

Research on More Sustainable Spinner Designs

Innovative material and manufacturing solutions for sustainable wind turbine spinner designs

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"You can change what you do, but you can't change what you want."

Thomas Shelby

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ABSTRACT

Wind energy, a type of renewable energy, has been increasingly used as it serves as a substitute for conventional sources of energy due to its numerous advantages, such as not polluting the environment during the energy generation process, along with the fact that it provides an inexhaustible source - the wind. In the year 2021, 14% of the electricity used in Europe came from wind energy, with an expected increase in this number in the coming years. Consequently, an increase in the amount of waste generated by this industry is also expected, making it necessary to manage it properly and adopt more sustainable practices.

Vestas Wind A/S presents itself as a global partner in the energy industry, focusing on mitigating negative impacts on the environment and society. Two pillars of their initial sustainability strategy, revealed in 2020, are carbon neutrality in their own processes by 2030 and the production of wind turbines without waste by 2040. In the process of wind energy generation, turbines play a fundamental role, as this equipment is responsible for converting the wind's force into electrical energy. The spinner constitutes a key component of these turbines and is partially composed of monolithic and sandwich laminates. The laminates of this panel are made of fiberglass and an unsaturated polyester matrix, while the core is manufactured from a network of interpenetrating polymers. The current manufacturing process of the spinner is the vacuum infusion process. Aligned with Vestas' sustainability aspirations, the goal of the current dissertation emerged - the creation of a more sustainable spinner, with a specific focus on the Vestas Mk1B spinner.

Fiber-reinforced polymers have been increasingly used in various industries due to their exceptional properties, including high mechanical and chemical resistance combined with low weight. However, there are several challenges in their recycling, requiring greater care in their use and a comprehensive assessment of their end-of-life phase to effectively mitigate their environmental impact. As a result, an exploration of different materials with the potential to replace those currently used, possessing comparable mechanical properties, a reduced carbon footprint over the life cycle, and recyclability or reusability, was undertaken. In addition, alternative manufacturing processes were studied. A simplified Life Cycle Cost (LCC) analysis was also conducted for most of the materials and processes used, allowing for cost comparisons between them.

After a thorough literature review and consideration of the objectives, basalt fibers, a biologically based epoxy resin, and two types of cores - cork and expanded polypropylene - were selected. Basalt fibers were examined in their virgin and recycled states, with the latter achieved through thermal recycling, facilitating a comprehensive comparison of their mechanical properties.

After conducting mechanical tests, it was concluded that composites containing recycled basalt fibers and the recycled basalt fibers themselves exhibited inferior mechanical properties when compared to the virgin ones. Regarding the cores, it was found that the polypropylene core had better mechanical properties than the cork core, in addition to having a lower density, a factor that deserves consideration.

For future work, the use of flax fibers, which were also identified as potential substitutes according to the literature, for composite manufacturing and subsequent mechanical characterization is recommended. The use of a scanning electron microscope for an analysis of the recycled basalt fibers, along with further in-depth investigation, is also recommended to better understand the consequences of the thermal recycling process on the fibers.

Furthermore, it has been concluded that the materials under study represent promising alternatives to the currently employed materials, albeit necessitating further research should they be considered for practical application.

Keywords: Composite material; Basalt fiber reinforced polymer; Sustainability; Wind Energy; Composite manufacturing process; Recycling

RESUMO

A energia eólica, um tipo de energia renovável, tem sido cada vez mais utilizada uma vez que atua como uma substituta das fontes convencionais de energia devido às suas numerosas vantagens, como o facto de não poluir o meio ambiente durante o processo de geração de energia, juntamente com o facto de apresentar uma fonte inesgotável - o vento. No ano de 2021, 14% da eletricidade usada na Europa, proveio da energia eólica, estando previsto um aumento deste número nos próximos anos. Como consequência, também é esperado um aumento da quantidade de resíduos gerados por esta indústria, sendo por isso necessário uma boa gestão dos mesmos e a adoção de práticas mais sustentáveis.

A Vestas Wind A/S apresenta-se como a parceira global na indústria de energia com um foco distinto em mitigar os impactos negativos tanto no meio ambiente quanto na sociedade. Dois pilares da sua estratégia de sustentabilidade inicial, revelados em 2020, são a neutralidade de carbono nos próprios processos até 2030 e a produção de turbinas eólicas sem resíduos até 2040. No processo de geração de energia eólica, as turbinas desempenham um papel fundamental, pois é este o equipamento responsável pela conversão da força do vento em energia elétrica. O *spinner* constitui um componente-chave dessas turbinas e é parcialmente composto por laminados monolíticos e painel sanduíche. Os laminados deste painel são feitos de fibra de vidro e uma matriz de poliéster insaturado, enquanto o núcleo é fabricado a partir de uma rede de polímeros interpenetrados. O processo atual de fabricação do *spinner* é o processo de infusão a vácuo. Alinhado com as aspirações no campo da sustentabilidade da Vestas, o objetivo da dissertação atual surgiu - a criação de um *spinner* mais sustentável, com foco específico no *spinner* Vestas Mk1B.

Os polímeros reforçados com fibras tem sido cada vez mais utilizados em várias indústrias devido às suas propriedades excepcionais, que englobam uma alta resistência mecânica e química aliadas ao baixo peso. No entanto, existem diversos desafios na sua reciclagem, exigindo portanto um maior cuidado do seu uso e uma avaliação completa da sua fase de fim de vida para mitigar seu impacto ambiental de forma eficaz. Como resultado, uma exploração de diferentes materiais com potencial para substituir os atualmente usados, possuindo propriedades mecânicas comparáveis, uma pegada de carbono reduzida ao longo do ciclo de vida e uma capacidade de reciclagem ou reutilização, foi empreendida. Além disso, processos alternativos de fabricação foram estudados. Uma análise simplificada de Custo do Ciclo de Vida (CCV) também foi realizada para a maioria dos materiais e processos usados, permitindo uma comparação de custos entre eles.

Após uma revisão aprofundada da literatura e consideração dos objetivos, foram selecionadas fibras de basalto, uma resina de epóxido de base biológica e dois tipos de núcleos - cortiça e polipropileno. As fibras de basalto foram examinadas em seus estados virgem e reciclado, sendo este último alcançado por meio de reciclagem térmica, facilitando uma comparação abrangente de suas propriedades mecânicas.

Após a realização dos ensaios mecânicos, concluiu-se que os compósitos que continham fibras de basalto recicladas e as próprias fibras de basalto recicladas apresentaram propriedades mecânicas inferiores, quando comparadas com as virgens. Relativamente aos núcleos, foi possível constatar que o núcleo de polipropileno apresentava melhores propriedades mecânicas que o núcleo de cortiça, além de possuir uma densidade inferior, factor que merece ser considerado.

Concluiu-se ainda que os materiais estudados são alternativas promissoras aos materiais atualmente utilizados, ainda que sejam necessários mais estudos sobre os mesmos, em caso de serem aplicados na prática.

Para trabalhos futuros, é recomendado o uso de fibras de linho, as quais também se apresentaram como possíveis substitutas segundo a literatura, para o fabrico de compósitos e posterior caracterização mecânica. O recurso ao microscópio electrónica de varrimento para uma análise das fibras recicladas de basalto assim como uma investigação mais aprofundada sobre as mesmas é também recomendado, para uma melhor compreensão das consequências do processo de reciclagem térmica nas fibras.

