the laminate/plate to acquire the composite. To produce it was used the heat press from the material lab at ISEP.

Four woven with the same size (20x20cm) and stripes on each direction were made (18, 9 respectively), to produce the laminate was put symmetrically, the external layers were looking in the same direction, and the two intermediate were turned 90° from the external ones, thus the plate would have the same rigidity in both directions.



Illustration 24. Woven entering Heat mould compression machine

It was programmed to heat the woven until 250°C while creating a restriction of movement, then when reached the temperature a second stress of two tones was done for about five minutes to ensure the woven got stuck. After this time, the temperature is lowered down until room temperature, still making pressure for 40 minutes. Then the composite plate is created.

Table 3. Heat mould compression phases

Temperature (°C)	Force (ton)	Time (min)
250	0	20
250	0	20
250	2	5
20	2	40

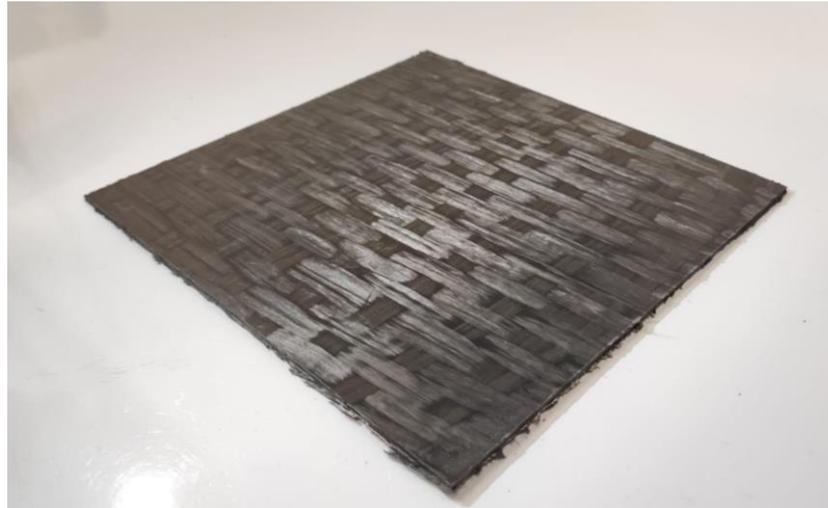


Illustration 25. Composite plate obtained

3.3.4. Polishing and cutting

To be tested properly, the plate needed to be straight-sided since it can't give valid results if the geometry is irregular, it may cause fast propagation of fractures ending with non-valid results, too. The result was a plate of 19x18 cm.

Twelve pieces were cut, 6 were the carbon fibers were aligned to the axis and 6 opposed to that direction, to test the mechanical capabilities of each direction.

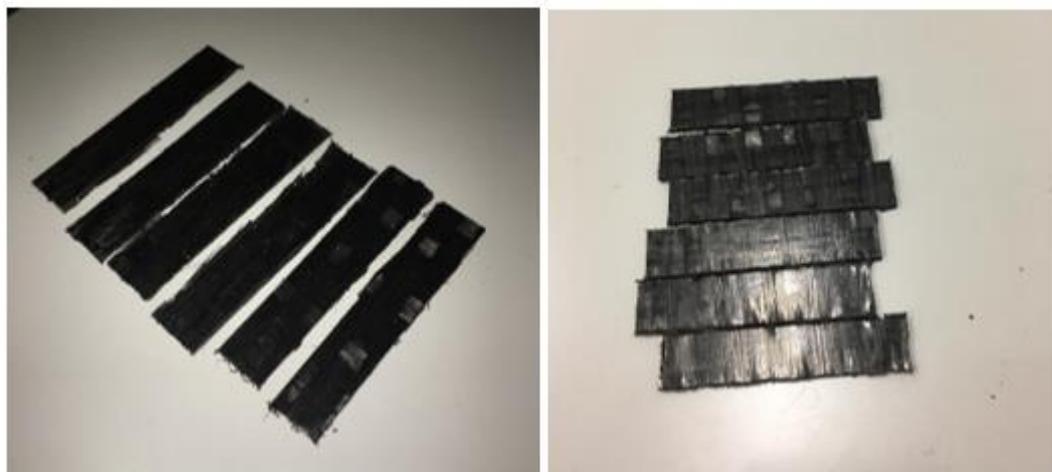


Illustration 26. Composite stripes for flexural test

3.4. Polymer mass

This testing permits to know how much polymer contains the composite, the percentage is a relevant factor since it will guarantee the success of the process, saying if the process realized is able to make a good impregnation between the polymer and the high text fibers. The more polymer containing the composite, the less carbon fiber implies resulting in a cheaper production process.

ISO 1172 linked to the calcination tests, explains the process and the fundamental aspects such as temperature to set for the thermosets and thermoplastics matrixes, but for the composites made of carbon fiber there is a problem, carbon fiber may lose some of the mass when exposed to high temperatures and this would make the testing not much reliable. Although at 430°C carbon fibers degradation starts, the ratio to lose its weight is much lesser than the polypropylene. The mass loss for the carbon fibers can be expected minimum and influence on the results none.

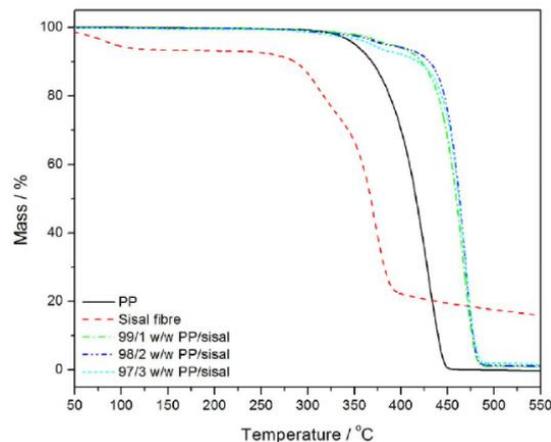


Illustration 27. TGA analysis for PP (via Researchgate)

As seen in illustration 29, polypropylene start to lose its mass when exposed to more than 450°C, when exposed to 475°C loses a substantially good part of its mass weight, the test was conducted under a 480°C for 12 minutes in the *NABERTHERM LHT08/16* oven to assure all the composite had reached the 475°C temperature mark.



Illustration 28. Calcination phases

To know how much polymer weight is contained in the composite there is an easy rule to estimate it, knowing the initial weight and the weight of the fibers, then it is possible to obtain the theoretical mass polymer weight.

The loss percentage mass of the composite is ruled by the equation 3.1:

$$\Delta p \% = \frac{(m_2 - m_1) - (m_3 - m_1)}{(m_2 - m_1)} \times 100 \quad (\text{Ec. 3.1})$$

Where:

- Δp is the tant per cent of mass variation
- m_1 is the mass of the cup
- m_2 is the mass of the cup plus the composite stripe before calcination, in grams (g).
- m_3 is the mass of the cup plus the composite stripe after calcination, in grams (g).

The fraction of the mass fibers is ruled by the calcination test, where:

- w_f is the carbon mass fraction

Knowing the mass fraction, by the mixture rule can be known the carbon fiber volume fraction from the equation 3.2:

$$v_f = \frac{\frac{w_f}{\rho_f}}{\frac{w_f}{\rho_f} + \frac{1 - w_f}{\rho_p}} \quad (\text{Ec. 3.2})$$

Where:

- v_f is the volume fraction of fibers
- ρ_f is the density of the fibers, (g/cm³)
- ρ_p is the density of the polymer, (g/cm³)

Then, the elastic module can be estimated, by the equation 3.3:

$$E_{comp} = E_f * v_f + E_p * (1 - v_f) \quad (\text{Ec. 3.3})$$

Where:

- E_{comp} it's the theoretical elastic module of the composite, in Giga Pascal (GPa).
- E_f it's the theoretical elastic module of the carbon fibers, in Giga Pascal (GPa).
- E_p it's the theoretical elastic module of the polymer, in Giga Pascal (GPa).

3.5. Flexural Test

The flexion or bending test was ruled by the ISO 14125 normative. ISO 14125 is a test method to determine the flexure properties of fiber-reinforced plastic composites. There are two methods used, Method A for a three-point flexure test and Method B for a four-point flexure test.

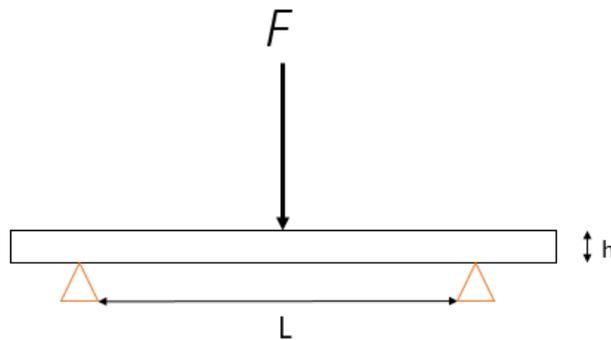


Illustration 29. Method A, three point test

This standard is based on ISO 178 but deals with fiber-reinforced plastic composites. As such it retains the test conditions relevant for glass-fiber-reinforced systems. The test conditions are extended from ISO 178 to include both three-point (Method A) and four-point (Method B) loading geometries, and to include conditions for composites based on newer fibers such as carbon and aramid fibers. The test is done to determine the property data for material screening or quality control.

Method A was chosen, realized under the SHIMADZU machine with a 100 kN force cell.

To avoid unacceptable breaks and have valid results the standard provides a relation of 16:1, 20:1, 40:1, or 60:1 ratio between the supports and the thickness of the composite. Our ratio was 40:1.

The properties tested were;

Rupture Stress

$$\sigma = \frac{3 * F * L}{2 * b * h^2} \quad (\text{Ec. 3.4})$$

Where:

- σ the flexural stress, in Mega Pascal (MPa)
- F is the maximal force applied by the machine, in Newton (N)
- L is the length of the between the two supports, in millimetres (mm)
- b is the width of the composite, in millimetres (mm)

- h is the thickness of the composite, in millimetres (mm)

Strain deformation

$$\varepsilon = \frac{6 * y * h}{L^2} \quad (\text{Ec. 3.5})$$

Where:

- ε is the strain deformation in the interior layers.
- y is the deformation in the medium layer, in millimetres (mm)

Elastic modulus by flexion test

$$E_f = \frac{L^3}{4 * b * h^3} * d \quad (\text{Ec. 3.6})$$

Where:

- E_f is the elastic modulus when flexed, in Mega Pascal (MPa)
- d is the slope of the strength-deformation elastic part test, in Newton-millimeters (N/mm)



Illustration 30. Flexural test

Experimental Results

4. Experimental Results.

4.1. Heat compression moulding

After heat and pressure for an hour and twenty minutes, the composite plate was obtained. Overall, the plate had a good looking, all the layers stuck together well, thus the polymer had melted creating one piece out of four previous crisscrossed layers. The thickness of the plate was averaging 2.06 mm. On the borders, the fibers had spread away a little bit but with a manual cutting, it re-gained the squared shape to be tested. The final dimension was 190x180 mm, twelve stripes were cut for flexural test and two for calcination.

4.2. Calcination test

It is really important to know the theoretical mass weight of the polymer in the composite, this factor will influence the mechanical properties of the future composite. For instance, the more polymer there is the less module it'll have the composite or consequently more resistance to fracture.

All formulas are referenced and explained in the chapter 3.4 of this report.

Table 4. Calcination results

	Specimen 1	Specimen 2
m_1 (g)	20,6914	19,0474
m_2 (g)	22,0913	20,6183
m_3 (g)	21,6502	20,1144
Mass loss (%)	31,50	32,07
Mass fibers (w_f)	0,6850	0,6793
Volume fraction (v_f)	0,5209	0,5143
E_{comp} (GPa)	85,18	82,89

The percentage obtained on mass loss is a high number, compared to past studies on the same subject and materials, the percentage has increased by 5%, although those are good news, still, the mechanical properties need to be tested.

The theoretical module predicted by the equations in chapter 3.4 is high enough to determine the composite stripes will have good mechanical properties. It has more Young modulus than many other metals, which, when compared in weights, this composite has the surplus of being lightweight.

4.3. Flexural test.

Test conditions were, distance between supports of 80mm, and final length about 100mm, machine speed of 2mm/min, average thickness of the tubes of 2.06 mm.

Table 5. Flexural test

FLEXURAL TEST RESULTS

<i>Test tube</i>	Rupture Stress (MPa)	Elastic Module (GPa)
1	154,29	43,28
2	151,45	40,06
3	153,56	38,15
4	169,51	41,82
5	160,01	41,74
6	147,25	38,81
7	85,31	16,90
8	86,48	18,06
9	75,32	14,52
10	71,01	13,77

Twelve test tubes were tested, on this chapter, only two graphics are shown and ten results due to two specimens had really low modules and were ruled out, the rest are on annex A1. These two graphics are from two different stripes, hence, the variety of the results, since in the first graphic the composite reaches stress of over 350 MPa, and in the second graphic shown the stress module is reduced to 140 MPa approximately. Why then this difference, on the first tube test, the carbon fibers were aligned

parallel to the long axis while on the other test tube the carbon fibers were perpendicular to the stressed axis being less resistant.

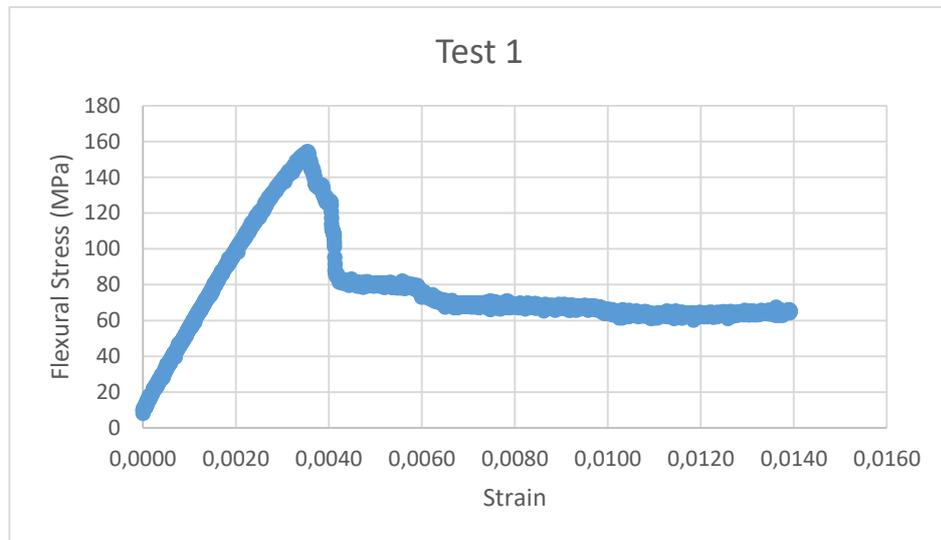


Illustration 31. Stress-Strain cure, parallel axis

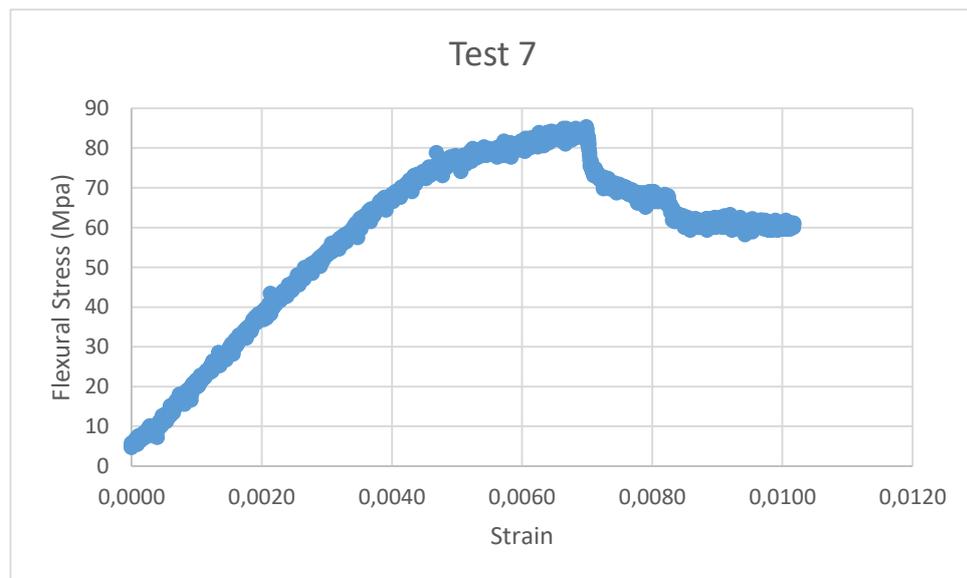


Illustration 32. Stress-Strain curve, opposite axis

By looking at the graphics, the stress-strain curve is expected as it is meaning the production of the material is alright and consistent, which by improving minor problems to make steady the production, this composite could be produced at the ISEP lab with satisfactory results.

The first 6 pieces tested (aligned stress axis) reach up to 160 MPa, by doubling the fibers in that direction, would mean double stress can be reached, this would be about 320 MPa, considering the manufacturer sheets that expects a maximum of 400 MPa for CF, it can be said that the produced composite is really good.