Palavras-chave: Material compósito; Polímeros reforçado com fibra de basalto; Sustentabilidade; Energia eólica; Processo de fabrico de compósitos; Reciclagem

CONTENTS

1. INTRODUCTION	14
1.1 Sustainability	14
1.2 Wind Energy	14
1.3 Wind Energy Market	14
2. STATE OF ART	15
2.1 Composite Materials	15
2.1.1 Matrix	16
2.1.2 Fiber	19
2.2 Sandwich Panel	22
2.3 Composite Manufacturing Methods.....	23
2.3.1 Vacuum Infusion	23
2.3.2 Resin Transfer Molding	24
2.3.3 3D Printing.....	24
2.3.4 HiPerDiF - High performance discontinuous fiber	25
2.3.5 Thermoforming.....	26
2.3.6 Compression Molding	27
2.4 End of Life Stages	27
2.4.1 Legislation	27
2.4.2 Landfill	27
2.4.3 Incineration	28
2.4.4 Types of Composites Recycling	28
3. LIFE CYCLE COST.....	30
3.1 Life Cycle Stages	30
3.2 Cost Analysis	30
4. CONTEXTUALIZATION OF THE CASE STUDY	33
4.1 Wind Turbine Operation.....	33
4.2 Spinner Specific Requirements.....	34
4.3 Spinner Material	35
4.3.1 Metallic Material	35
4.3.2 Composite Material	35
4.4 Spinner Manufacturing Process	36
4.5 Alternative Materials and Selection Process.....	37

4.5.1	Matrix	37
4.5.2	Fiber	38
4.5.3	Core	38
5.	MATERIALS AND METHODS	40
5.1	Composites in study	40
5.1.1	Raw Materials.....	40
5.2	Laminate Production Process.....	40
5.3	Sandwich Panel Production Process	42
5.4	Characterization Methods	43
5.4.1	Physical Characterization Tests.....	43
5.4.2	Thermal Characterization Tests	45
5.4.3	Mechanical Characterization Tests.....	45
5.4.3.5	Single Fibre Test.....	49
6.	RESULTS AND DISCUSSION	50
6.1	Density, Void Content and Fibre Content Test.....	50
6.2	Differential Scanning Calorimetry – DSC Test	51
6.3	Mechanical Tests of the Composite	51
6.3.1	Tensile and Shear Tests	51
6.3.2	Flexural Test.....	53
6.3.3	Fibre Testing and Optical Microscopy.....	55
6.4	Mechanical Tests of Sandwich Panels	56
6.4.1	Compression and Flexural Tests	56
7.	Conclusion.....	58
8.	Limitations and Future Work.....	59
9.	REFERENCES	60
	Appendix A – Technical sheet of raw materials	65
	Appendix B - View of the construction of the various layers	78
	Appendix C – Conversion Factor for Density Test.....	79
	Appendix E - Differential Scanning Calorimetry Test Results	81
	Appendix F – Tensile and Shear Tests Results	83
	Appendix G – Flexural Test - Laminates.....	86
	Appendix H - Flexural Tests Graphs - Sandwich Panels.....	91
	Appendix I – Compressive Tests Graphs Results - Sandwich panels	94

Appendix J - Microscopic images obtained	95
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LIST OF FIGURES

Figure 1 - Schematic representation of different types of composites. [9]	16
Figure 2 – Classification of biodegradable and non-biodegradable polymers. Adapted from [11]	16
Figure 3 – Different fiber types. [24].....	19
Figure 4 - Schematic of a sandwich pane. [38]l.....	22
Figure 5 - Representative schematic of vacuum infusion process. [49].....	24
Figure 6 - Representative schematic of resin transfer molding process. [51]	24
Figure 7 - Representative schematic of the 3d printing of a continuous fiber reinforced thermoplastic. [53]	25
Figure 8 - (a) Flow chart and (b) Representative scheme of the discontinuous fiber alignment process. [57]	26
Figure 9 - Representative scheme of basic vacuum thermoforming. (a) Heating; (b) sealing or pre-stretch; (c) forming and cooling. [58]	26
Figure 10- Representative scheme of the compression molding process. [59]	27
Figure 11 – Life Cycle Stages of a wind turbine. [69]	30
Figure 12 – (1) Representative image of a wind turbine [70] and (2) the interior of a wind turbine [71].	33
Figure 13 — Real image of the spinner of the Vestas EnVentus v162 turbine, Mk1B model. [73]	34
Figure 14 - Fiber orientation of (1) 45° and (2) -45°	41
Figure 15 - Various stages of the vacuum infusion process for laminate production.....	42
Figure 16 - Experimental setup used in density tests.	43
Figure 17 - Muffle furnace used in the fiber content and void volume test.	44
Figure 18 - Photograph of the equipment used in the DSC tests - Model Q20 from TA Instruments®	45
Figure 19 - Example of various transitions that can be obtained through DSC. [83]	45
Figure 20 - Photograph of the equipment used in flexural tests.	46
Figure 21 - Photograph of the equipment and sample used in the compression tests.	47
Figure 22 - Photograph of the equipment used in the tensile tests	48
Figure 23 – (1) Impregnated recycled fibres and (2) dry recycled fibres used in tensile test.	49
Figure 24 –Photograph of the microscope Leica	50
Figure 25 – <i>Specimens after the tensile (1) and shear (2) test</i>	52
Figure 26 - Photographs of composites 3 and 4 after being removed from the muffle.	53
Figure 27 - Comparison of the results obtained in the bending test between different composites in the 0/90 and 45/45 direction	54
Figure 28 - Comparison between the flexural modulus of the different composites in the 0/90 and 45/45 directions.	55
Figure 29 - Comparison of the results obtained in the fibre test, between virgin and recycled virgin fibres and virgin and recycled impregnated fibres.	56

LIST OF TABLES

Table 1 - Mechanical properties of various thermoplastics. (Adapted from GRANTA_Edupack).....	18
Table 2 - Mechanical properties of various thermosetting polymers. (Adapted from GRANTA_Edupack).....	18
Table 3 - Mechanical properties of some natural fibers compared to conventional fibers (adapted from GRANTA_EduPack).....	20
Table 4 - Comparison of properties between basalt fibers and E-glass fibers (adapted from [32])	21
Table 5 - Mechanical properties of different core materials. (adapted from GRANTA_Edupack)	23
Table 6 - Average costs of current and alternative materials and their respective comparison, in percentage	31
Table 7 - Average costs of different variables in the studied processes and their respective comparison with the currently used method	32
Table 8 - Reference values to be used for UD fiber mat.[74].....	34
Table 9 – Reference value to be used for CSM fiber mat.[74]	35
Table 10 – Reference values to be used for resin (generic).[74]	35
Table 11 - Decision matrix table.....	37
Table 12 – Decision fibre table.....	38
Table 13 – Decision core table	39
Table 14 - Mechanical properties of materials used in composite manufacturing	40
Table 15 – Temperature and time cycled applicated to different composites, inside muffle.	42
Table 16 – Specimens tested for flexural test	46
Table 17 - Density tests results	50
Table 18 – Information to calculate void volume and fibre content.	51
Table 19 - Fiber content test results.	51
Table 20 - Tensile and shear tests results	52
Table 21 - Tensile test results.....	53
Table 22 - Shear test results.....	53
Table 23 - Compression tests results for sandwich panels.	56
Table 24 - Flexural tests results for sandwich panels.	57

LIST OF SYMBOLS

b	Sample width
c	Core thickness
E_f	Flexural elasticity modulus
F	Applied force
F_f	Maximum tensile force
F_{max}	Maximum applied force
F_s^{ult}	Maximum shear resistance of the core
F^{tu}	Ultimate tensile strength
h	Sample thickness
L	Distance between rollers
p	Panel thickness
t	Laminate thickness
T_g	Glass transition temperature
V	Volume percentage content
V_{void}	Void volume
W	Mass percentage content

Greek Letters

ν	Poisson's ratio
ρ	Density
σ_c	Maximum compression resistance
σ_f	Flexural stress
σ_{ft}	Tensile strain of the yarn
γ_{12}	Shear strain
ϵ	Strain at maximum load
ϵ^{chord}	Tensile chord modulus of elasticity
ϵ_i	Tensile strain
τ_{12}	In-plane shear strength

Indexes

fi	Final
i	Initial

List of Acronyms

ASTM	American Society for Testing and Materials
CCV	Ciclo Custo de Vida (from portugues)
CSM	Chopped Strand Mat
DSC	Differential Scanning Calorimetry
FEM	Finite Element Method
FRP	Fibre Reinforced Polymer
GFRP	Glass Fibre Reinforced Polymer
INEGI	Institute of Science and Innovation in Mechanical and Industrial Engineering
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
PA	Polyamide
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
RTM	Resin Transfer Molding
SEM	Scanning electron microscope
UD	Unidirectional
UNCED	United Nations Conference on Environment and Development
UV	Ultraviolet

1. INTRODUCTION

This chapter aims to provide an overview of the practical study, which has been divided into two main themes. The theme explored in this dissertation focuses on the investigation of more sustainable materials and alternative manufacturing methods, with the objective of creating a spinner, a component of a wind turbine, with a reduced environmental impact. The complementary theme, involving the life cycle assessment (LCA) of the mentioned structure as well as its structural analysis using the Finite Element Method (FEM), was developed by *Cai* [1].

Throughout the development of both dissertations, there was a continuous exchange of information to ensure that each part possessed all the necessary tools and knowledge to conclude the study.

1.1 Sustainability

The term sustainability can be defined as the ability to meet the needs of the present generation without compromising the ability of future generations to meet their own needs. Presently, companies are increasingly considering the environmental, economic, and social aspects of sustainability to align themselves with the response required by market demands [2].

After the publication of the Brundtland Report by the World Commission on Environment and Development in 1987 and the United Nations Conference on Environment and Development (UNCED) in 1992, this concept became a part of the frameworks of major organizations worldwide. However, it still poses a challenge for current practices as it addresses long-term well-being as well as the need for assessing various policy options regarding sustainability. For medium to large-sized companies, numerous criteria based on indicators are available in the literature. However, the same does not apply to micro and small businesses due to the lack of indicators such as data, information systems, and strategic planning [2].

1.2 Wind Energy

Air pollution, water pollution and climate change relate to the energy industry. Emission of pollutants from the combustion of fossil fuels stands out as a key contributor to urban air pollution, while oil spills remain a significant factor in water pollution [3]. Given this complex issue, adopting more sustainable measures and pathways is of paramount importance. Over the past years, a shift away from fossil fuels and conventional energy sources towards the utilization of renewable energy has been underway. This shift has been driven by escalating prices and the various adverse impacts associated with fossil fuels [4].

Wind energy is a type of energy generated through harnessing the power of the wind. This energy is classified as entirely clean, as it does not cause any form of environmental pollution during its generation process. The primary advantage of wind energy lies in its environmental contribution since it does not generate pollutants and relies on a renewable and inexhaustible energy source. Moreover, this energy form aids in reducing reliance on fossil fuels, which are responsible for emitting substantial amounts of CO₂ into the atmosphere, thereby mitigating the environmental impact [5].

1.3 Wind Energy Market

In the year 2021, wind energy supplied 14% of the electricity demand in the European Union, a number projected to increase in the coming years. The European Union aims to raise the share of renewable energy to 32% and achieve carbon neutrality by 2050. Considering the anticipated growth in

wind energy utilization, a challenge emerges regarding the lifespan of wind turbines, which is approximately 30 years. Disposal will be necessary in the future. Presently, there are 34,000 turbines that have been in operation for over 15 years, representing 36 GW of onshore wind capacity. This implies that within the next 10 years, these turbines will need to be decommissioned. This presents an issue due to the substantial logistical challenges associated with the entire process of dismantling, collecting, transporting, and treating waste [6].

1.4 Vestas and its Sustainable Vision

Vestas Wind A/S is a global partner in the energy industry. The company manufactures, installs, and maintains wind turbines in 88 countries and is one of the leaders in the wind energy market. In 2020, the company introduced its first sustainability strategy. The strategy consists of four primary objectives: “achieving carbon neutrality by 2030 (in own operations)”, “producing wind turbines with zero waste by 2040”, “leading the transition to a planet powered by sustainable energy” and “making the company safer, more inclusive, and socially responsible within the energy sector” [7].

1.5 Objective

The objective of this dissertation is to investigate alternative materials and processes that can serve as efficient and sustainable options compared to the current materials and processes used in spinner manufacturing. These materials should be 100% recyclable, aiming to eliminate the need for landfill disposal and reduce the carbon footprint associated with this component by up to 45%. These details will be explored further in Chapter 2.

Additionally, a life cycle cost analysis of the alternatives is expected to be conducted, followed by a comparison with the current life cycle cost practices at Vestas. Concurrently, as conducted by *Cai*, a structural analysis of the current spinner design and alternative materials will be performed using the finite element method. This analysis aims to determine the feasibility and practical applicability of the chosen options based on the literature review.

2. STATE OF ART

2.1 Composite Materials

A composite material is the result of combining two or more macroscopically distinct constituents with different compositions, structures, and properties. Together, these constituents enhance the mechanical properties of the final material compared to those of the individual components. In the case of polymer matrix composites reinforced with fibers, the matrix's role is to provide cohesion to the fibers, protect them from the environment and handling damage, distributing the load across the fibers, and redistributing this load in case of local fibre failure. On the other hand, the function of the reinforcement, which is usually stronger than the matrix, is to bear the external load, providing the composite with increased strength, wear resistance, and stiffness. It also enhances the coefficient of thermal expansion as well as thermal and electrical conductivity [8].

Composite materials can be categorized into three types, considering the types of reinforcement as illustrated in Figure 1:

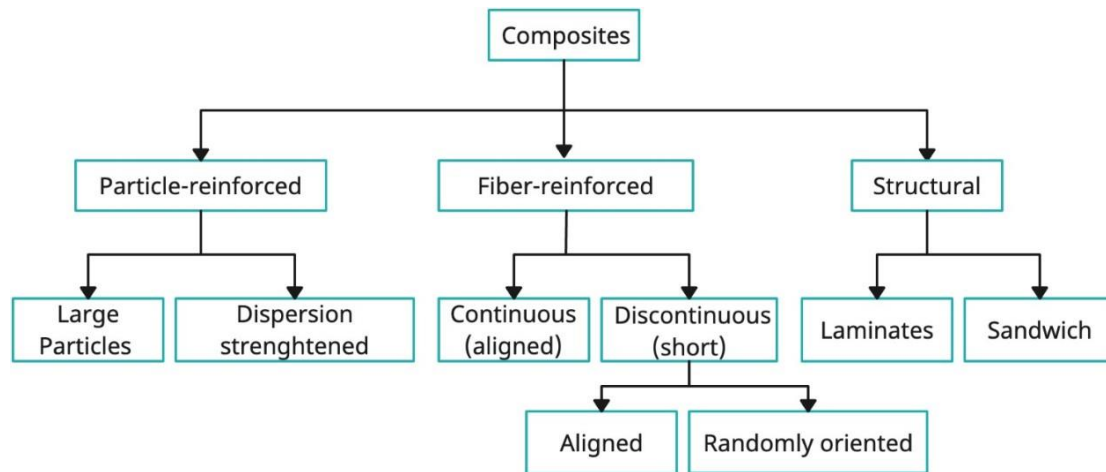


Figure 1 - Schematic representation of different types of composites. [9]

2.1.1 Matrix

The matrices of the composites can be polymeric, metallic, or ceramic. One of the most used matrix materials are the polymers, which consist of macromolecules composed of repeated units called monomers [10].

Polymers can be divided into two major groups, taking into consideration its biodegradability, as depicted in Figure 2:

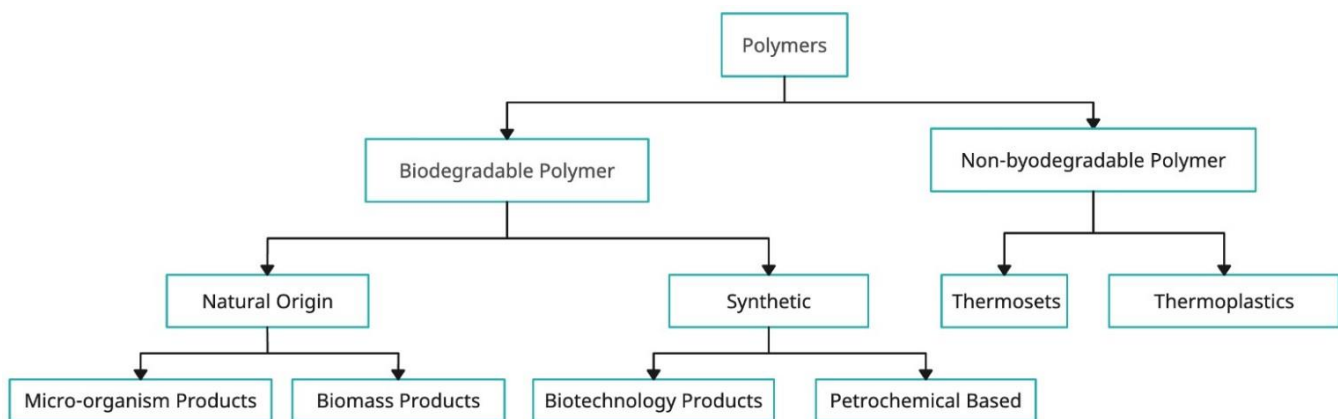


Figure 2 – Classification of biodegradable and non-biodegradable polymers. Adapted from [11]

Polymer matrices based on fully degradable materials have been a significant focus of research. This class of polymers is divided into two types based on their source: biological polymers with a natural origin and synthetic polymers. Biological polymers can be further categorized into biomass-derived and microbial-derived, while synthetic polymers are divided into biotechnology-derived and petrochemical-derived products. Synthetic polymers based on biotechnology are synthesized from natural monomers. This process is advantageous as it reduces the dependence on fossil resources and carbon footprint, contributing to environmental sustainability. Lastly, biodegradable polymers based on petrochemicals are

synthetic polymers sourced from petroleum that could naturally decompose through biological processes. Unlike conventional petrochemical-based polymers, which are mostly non-biodegradable, these polymers present a more sustainable alternative as they readily break down into natural elements. [11] Biopolymer-based composites are referred to as "green composites" due to their ability to be degraded by environmental factors such as air, light, heat, or microorganisms. Despite the low environmental impact of this polymer class, their application in structures requiring high durability without degradation of mechanical properties needs careful consideration, as they are susceptible to degradation by external environmental agents [12].