Table 6. Deviation of specimens

<i>Experimental/ Flexural test (GPa)</i>	<i>Media (GPa)</i>	<i>Sstandard Deviation (%)</i>	<i>Experimental/ Flexural test (GPa)</i>	<i>Media (GPa)</i>	<i>Standard Deviation (%)</i>
43,28	40,90	1,68	13,77	15,71	1,37
40,06		1,67	16,90		1,58
38,15		2,13	18,06		1,83
41,82		1,92	14,52		1,74
41,74		1,76			
38,81		1,80			

As mentioned before on the flexural stress accepted by each test tube and its variety, mention the 40,90 and 15,71 GPa average respectively are really good numbers for these plates, having a tremendous good elasticity module, therefore many new pieces can be made to replace the non-environmentally ones or heavier ones. Besides, be noted, that if the manufacturing of the lab pieces had been made all in the same direction, aligning them with the stress axis, the elasticity module could double the first module, which would be even a better result.

The deviation between the stripes modules is minimum, endowing the results with authenticity.

4.3.1. Theoretical vs Experimental Modules

As seen in chapter 4.2 with the calcination test, two theoretical modules could be calculated thanks due to the mass loss, on chapter 4.3 the modules were taken experimentally from a linear regression. Although are different pieces, the stripes come from the same plate.

Note: On the experimental column, only the 6 first test tubes are shown due to having the same align of the fibers as the calcination test tubes.

Table 7. Comparison of Elastic Modules

<i>Theoretical/Calcination test</i>	<i>Experimental/Flexural test</i>	<i>Difference (%)*</i>
85,18	43,28	49,18
82,89	40,06	52,97
	38,15	55,21
	41,82	50,90
	41,74	50,99
	38,81	54,43

*difference between module 1 from calcination test and rest of experimental modules

If a comparison is made between the second module of the calcination test and the rest of the modules obtained by the flexural test, differences reduce a little bit, but still spare enough to accept them.

The disparity in the numbers is quite elevated, although that doesn't mean one column might be wrong, the calcination test only has in mind the quantity of fibers, and if in the flexural test the fibers were aligned together the module would look almost exact, therefore, it can be concluded that those stripes from the plate have a really good elastic module.

Conclusions

Conclusions

To sum up, for this project, the work carried was to produce thermoplastic composites plates out of carbon fibers as the reinforcing material and polypropylene in form of powder as the matrix, thanks to the melt impregnation machine and heat compression moulding process. Finally, it was tested to evaluate the quality of the material produced.

The first conclusion is that producing composite made of high TEX carbon fibers and a thermoplastic matrix at the ISEP lab with equipment that is not state of art equipment, has been possible.

Some tweaks to the process and a new melting machine where the heat induced to the polymer is more precise can lead to a more optimal composite in mechanical terms, but overall, the whole manufacturing has been steady and the resulting stripes for practical tests are close to homogeneity, that would be expected when wanted to be produced at higher scales.

Controlling better the conditions, especially the temperature when melting the polypropylene will result in better efficiency of the polymer employed since the losses will be lessened and the probability of the PP sticking to the CF is higher.

The second conclusion is that more precise equipment may be beneficial to start making different combinations on the polymer amount in the composite to obtain different mechanical properties since it'll be easier to control all the factors.

When producing the tape, after two bobbins rolled, the best combination for an optimal tape was about a speed of 1 m/min for a desired impregnation.

The composite plate tested at the ISEP lab has proved the carbon fibers have extraordinary mechanical properties, and combined with suitable thermoplastics such as PP, can be employed in various aspects in the engineering world. The composite produced at ISEP could already be used in the market for some applications.

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Annexes

Annex

A1. Flexural test results

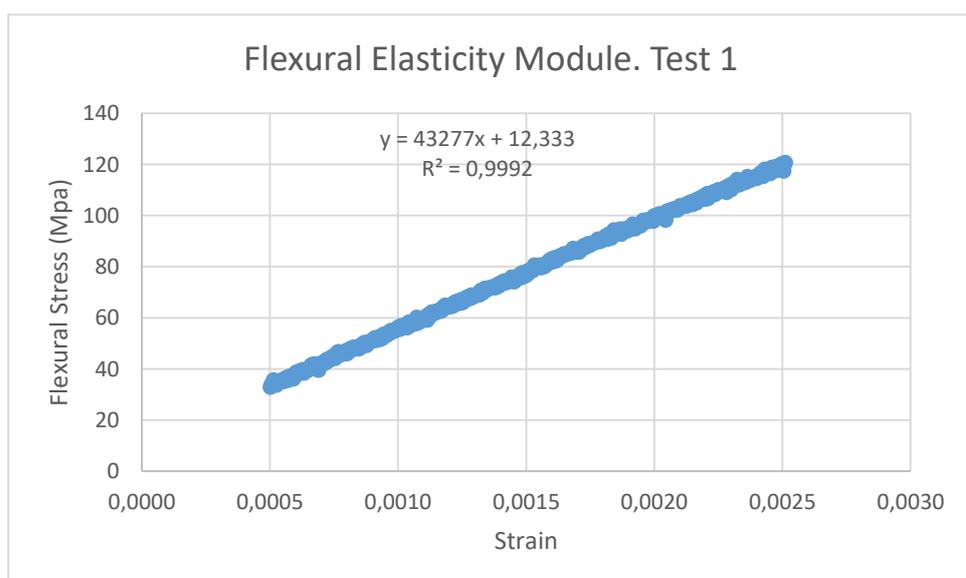
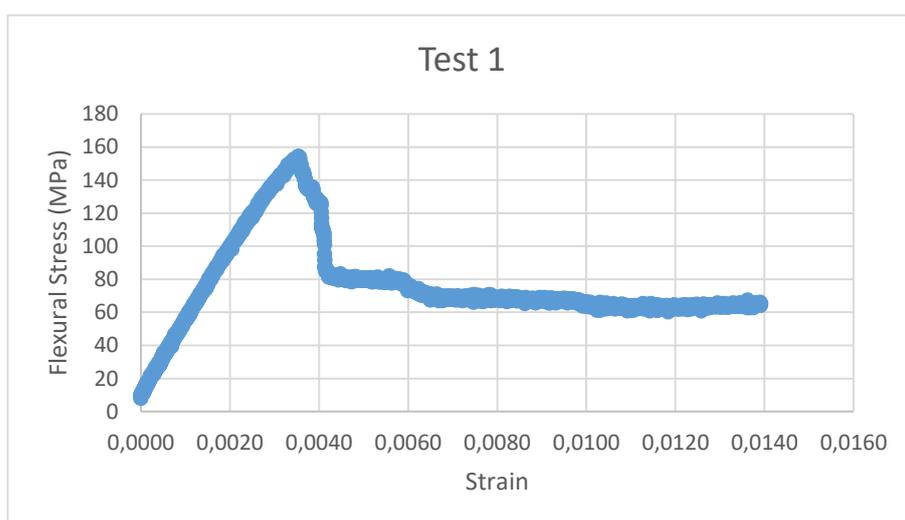
*All units are in milimeters (mm).

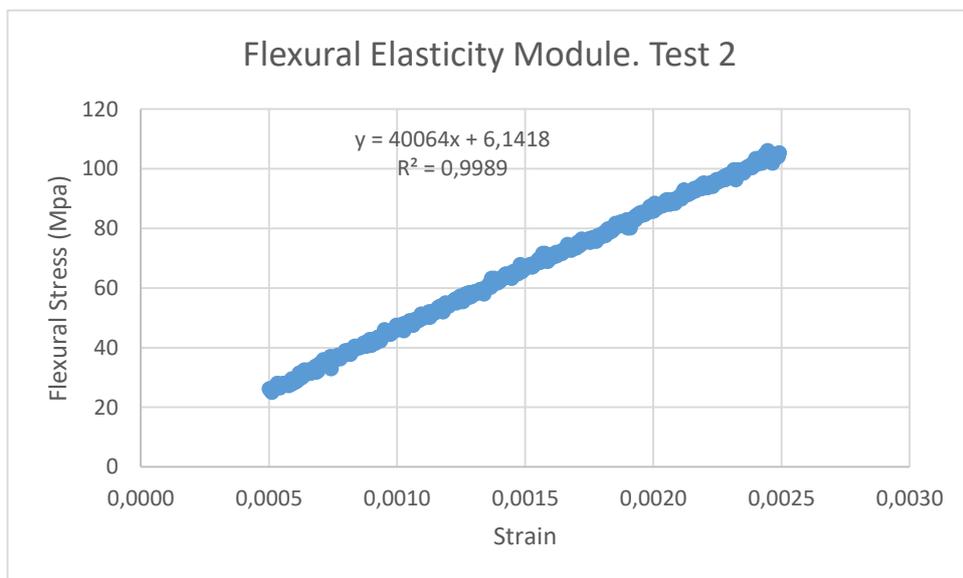
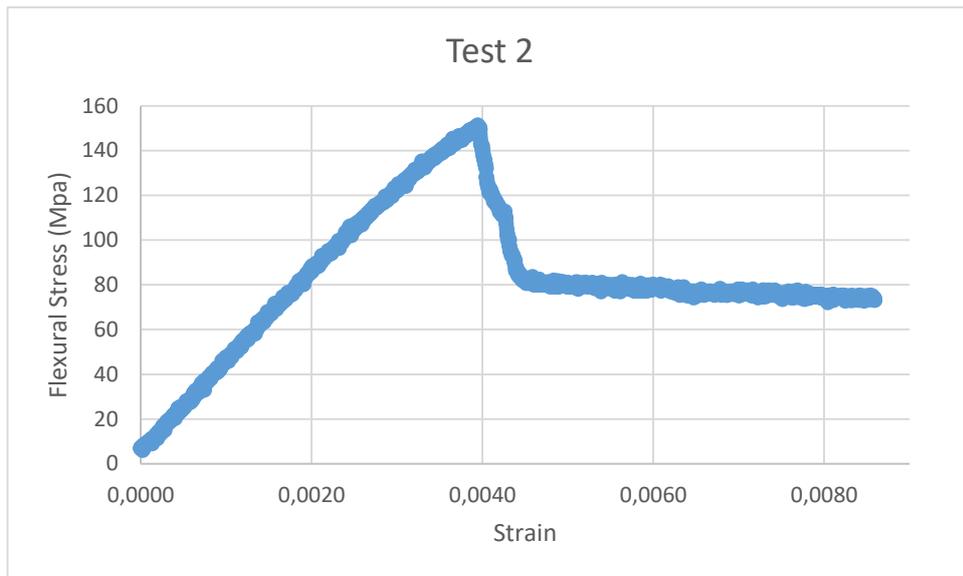
Test tubes	Width	Average	Thickness	Average
1	20,21	20,67	2,13	2,23
	20,81		2,32	
	21		2,24	
2	21,02	21,11	2,22	2,18
	21,15		2,2	
	21,17		2,11	
3	19,04	18,93	2,27	2,26
	18,83		2,21	
	18,93		2,3	

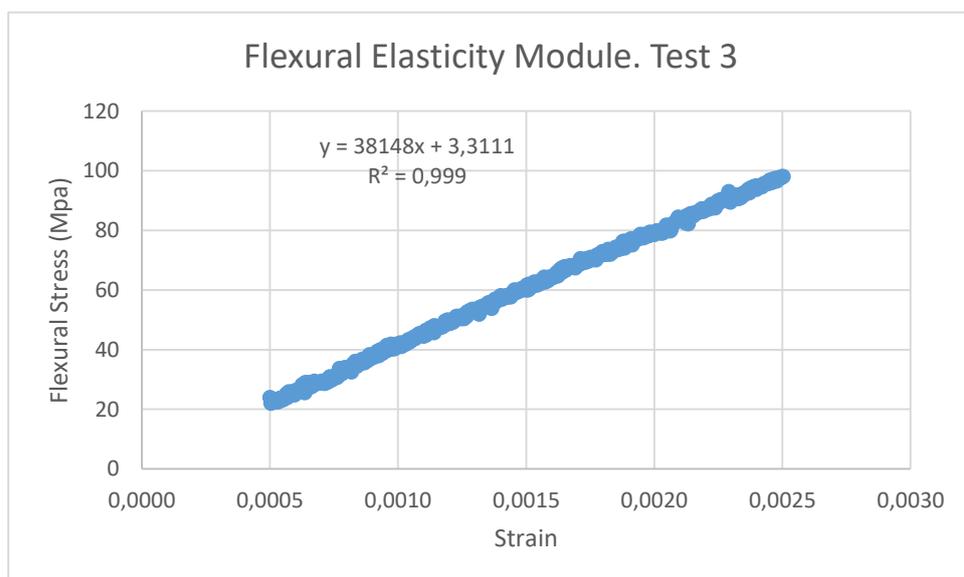
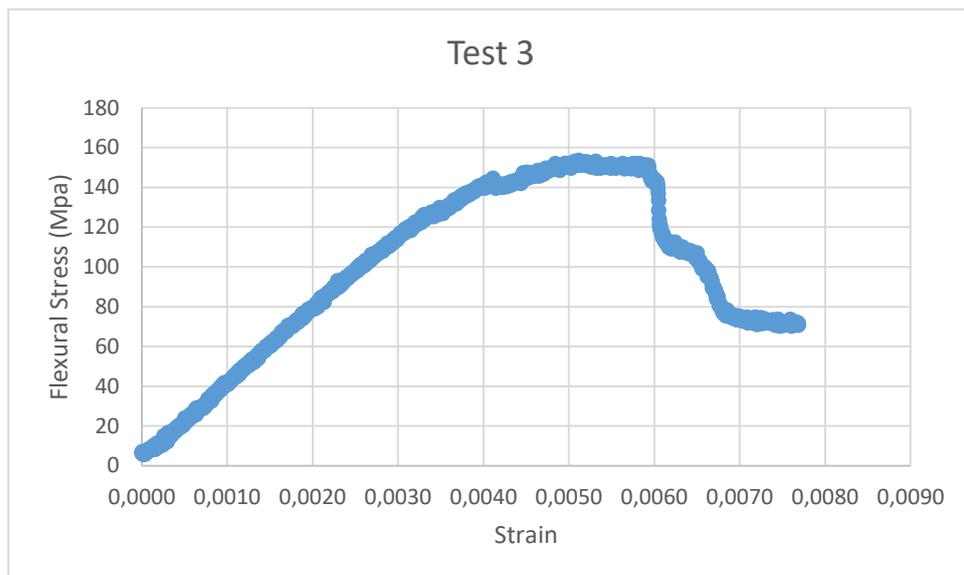
Test tubes	Width	Average	Thickness	Average
4	19,12	19,54	2,12	2,22
	19,5		2,26	
	20		2,27	
5	19,87	20,12	2,45	2,30
	20,22		2,32	
	20,26		2,12	
6	19,76	19,74	2,09	2,17
	19,74		2,17	
	19,72		2,25	

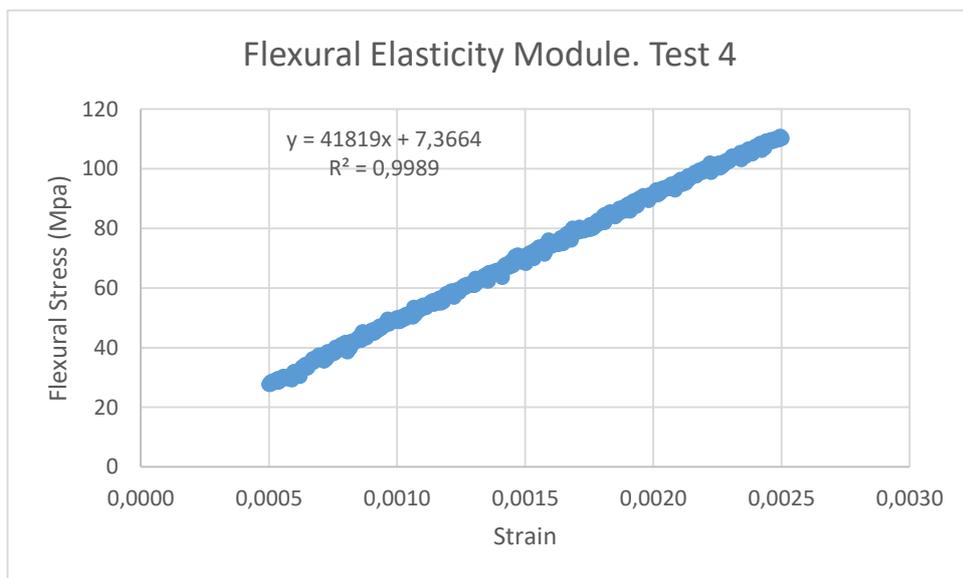
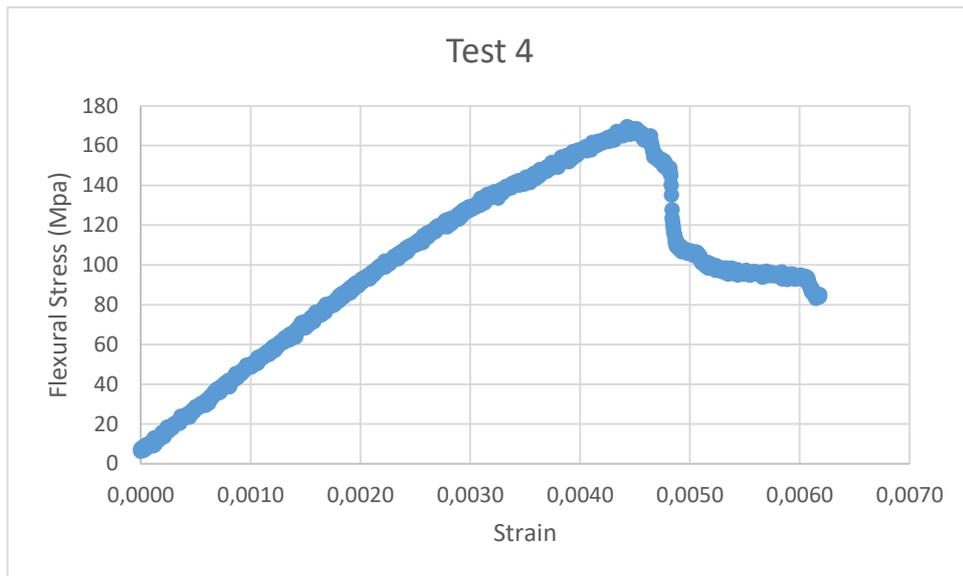
Test tubes	Width	Average	Thickness	Average
7	19,8	19,78	2,25	2,29
	19,8		2,31	
	19,74		2,31	
8	19,63	19,66	2,37	2,28
	19,69		2,29	
	19,66		2,17	
9	19,05	19,53	2,53	2,39
	19,59		2,37	
	19,95		2,26	