Within the other major group of non-degradable polymers, there are thermosetting and thermoplastic polymers. Thermosetting polymers consist of three-dimensional polymer chains, where covalent bonds between oligomers and polymer chains are formed during the curing process, resulting in a stable, highly heat-resistant three-dimensional structure. Once cured, thermosetting polymers cannot be melted again due to the strong nature of their chemical bonds. This inability to remelt is a significant obstacle to their recycling process [13].

This type of polymer is characterized by its rigidity, dimensional stability, high thermal and electrical resistance, making it highly attractive for industries that require polymers with strong resistance and durability. Two groups of resins widely utilized in the field of engineering are epoxy resins and vinyl ester resins [14]. Currently, environmentally friendly thermosetting resins have been developed, such as bio-based epoxy resin. This resin exhibits the same mechanical properties as standard epoxy resin, as proved from the technical datasheets of two standard and bio-based epoxy resins presented in Appendix A. The difference lies in the raw materials used; the bio-based resin includes a percentage of naturally derived, non-petroleum-based raw materials, resulting in a reduced carbon footprint [15]. Epoxy resin offers various advantages, being highly versatile and allowing for formulation to meet diverse requirements. It boasts high tensile, flexural, compressive, and impact strength, as well as the ability to withstand cyclic loads. Another thermosetting polymer, vinyl ester, also presents numerous advantageous properties, including resistance to corrosive environments, tensile and flexural strength, and high dimensional stability.

Thermoplastics, on the other hand, consist of linear polymer chains held together primarily by weak intermolecular forces. When heated to high temperatures, these bonds break, and upon solidification, they strengthen again. This characteristic renders thermoplastics more readily recyclable compared to thermosetting polymers, as they do not undergo significant degradation even after repeated melting and solidification processes [16].

Despite the better recyclability of thermoplastics, they generally exhibit lower mechanical properties compared to thermosetting polymers. This difference can be observed through the analysis of Tables 1 and 2, which depict various properties. It is important to note that despite the differences in mechanical properties presented in the mentioned tables, these differences do not necessarily translate in the same proportion to the final composite. This is because the primary functions of the matrix are to ensure adhesion between the fibers and to facilitate the transfer of loads between them.

Table 1 - Mechanical properties of various thermoplastics. (Adapted from GRANTA_Edupack)

THERMOPLASTICS	TENSILE STRENGTH (MPa)	YOUNG MODULUS (GPa)	COMPRESSIVE STRENGTH (MPa)	FATIGUE STRENGTH (10 ⁷ CYCLES; MPa)
PE – UHMW	38,6-48,3	0,89-0,96	25,7-33,1	15,2-19,8
PA 66	58-71,7	2,2-4	73,7-82	24-27,3
PP	25,9-53,4	0,9-1,5	23,8-25	7,65-7,9
PET	62,7-72,4	2,3-2,4	68,9-86,1	23,7-30,8

Table 2 - Mechanical properties of various thermosetting polymers. (Adapted from GRANTA_Edupack)

THERMOSETTING	TENSILE STRENGTH (MPa)	YOUNG MODULUS (GPa)	COMPRESSIVE STRENGTH (MPa)	FATIGUE STRENGTH (10 ⁷ CYCLES; MPa)
EPOXY	45-89,6	2,35-2,46	102,7-171,7	29,9-35
VINYL ESTER	68- 102	3-6	75,8-113,7	27-35,9
PU	68,94-75,8	4-4,3	66,2-73,1	25,3-33
PES	41,4-89,6	2,06-4,4	139,9-206,8	16,5-35,8

There exists an extensive array of thermoplastics, employed for a multitude of purposes.

Polyamide, polyethylene, and polyethylene terephthalate polymer groups are widely employed in various industries due to their properties coupled with a favorable cost-benefit ratio. Polyamides are characterized by good chemical resistance, strong resistance to associated abrasion, and high tensile strength. However, they are quite sensitive to notching and behave in a brittle manner when notched, rather than exhibiting ductility. Another drawback is their susceptibility to variation in several properties based on the humidity they are exposed to, due to their hydrophilic nature [17].

High-density polyethylene, despite its high chemical, impact, and moisture resistance, becomes brittle when exposed to high temperatures due to crosslink rupture. It also exhibits low resistance to UV radiation, as UV rays cause chain degradation [18]. The same holds true for polypropylene, a type of polymer that is highly susceptible to UV degradation, leading to a significant reduction in its mechanical properties [19].

Polyethylene terephthalate, commonly known as PET, is one of the thermoplastic polymers with excellent mechanical properties, including tensile strength, stiffness, and dielectric properties. However, it is also characterized by low heat resistance [20].

Vitrimers, although not represented in Figure 2, are a class of polymeric materials recently developed that exhibit unique self-healing and recyclability properties and have garnered significant attention due to their classification as renewable polymers with excellent mechanical characteristics, including strength, durability, and chemical resistance. These properties closely resemble the behavior of traditional thermosetting polymers. Vitrimers have the remarkable advantage of being easily recyclable since they can be molded and remolded multiple times, enabling both chemical and mechanical recycling of the material [21]. Another property that makes vitrimers unique is the fact that they are composed of dynamic covalent bonds, which can break and reform under specific stimulus conditions such as heat,

light, and pressure. This reconfiguration process enables vitrimers to be repaired after sustaining damage such as cracks and fissures. The most widely used method for preparing vitrimers involves introducing crosslinking agents into commercially available and inexpensive pre-polymers, such as certain thermosetting and thermoplastic polymers. This generates dynamic crosslink networks with enhanced performance [21]. Currently, it is not possible to manufacture composite materials using vitrimers through the vacuum infusion method. The most used method for vitrimer composites is compression molding.

2.1.2 Fiber

A fiber is a long or short highly resistant material, with diameters ranging from 3 μm to 20 μm , that is embedded within the matrix of a composite. Fiber-reinforced composites (FRP) are a type of material extensively utilized in the field of engineering due to their advantageous characteristics, such as a high strength-to-weight ratio, corrosion resistance, and a wide range of applications. These composites have been increasingly employed, especially in industries such as maritime, aerospace, and wind energy, where their benefits are highly valuable [23]. Fiber-reinforced composites can be divided in two groups based on the type of fiber used, which can be continuous or discontinuous. These are illustrated in Figure 3:

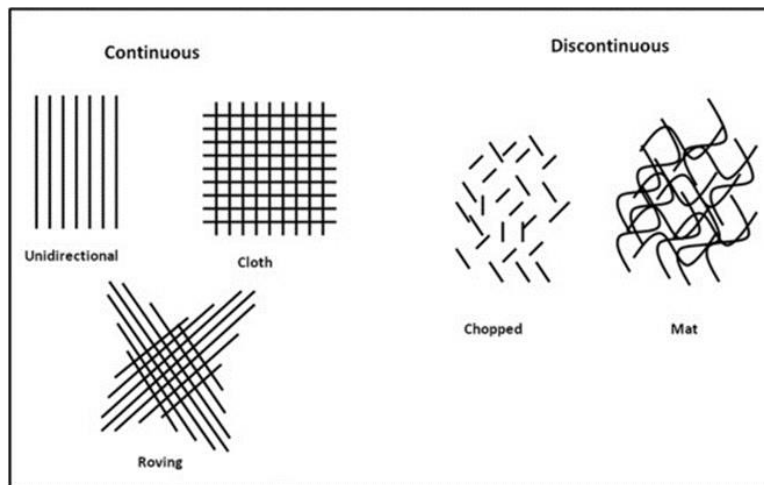


Figure 3 – Different fiber types. [24]

Continuous fibers are those that extend along the entire length of the composite without significant interruptions, unlike discontinuous fibers which are introduced into the matrix in the form of shorter fibers. Continuous fibers offer better mechanical properties compared to discontinuous fibers, as they have greater length and are evenly distributed within the composite matrix. Continuous fibers can be designed to make the composites anisotropic, meaning they exhibit different properties in different directions. Composites exhibit greater strength when fibers are oriented unidirectionally, namely in the direction of the tension. However, in this case, they have lower strength in the perpendicular direction [25].