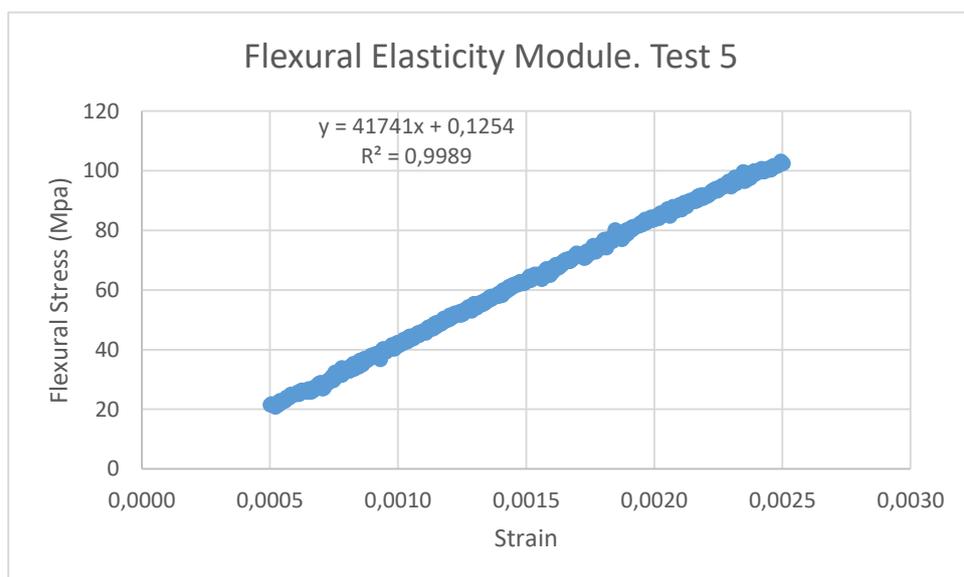
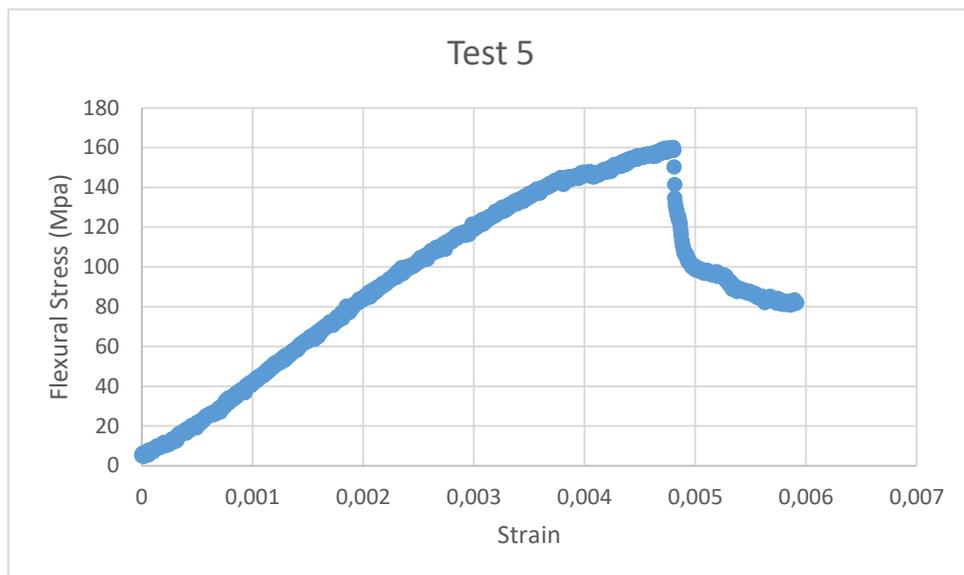
Test tubes	Width	Average	Thickness	Average
10	19,55	19,63	2,23	2,31
	19,59		2,31	
	19,75		2,4	
11	18,16	18,54	2,18	2,32
	18,63		2,41	
	18,84		2,37	
12	19,87	19,86	2,26	2,28
	19,77		2,26	
	19,93		2,33	

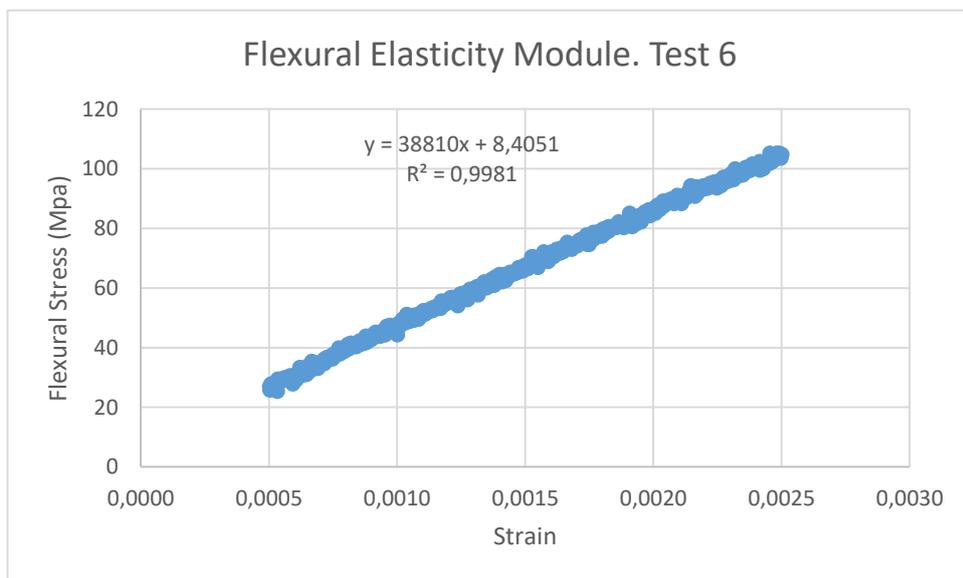
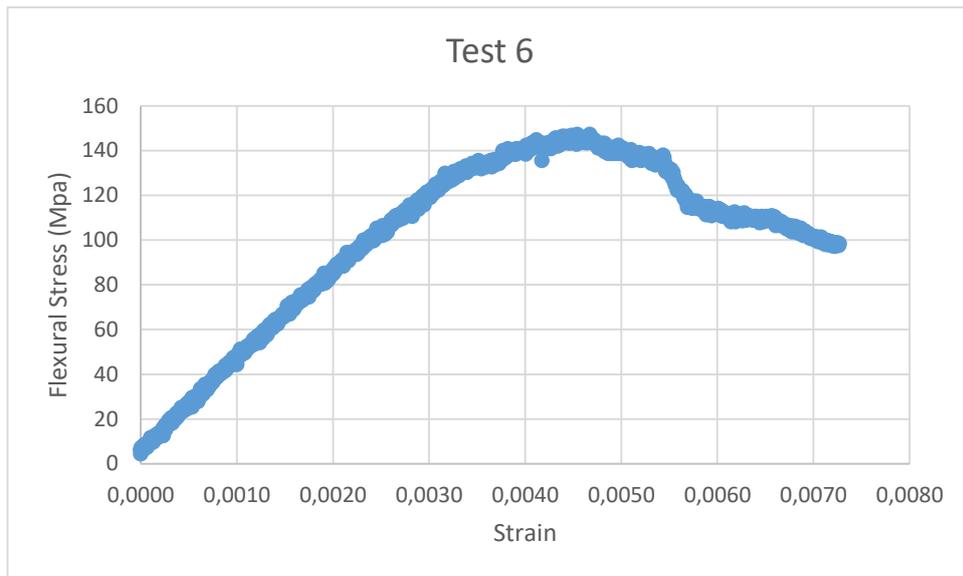