The fibers used in composite manufacturing can be categorized into two main groups: natural fibers and non-natural or synthetic fibers, mainly distinguished by their origin. Natural fibers can be further classified into mineral, animal, and plant-based fibers, encompassing thousands of different options. These natural fibers have increasingly been considered as replacements for synthetic fibers in various applications. Apart from their commercial appeal due to their renewable and inexhaustible sources, these fibers offer additional benefits such as low density, strong adhesion capabilities with

different polymer matrices, minimal wear on processing machinery, good impact resistance, favorable thermal and electrostatic properties, and reasonable stiffness [26].

Natural fibers also offer significant advantages over synthetic fibers in terms of sustainability, particularly in end-of-life management and the carbon footprint generated during processing. Most of these fibers are recyclable and biodegradable, meaning they naturally decompose in the environment without leaving behind residues, resulting in much lower environmental impact on a large scale. However, using these fibers as reinforcement or substitutes for conventional fibers remains a challenge because their mechanical, physical, and chemical properties vary based on cultivation conditions, such as soil, climate, and humidity. These conditions differ in various parts of the world where these fibers are grown. Despite the substantial environmental impact and recycling challenges associated with synthetic fibers, they offer higher tensile strength, greater mechanical strength, lower moisture absorption, and greater dimensional stability [27].

The most extensively explored bio-based fibers in composites are those of plant origin due to their biodegradability, abundant sources, low cost, and lower environmental footprint. One of the primary choices when considering the production of composites with natural plant-based fibers is flax fiber [28].

In the presented Table 3 below, it is evident that plant fibers, a significant category of natural fibers, exhibit inferior mechanical properties when compared to the more commonly used conventional fibers, such as glass and carbon fibers.

Table 3 - Mechanical properties of some natural fibers compared to conventional fibers (adapted from GRANTA_EduPack)

FIBER	DENSITY (g/cm ³)	ELONGATION AT BREAK (%)	TENSILE STRENGTH (MPa)	YOUNG'S MODULUS (GPa)
HEMP	0.86-1.51	1.5-2.1	550-889	27-79
COTTON	1.5-1.6	7-8	287-597	5.5-12.6
FLAX	1.2-1.5	1.2-3.2	751-937	27-79.9
SISAL	1.45-1.5	2-2.9	500-790	9.37-23.9
JUTE	1.3	1.5-1.8	393-773	36,5
E-GLASS	2.5-2.6	2.5	2000-3500	70-80
CARBON	1.4-1.78	0.7-2	4000-5000	230-240

One of the primary choices when considering the production of composites using natural plant-based fibers is flax fiber. Flax fibers are extracted in bundles from the stem of the *Linum Usitatissimum* plant, which is primarily cultivated in Europe nowadays due to its temperate climate. This choice is because, in general, they exhibit superior mechanical properties compared to other natural fibers, as can be observed in the previously mentioned Table 3 [28].

Hemp fibers constitute another category of plant-based fibers, and they offer substantial environmental advantages. These fibers do not require pesticides or herbicides and contribute to soil quality enhancement by restoring microbial health and promoting moisture retention. Despite a notable loss of properties during reprocessing, factors such as low water consumption during cultivation and the biodegradability of the fiber make it a subject of study for industries interested in more eco-friendly materials [29].

Basalt fibers are a type of natural mineral-based fiber, which possess the significant advantage of basalt being the most abundant rock in the Earth's crust. This abundance ensures a ready supply of raw material for subsequent fiber manufacturing. The composition of basalt varies based on the cooling

conditions of lava as it reaches the surface. In other words, the chemical composition of basalt varies depending on the geographic location on Earth where the rock is formed. This variation in composition has an impact on the physical and mechanical properties of the fibers [30]. Despite being a natural fiber, the basalt fiber is not biodegradable like plant-based or animal-based natural fibers. This is because basalt is an inorganic material, resulting in a significantly longer degradation time, ranging between 50 and 100 years [31]. The application of these fibers is relatively recent; however, they have emerged as strong contenders to glass fibers due to certain similar properties. These include tensile and compressive strength, low thermal conductivity, and high durability [28]. Some of these properties are exemplified in Table 4.

Table 4 - Comparison of properties between basalt fibers and E-glass fibers (adapted from [32])

PROPERTIES	BASALT FIBERS	E GLASS FIBERS
TENSILE STRENGTH (MPa)	2800-4800	3450
MODULUS OF ELASTICITY (GPa)	89	72.4
DEFORMATION (%)	3.1	4.7
DENSITY (G/CM ³)	2.8	2.6

Basalt fibers can be recycled through mechanical, thermal, and chemical recycling processes. Mechanical recycling enables the recovery of fibers with the same molecular chemical structure as virgin fibers. Although sustainable, as it doesn't generate toxic substances and requires low energy input, the product consists of short fibers suitable for applications with low mechanical requirements than structural components. The most used type of thermal recycling for basalt fibers composites is incineration of the polymer matrix. In this process, the composite containing the fibers is subjected to high temperatures, leading to the combustion of organic materials. As basalt fiber is highly heat-resistant, the resulting product is loose recycled fibers, no longer bound by a matrix. Pyrolysis, another form of thermal recycling, is also employed for basalt fibers, offering the energy and environmental benefits of mechanical recycling. However, the mechanical properties of the fibers can decrease by up to 65%, partly due to the loss of sizing, a treatment designed to protect, lubricate, and bind the fibers. These properties can be partially restored through chemical regeneration processes using hydrochloric acid and sodium hydroxide solutions [31].

Glass fibers are synthetic fibers widely used in various industries, such as aerospace, maritime, military, and wind energy, due to their excellent mechanical properties, particularly their high strength-to-weight ratio, low weight, affordability, high durability, and ease of manufacturing. Currently, there are several types of glass fibers produced, each labeled with a specific index based on their chemical composition and mechanical properties [33]. Depending on the final objectives and applications of the fibers, thermal treatments can be performed to reduce internal stresses or enhance specific properties [34]. The most used recycling processes for recycling Glass Fiber Reinforced Polymers (GFRP) composites are mechanical recycling, [23] and the processes of pyrolysis and solvolysis, which are two types of thermal and chemical recycling, respectively [35].

Carbon fibers are another type of synthetic fibers that exhibit high performance. These fibers are widely used in advanced composite materials due to various factors, such as high specific modulus and strength, resistance to external factors like humidity and acidic solvents, and the ability to maintain their mechanical properties even when exposed to high temperatures. One of the most used methods in recycling carbon fiber composite materials is high-temperature pyrolysis. This method has a shorter recycling cycle, especially for composites based on thermosetting resins, compared to others [36].

2.2 Sandwich Panel

Sandwich panels are used in applications where a combination of high structural rigidity and low weight is required [37].

When manufacturing a sandwich panel, a core material is used and placed between the produced composites. Figure 4 provides a simplified illustration of the structure of a sandwich panel.

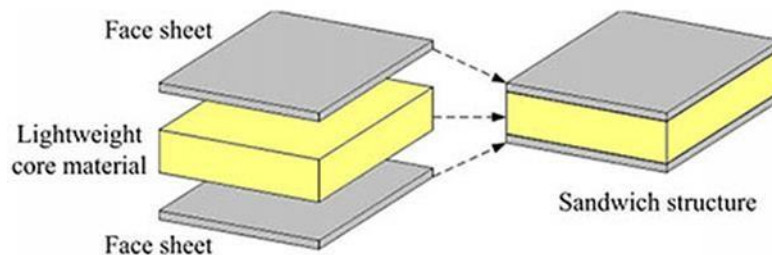


Figure 4 - Schematic of a sandwich pane. [38]

The functional performance of sandwich panels is primarily attributed to the choice of materials used and the structural configuration. There is a wide variety of combinations of laminates composites and cores, as well as variations in the geometry and thickness of these materials. In structural applications, the thickness of the laminates rarely exceeds millimeters, while the core thickness can exceed 50 mm. Therefore, the core is the largest component of the panel [38].