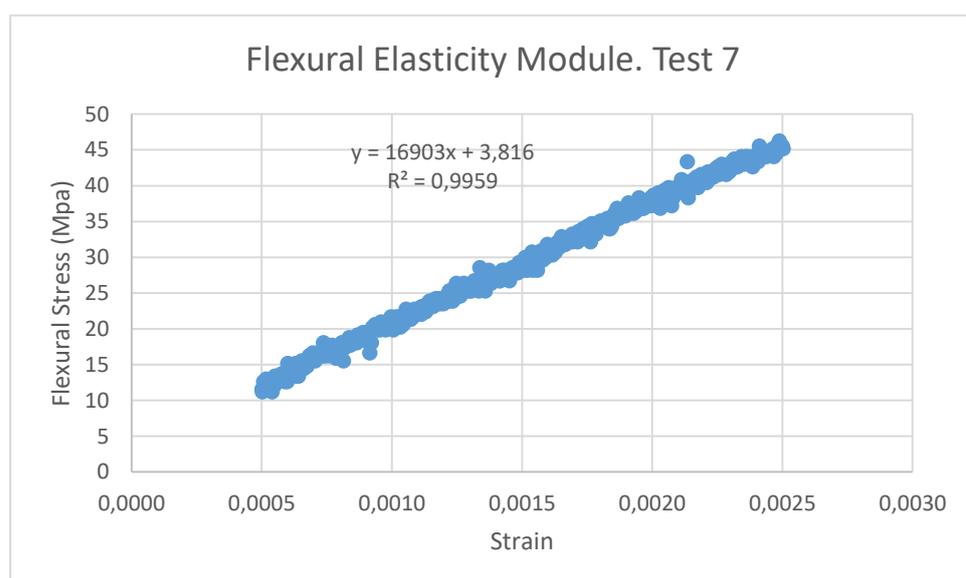
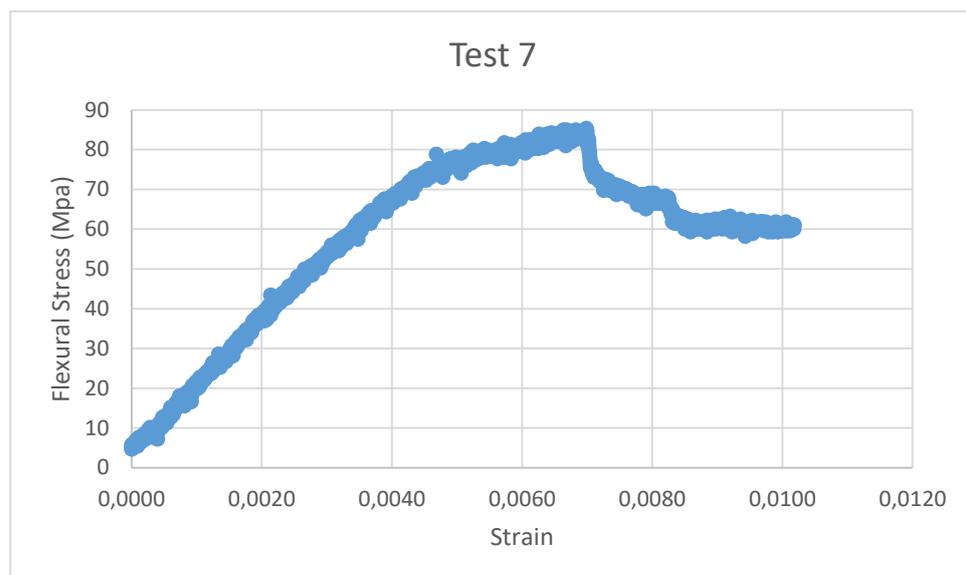


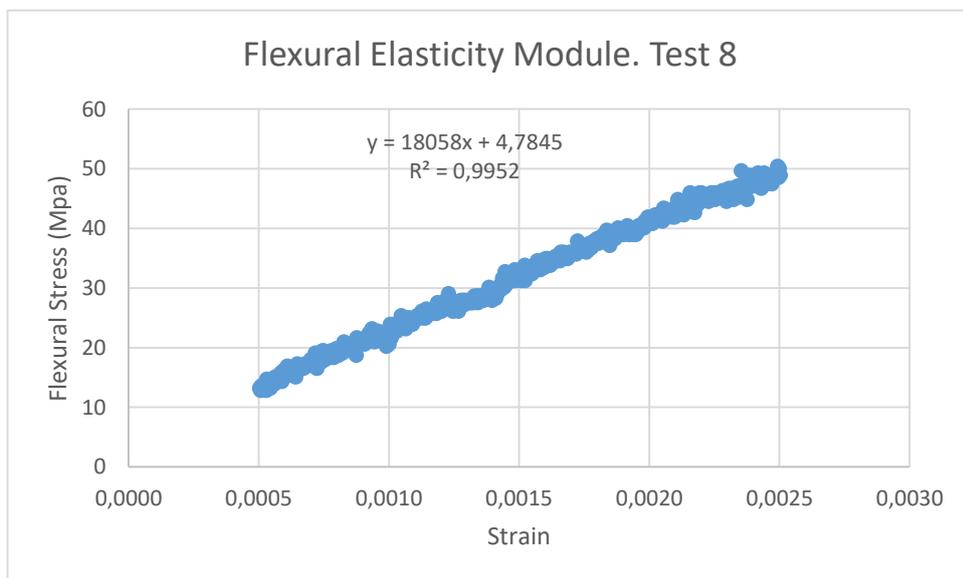
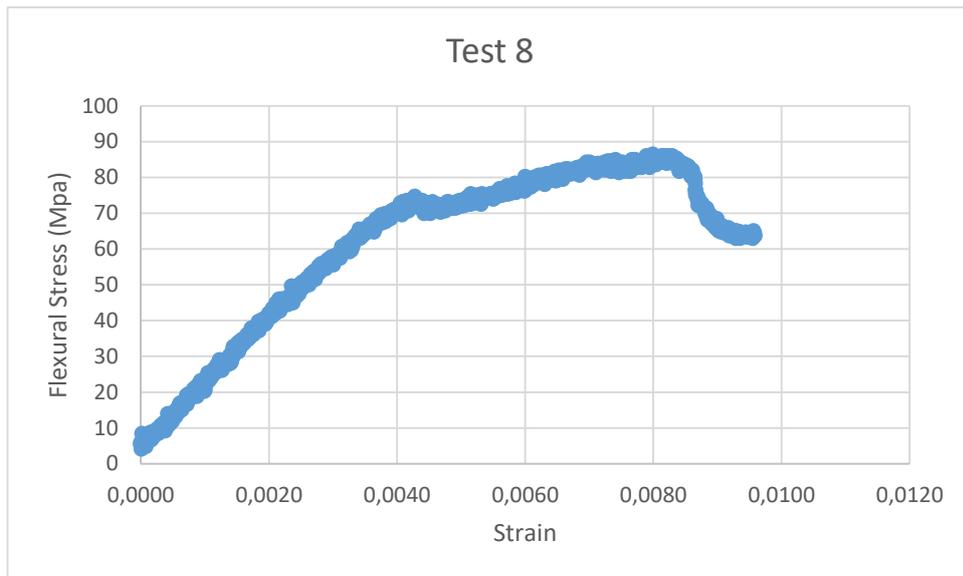


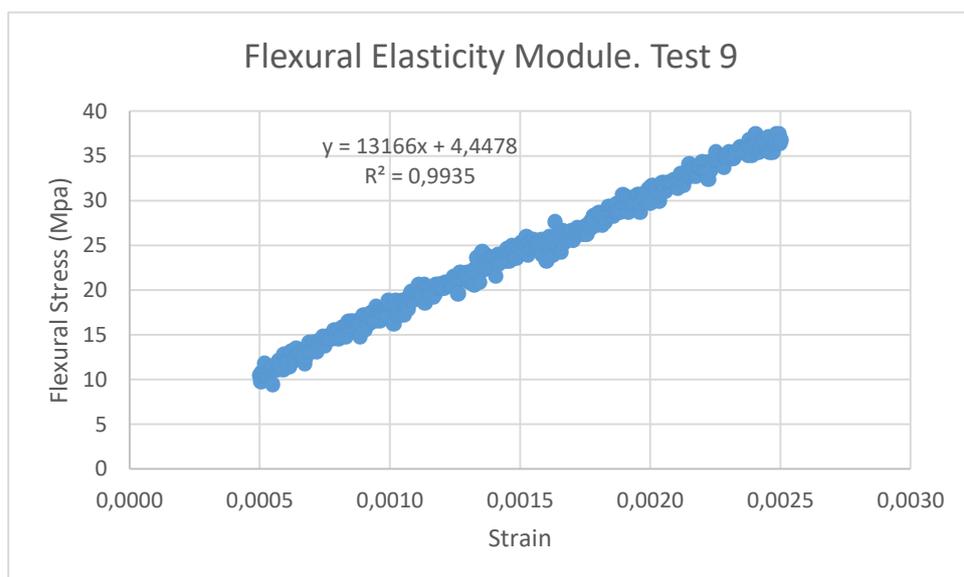
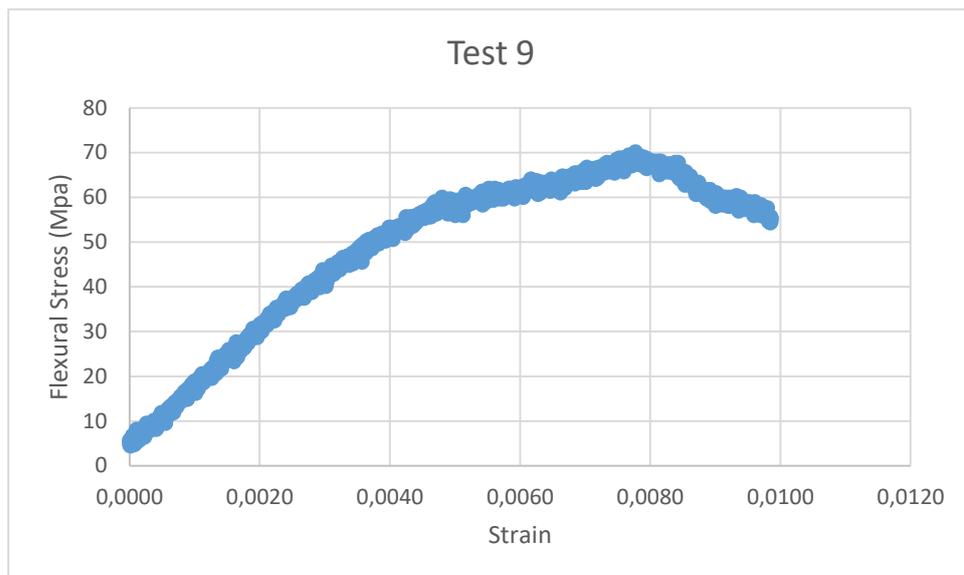


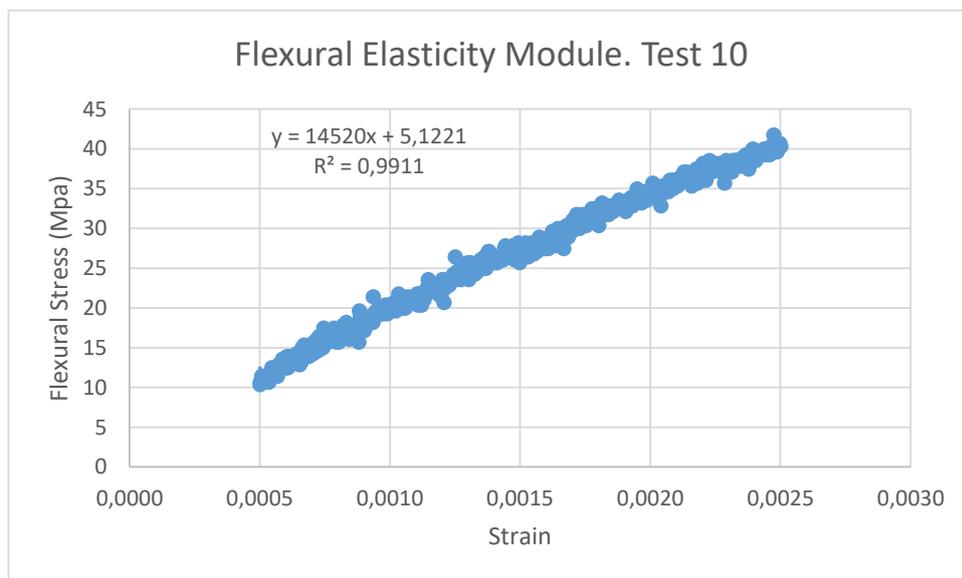
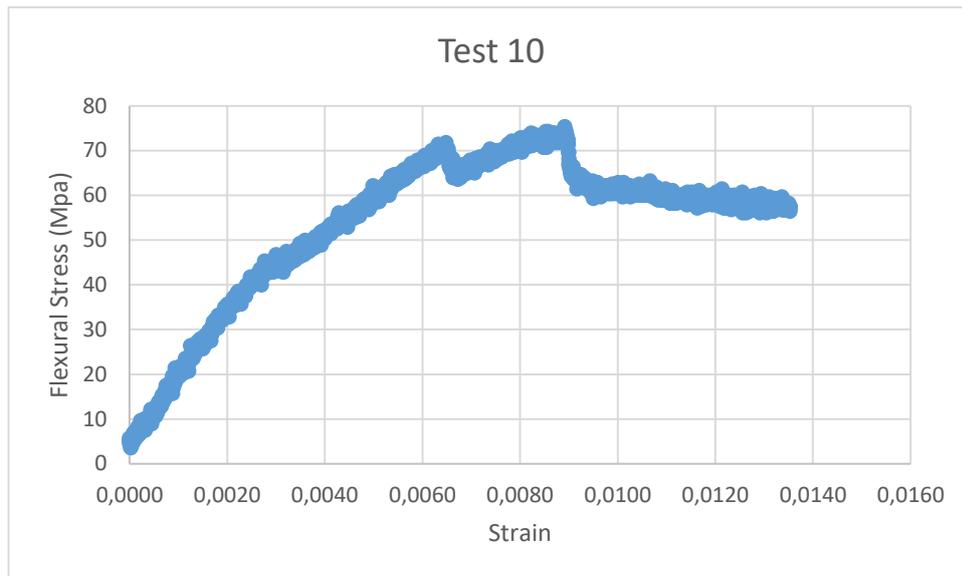


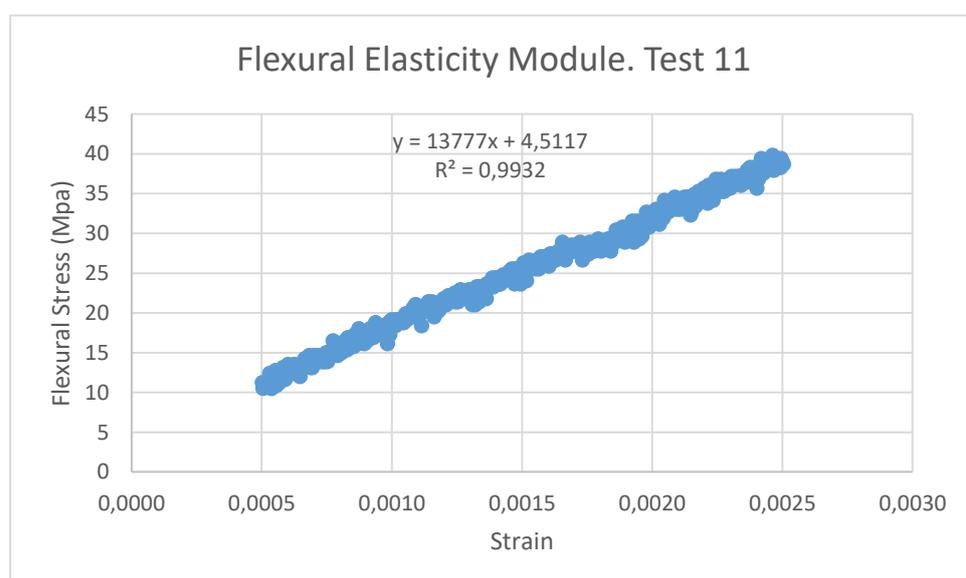
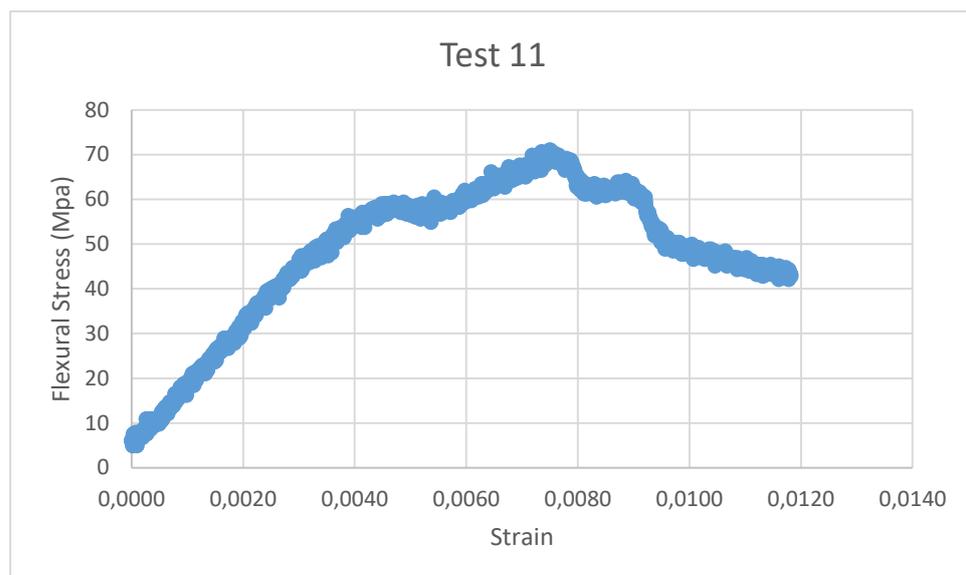