This technology, like any other, has some disadvantages, such as increased production complexity and higher manufacturing costs. Additionally, it can be challenging to predict one of the various failure modes, which is something to consider depending on the final application [40]. In practice, the process of selecting the core material must be carefully considered, considering the structure and purpose of the component to be manufactured. This is because maximizing one property can lead to a decrease in another equally important property. Cores can be divided into two main groups, considering its internal structure: homogeneous cores and non-homogeneous cores:

- Homogeneous cores, usually made of materials such as foams, wools, or different types of plastics, facilitate the panel manufacturing process. This is since the surface is easy to bond, and the preparation and molding are straightforward, resulting in a quick bond to the laminates using an adhesive [41].
- Non-homogeneous or structured cores are produced by repeating a unit cell, which can be a two-dimensional or three-dimensional structure. Honeycomb cores, consisting of open cells arranged perpendicular to the laminates, are typically used in low-velocity impact and shock resistance applications. While compared to homogeneous cores, this type of core performs better in terms of compression and shear, the presence of cavities in these cores reduces the panels' ability to maintain mechanical connections. Additionally, the manufacturing process for these cores tends to have higher costs [42].

Cork, a natural cellular material that constitutes the bark of the cork oak tree, is widely used as a homogeneous core in the manufacturing of sandwich panels. This material features a cellular structure, providing high specific strength and stiffness, excellent impact load tolerance, high resistance to reactive

agents and microorganisms, and exceptional damping characteristics [43]. In addition to being a natural, renewable, 100% biodegradable, and recyclable material, cork comes from cork oak trees that play a crucial role in capturing CO₂. These trees are responsible for sequestering around 4.8 million tons of CO₂ per year in Portugal alone [43].

Polypropylene competes with other polymers due to characteristics such as low cost, low density, and high rigidity. The lightweight nature of this material is one of the attributes that make it highly attractive for structural components, considering that the core is the largest constituent of sandwich panels. Despite not being biodegradable, it is a recyclable thermoplastic, although it is quite challenging to produce a recycled product with properties like virgin polypropylene. While the recycled product might not be suitable for structures with high mechanical requirements, it can find applications in other industries that do not demand such stringent properties, such as packaging, household items, and some automotive parts. [44] Polypropylene cores can be found in either homogeneous or non-homogeneous structures, in the form of honeycomb. In the latter case, film barriers can be used under a polyester veil to limit the resin consumption [45].

Polystyrene cores, a polymer derived from petroleum, are one of the most used core types due to their favorable cost-effectiveness and extreme lightweight nature. However, the environmental impact of this material is extensive, as it not only occupies millions of hectares in landfills but also poses serious health problems to both human and animal populations due to soil and water contamination [46].

In Table 5, some of the properties of the materials mentioned earlier in this chapter are depicted:

Table 5 - Mechanical properties of different core materials. (adapted from GRANTA_Edupack)

Core	Density (g/cm ³)	Flexural Strength (Mpa)	Flexural Modulus (MPa)	Compressive Strength (Mpa)	Tensile Strength (Mpa)	Fatigue Strength at 10 ⁷ cycles (Mpa)
Cork	0.12 – 0.18	0.009-0.015	0.49-1.2	0.54 – 1.1	0.49 – 1.2	0.29 – 0.6
Polypropylene	0.058 – 0.062	0.005 – 0.011	0.439 – 0.41	0.39–0.41	0.84 – 0.88	0.65–0.7
Polystyrene	0.027 – 0.032	0.008-0.011	0.33 – 0.57	0.19 – 0.25	0.29 – 0.48	0.29 – 0.39

2.3 Composite Manufacturing Methods

There are various methods for producing all types of composites, based on the materials that compose them as well as the size and complexity of the final product.

2.3.1 Vacuum Infusion

The vacuum infusion method is a technique for molding liquid composites, based on the pressure difference between the vacuum bag, which is lower than atmospheric pressure, and the resin supply [47]. The initial step involves preparing the piece with an agent and a release film, enabling the demolding of the composite after the curing process. Subsequently, the fiber is placed within the previously prepared mold, layer by layer, covered with a film sheet, and sealed to the air, utilizing a vacuum bag film, and sealing tape. The coating layer ensures a separation between the vacuum bag film and the piece's resin channels, at the culmination of the process. It is typical for there to be a variation in the preforms thickness throughout the process, as the pressure within the cavity increases while the resin is pressed into it, leading to fiber relaxation and consequently an increase in thickness. It is worth noting that in this process,

thermosetting materials are typically used rather than thermoplastics, due to their lower melting point and curing temperature [48]. The process is schematized in Figure 5.

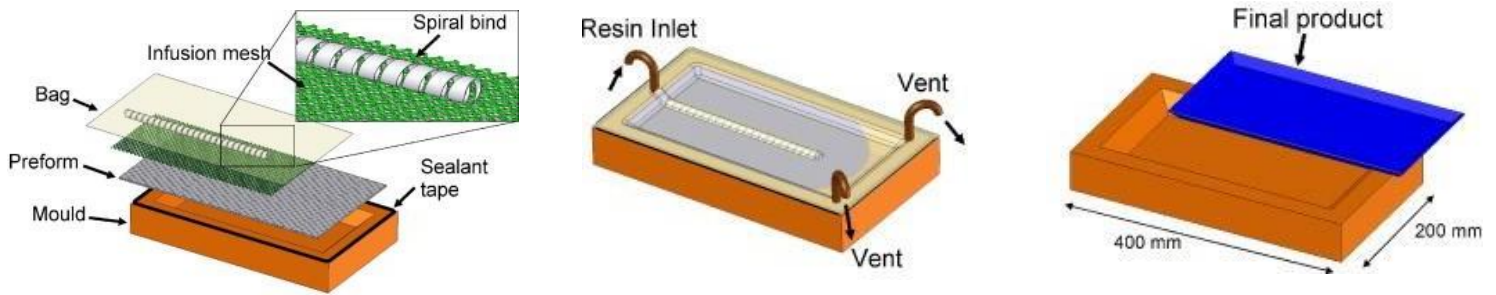


Figure 5 - Representative schematic of vacuum infusion process. [49]

2.3.2 Resin Transfer Molding

Resin transfer molding is another technique for molding liquid composites, closely akin to the previously mentioned method, which is schematized in Figure 6. It distinguishes itself in terms of tool design, as resin transfer molding necessitates a rigid mold capable of withstanding the injection pressure, which exceeds ambient pressure and comes with a higher cost as well [50].

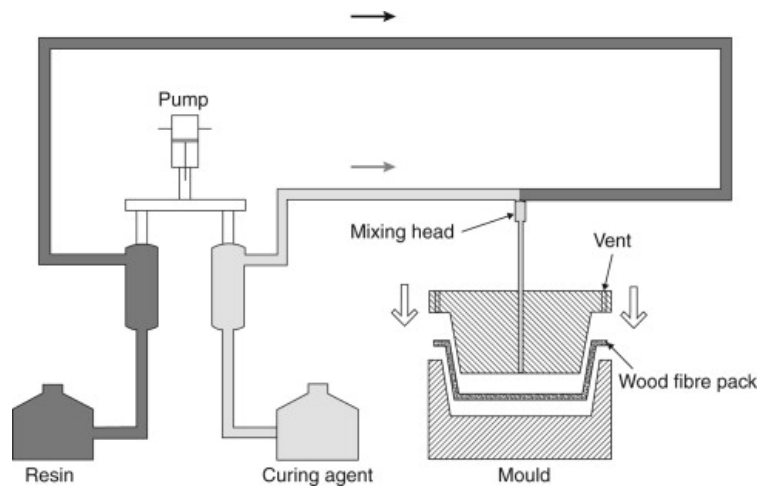


Figure 6 - Representative schematic of resin transfer molding process. [51]

2.3.3 3D Printing

The 3D printing method, also known as additive manufacturing, is a rapidly advancing technology that facilitates the creation of physical objects from a geometric representation through the successive addition of materials. This method offers advantages such as the design freedom of the resulting piece, enabling intricate details, and boasting high production efficiency [52].

In Figure 7, it is possible to observe a schematic example of a 3D printer, as well as its various components.

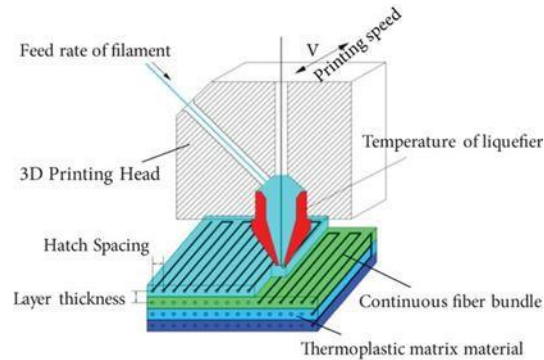


Figure 7 - Representative schematic of the 3d printing of a continuous fiber reinforced thermoplastic. [53]

The most used 3D printing processes in composite manufacturing are material extrusion printing and powder bed fusion. The material extrusion printing process involves the extrusion of a solid thermoplastic filament through a nozzle that melts it, which is then deposited onto the printing platform according to a predefined path. Following these steps, the formed piece cools and solidifies, resulting in the desired object. This technique offers several advantages, including the ability to work with diverse materials, low production costs, economical equipment requirements, and a high-quality surface finish.

Powder bed fusion is a process centered around fusing particles of powder, which can be metallic, ceramic, or plastic particles. This renders the technique highly flexible. This process is responsible for producing functional parts with good mechanical properties and intricate geometries. Additionally, it generates minimal waste, as all unfused particles can be reused [54]. Currently, 3D printing to produce composites comprised of continuous fiber-reinforced resin primarily revolves around thermoplastics. This group of polymers can be melted and rapidly solidified at room temperature while effectively bonding the composites during the printing process. However, when it comes to manufacturing continuous fiber-reinforced thermoset resin composites, there remains a significant challenge. This challenge arises due to the inadequate bonding between the resins and fibers during printing. The available literature on 3D printing with thermoset resins is still quite limited and lacks in-depth investigations [55].

2.3.4 HiPerDiF - High performance discontinuous fiber

The HiPerDiF method, developed at the University of Bristol, is an effective approach for manufacturing discontinuous fiber composites with high levels of alignment using fibers ranging from 1 to 12 mm in length. In this process, the discontinuous fibers are suspended in a water tank and then accelerated through a nozzle, directed between two parallel plates. The alignment mechanism is based on the moment when the fibers hit the plate, causing them to change direction and align between the plates. Water is removed by suction, and the aligned fiber preform is dried using infrared radiation, facilitating the resin impregnation process. Finally, the dried aligned fiber preform is coupled with a resin film and partially impregnated through the application of heat and pressure [56].

In Figure 8, this method is depicted in a simplified manner:

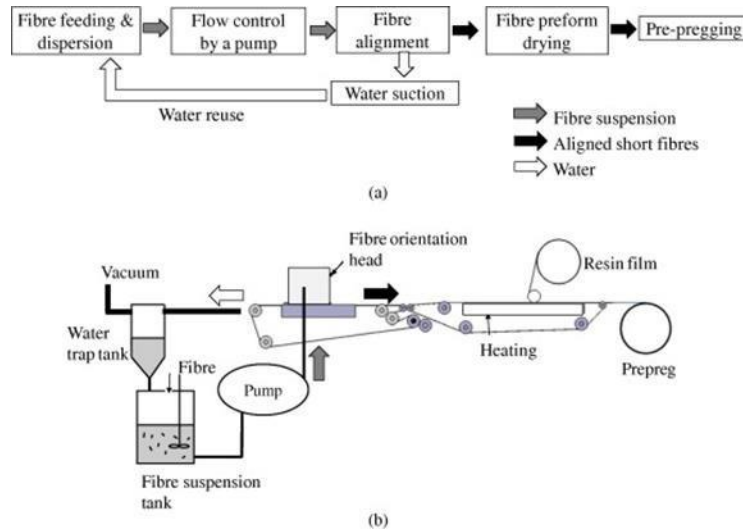


Figure 8 - (a) Flow chart and (b) Representative scheme of the discontinuous fiber alignment process. [57]

The significant advantage of this method lies in its ability to process fibers that have undergone recycling processes. It enables the production of highly aligned and high-performance discontinuous fiber composites from fragmented and randomly oriented fibers [57]. This process also comes with other benefits, such as a reduction in raw material costs due to the use of discontinuous fibers sourced from recycled composites. Additionally, it offers an automated and high-volume procedure that aligns the discontinuous fibers into a pre-impregnated tape. The current tape production is focused on a wide array of matrix materials including thermosetting polymers, thermoplastics, and vitrimers. Moreover, various fibers like basalt fibers and plant-based fibers are incorporated into the process [56].

2.3.5 Thermoforming

To produce composites by thermoforming process, a thermoplastic reinforced sheet is heated and shaped to achieve the desired form of a given mold, as depicted in Figure 9. The required duration of the heating cycle to adequately soften the sheet depends on the physical, chemical, and mechanical properties of the polymer from which the thermoplastic sheet is made [58].

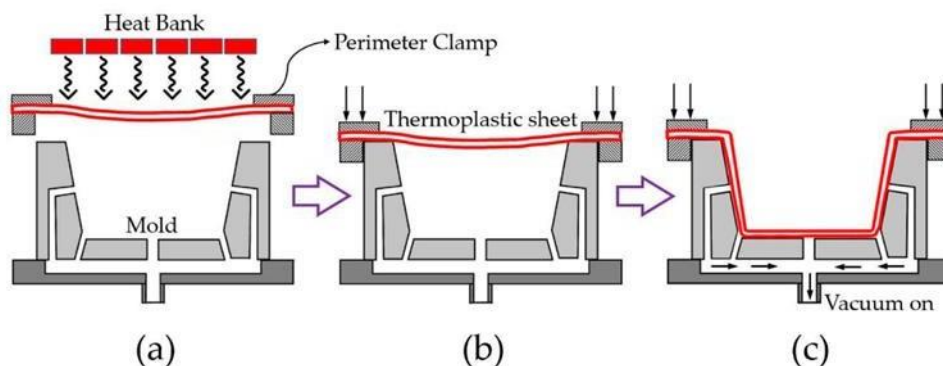


Figure 9 - Representative scheme of basic vacuum thermoforming. (a) Heating; (b) sealing or pre-stretch; (c) forming and cooling. [58]

In this process, the temperature used to heat the thermoplastic is crucial to avoid defects such as non-uniform thickness in the resulting piece. Thermoforming offers a high design flexibility, as it is defined by a mold, and allows for the use of a wide range of thermoplastics. Additionally, it boasts short production cycles [58].

2.3.6 Compression Molding

The compression molding technique is extensively employed for processing polymeric composite materials, which consist of either thermosetting or thermoplastic matrices. This approach is sometimes referred to as combined matrix molding, wherein the composite material is induced to deform or flow within the mold, [59] as illustrated in Figure 10 below:

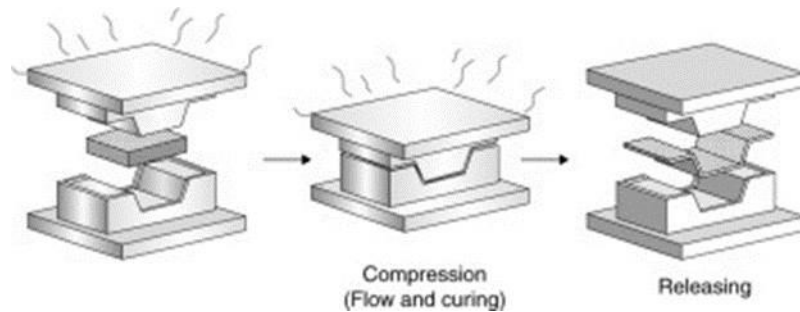


Figure 10- Representative scheme of the compression molding process. [59]

This process is highly appealing due to its ease of automation and its capability to produce highly complex geometries without generating waste [60]. Other advantages include the ability to consolidate many components into a single piece, eliminating the need for secondary operations or assembly steps. Additionally, the process enables control over the fiber.

2.4 End of Life Stages

Given the increasing interest of industries in more sustainable alternatives, the end-of-life stage of products has become a significant area of study and investment. This chapter will describe various end-of-life scenarios that composites can undergo, with a particular emphasis on the different existing recycling processes.