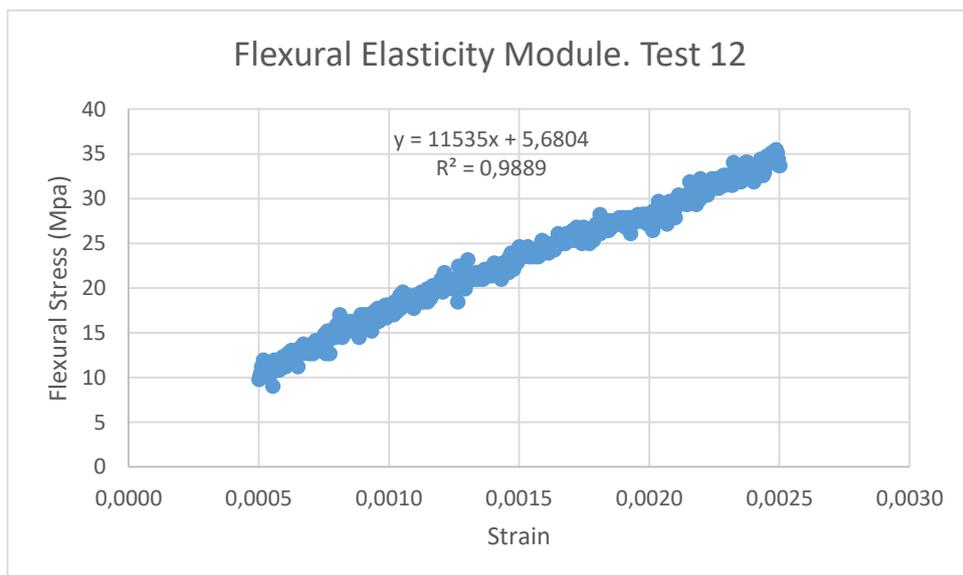
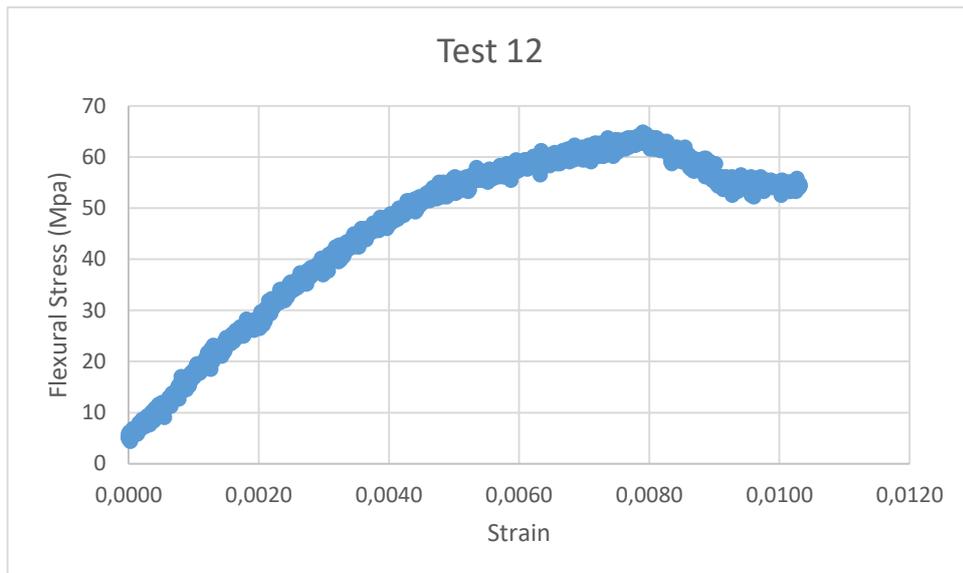












A2. Technical Sheets

Carbon Fiber from SGL Group.*

+

Continuous carbon fiber tow for fiber-reinforced thermoplastics



† Continuous carbon fiber tow with thermoplastic-compatible size

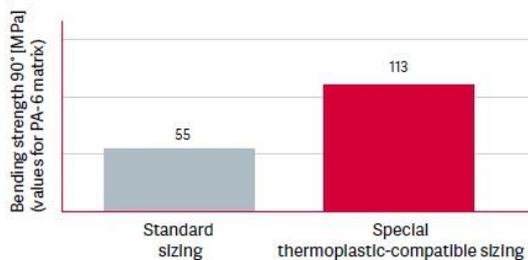
One of our innovations is a continuous carbon fiber tow for fiber-reinforced thermoplastics.

Thanks to a special size developed by us, the carbon fibers can be optimally bonded to the thermoplastic matrix. In this way, the high stiffness and strength of the fiber can be fully transferred to products and their components.

Thermoplastic carbon fiber composites open up new possibilities for serial production. Our innovative fibers are suitable for very diverse thermoplastic production chains and show good spreading behavior for textile processes.

Our fibers form the basis for these composites, enabling the outstanding properties of carbon fibers to be combined with the typical processing properties of thermoplastics. The composites can be readily shaped, repaired, and recycled. In addition, they permit short production cycles and facilitate product manufacture by making components weldable. So our material makes an important contribution to sustainability and efficiency.

Mechanical properties achieved with thermoplastic-compatible sizings



Material data of our SIGRAFIL® continuous carbon fiber tow

Properties	Units	C T50-4.0/240-E100
Number of filaments		50k
Fineness of yarn	tex	3300
Density	g/cm ³	1.80
Filament diameter	µm	7
Tensile strength	GPa/ksi	4.0/580
Tensile modulus	GPa/Msi	240/35
Elongation at break	%	1.7
Single filament resistivity	µΩm/µΩin	15/590

Polypropylene ICORENE 4014. *



ICORENE[®] 4014
Polypropylene Copolymer
Rotomolding

Product Description

ICORENE[®] 4014 is a polypropylene copolymer that has been specifically developed for rotational moulding.

This grade is UV stabilised and suitable for applications requiring high stiffness and high temperature resistance.

General

Material Status	• Commercial: Active		
Availability	• Asia Pacific	• Europe	• Latin America
Additive	• UV Stabilizer		
Features	• High Heat Resistance	• High Stiffness	• UV Resistant
Uses	• Automotive Under the Hood		
Appearance	• Black	• Natural Color	• Unspecified Color
Forms	• Powder		
Processing Method	• Rotational Molding		

Physical	Nominal Value (English)	Nominal Value (SI)	Test Method
Density	0.900 g/cm ³	0.900 g/cm ³	ASTM D1505
Melt Mass-Flow Rate (MFR) (230°C/2.16 kg)	15 g/10 min	15 g/10 min	ASTM D1238
Mechanical	Nominal Value (English)	Nominal Value (SI)	Test Method
Tensile Strength (Yield)	3480 psi	24.0 MPa	ASTM D638
Flexural Modulus	167000 psi	1150 MPa	ASTM D790
Impact	Nominal Value (English)	Nominal Value (SI)	Test Method
Charpy Notched Impact Strength ¹ (73°F (23°C))	3.9 ft-lb/in ²	8.2 kJ/m ²	ISO 179
Thermal	Nominal Value (English)	Nominal Value (SI)	Test Method
Deflection Temperature Under Load			ASTM D648
66 psi (0.45 MPa), Unannealed	194 °F	90.0 °C	
264 psi (1.8 MPa), Unannealed	122 °F	50.0 °C	

Notes

¹ @ PIAT 210°C is 8.2KJ ± 1.1

* Extract from the article "Processing of pre-impregnated thermoplastic tape reinforced by continuous glass fiber and recycled PET by pultrusion" from Púria Esfandiari.