2.4.1 Legislation

In accordance with the European Waste Classification, composite materials are often classified as plastic waste originating from construction and demolition, with the code 17 02 03. There is a suggestion to revise this classification, aiming to encourage the development of composite material recycling techniques and thus promoting a circular economy [61].

2.4.2 Landfill

Currently, landfill disposal is the chosen option for the disposal of composites used in turbine structures due to its lower cost compared to other waste disposal methods, such as recycling. However, this method has significant environmental impacts, including damage to vegetation, potential risks to public health, unpleasant odors, atmospheric and water table pollution, among others, reasons why it may not be a viable solution in the future [62].

2.4.3 Incineration

Incineration is another common method used for disposing of composites. It involves cutting the composite into smaller pieces and then burning them in specialized incinerators at high temperatures. This process can involve energy recovery. However, it also releases harmful gases into the environment [63].

2.4.4 Types of Composites Recycling

Recycling of composites poses a challenge due to the variability of their constituent materials based on their intended use. Finding a recycling method that encompasses all types of composites is difficult. Moreover, composites are often manufactured with additional materials like metal cores and inserts, which further complicates the recycling process. These elements need to be removed before recycling, making the process time-consuming [64]. Recycling methods can be categorized into mechanical, chemical, or thermal approaches.

There are two mechanical recycling methods, namely grinding and co-processing in cement kilns. These methods offer low cost and require minimal energy input. Additionally, if proper precautions are taken during manufacturing, no hazardous fluids are produced. However, this process has a major drawback, which is why it is not widely employed: a significant reduction in mechanical properties occurs, making it less suitable for many applications [65].

Chemical recycling is a method that employs a chemical reagent and a reactive medium at low temperatures to dissolve the resin. After decomposition and separation from any residual material, the fibers can be extracted, and energy recovery from the matrix becomes possible. The selection of chemicals in this process is crucial to minimize environmental impacts. Solvolysis is the most common form of chemical recycling, involving the use of water, alcohols, and acids to break down the matrix's bonds. The resin type dictates both the necessary temperature and solvents for successful degradation [66]. Another type of chemical recycling is the electrochemical process, also referred to as high-voltage fragmentation, a rather costly method involving the separation of fiber matrices through the application of electricity.

This form of recycling is also employed for the recycling of thermosetting polymers. Despite several projects aiming to replace thermosetting polymers with thermoplastics due to the latter's greater recyclability, there are cases where such substitution is unsuitable, making it crucial to develop methods for the recycling of thermosetting polymers. Currently, recycling these polymers remains a challenge due to the permanent structure they acquire after the curing process. The high density of cross-linkages that imparts good mechanical properties to these polymers paradoxically contributes to their difficult recyclability.

The use of Poly-dicyclopentadiene, an industrial thermosetting polymer used as a model, has demonstrated that when a small number of clickable bonds – a specific type of chemical bonds designed to facilitate the efficient connection of monomers and polymeric segments, resulting in a rapid and selective formation of larger polymeric chains – are selectively incorporated into the chains of thermosetting polymers using an economical additive in traditional curing workflows. The materials can retain the mechanical properties of the virgin material, albeit with slight controlled degradation triggered to produce soluble and recyclable products. In contrast, the incorporation of clickable cross-linkages does not yield degradable materials, underscoring that optimizing the location of the clickable bond can serve as a principle to achieve controlled degradation of thermosetting polymers. In contrast, the incorporation

of clickable cross-linkages does not yield degradable materials, highlighting that optimizing the location of the clickable bond can be employed as a principle to attain controlled degradation of thermosetting polymers [67].

Thermal recycling is a more aggressive method compared to the ones described earlier, that involves recovering fibers. After the process, the recycled material can be used in applications that do not require high requirements. It is worth noting that this method is still under development for large-scale industrial recycling [63].

Pyrolysis is a type of thermal recycling that involves the thermal degradation of the resin in a static pyrolysis reactor in the presence of nitrogen. This process allows for the recovery of fibers, cores, and inserts. The decomposition of the matrix yields oily products, and the solid carbon residues can negatively impact the bond between the fiber and matrix during post-processing. Ultimately, the fibers can undergo a careful treatment to ensure they are cleaned and not further degraded [65].

3. LIFE CYCLE COST

Life Cycle Cost (LCC) can be defined as the sum of costs throughout the entire lifecycle of a product or project. This economic evaluation considers the costs associated with a product over its entire lifespan, aiding in decision-making by helping choose the most beneficial investment based on cost considerations [68].

In this analysis, factors such as end-of-life considerations, like landfilling or recycling, can also be considered. In a traditional LCC approach, the focus is often on minimizing the initial acquisition cost. However, this perspective has evolved into a long-term view that takes into consideration not only short-term benefits but also overall costs and impacts. The significance of LCC can be demonstrated as follows: [68]

- Aligning with sustainable development strategies.
- Preventing unnecessary losses caused by ill-considered selections.
- Efficiently allocating resources.

3.1 Life Cycle Stages

The complete life cycle of a wind turbine can be divided into four distinct phases, each containing various stages, [69] as illustrated in the Figure 11. The production of composites is in the manufacturing stage.



Figure 11 – Life Cycle Stages of a wind turbine. [69]

In the current dissertation, the focus is on the raw materials constituting the wind turbine spinner, as well as its manufacturing process. Therefore, these will be the only stages considered in the cost analysis, specifically within the first phase of the life cycle, the manufacturing phase. The costs associated with other variables, such as the production of other turbine components, transportation and installation of components, energy consumption, and maintenance services, will be assumed to be equal and constant across all studied raw materials and processes. It is important to note that the end-of-life stage of the turbine is not within the manufacturer's responsibility (in this case, Vestas), but rather the responsibility of the customer.

3.2 Cost Analysis

For a consistent and standardized analysis of the average costs of the studied materials and processes, all data were extracted from the same database, the Granta EduPack software. The only value not taken from the software was the cost of the core currently used (the AtlasFoam), since the exact composition is not known. The manufacturer was therefore contacted to determine the cost of the core. Initially, the

costs of the materials currently used in the spinner manufacturing were examined: glass fiber, polyester matrix, and interpenetrating polymer core.

All costs of the other materials studied throughout the dissertation were compared to these reference values. The aim was to calculate the percentage difference between the costs, as indicated in Table 6. The costs of vitrimers are not represented due to being a relatively recent polymer group, and their corresponding data are unavailable in the utilized database. The calculation used to calculate the percentage difference between the cost of materials used and the cost of alternative materials is expressed in Equation 1:

$$(1) \text{ Cost Difference}_{\text{materials}} = \left(\frac{\text{Alternative Materials}^{\text{F}} \text{Cost}}{\text{Current Materials}^{\text{F}} \text{Cost}} - 1 \right) \times 100$$

Table 6 - Average costs of current and alternative materials and their respective comparison, in percentage

Thermoplastics constitute the most cost-effective group of polymers, with an average cost of approximately 0.6 EUR/kg. However, since thermoplastic polymers and certain biopolymers are not suitable for the vacuum infusion process, changing the polymer matrix, from a thermoset to one of these groups necessitates a mandatory shift in the manufacturing process to 3D printing, thermoforming, or compression molding, accompanied by the associated initial investment.

Table 7 displays the initial investments, along with some associated costs and other variables, for various processes that were discussed in Chapter 2. Once again, these costs and variables were compared to those of the vacuum infusion process, acting as reference values in Table 7, given that it is the currently practiced method for spinner manufacturing. Due to this fact, the initial investment of this process is not represented in the table, as it is unnecessary.

It should be noted that data for the HiPerDiF process are not included in the table since they were not available in the used software, likely due to the process being relatively recent. The formula used to calculate the percentage difference between the costs of the process used and the costs of alternative processes is expressed in Equation 2:

$$(2) \text{ Cost Difference}_{\text{process}} = \left(\frac{\text{Alternative Process Variant Cost}}{\text{Current Process Variant Cost}} - 1 \right) \times 100$$

Table 7 - Average costs of different variables in the studied processes and their respective comparison with the currently used method¹

PROCESS	VACUUM INFUSION	RESIN TRANSFER MOLDING		3D PRINT - MATERIAL EXTRUSION		3D PRINT - LASER POW
		Average Price (eur)	Percentual Difference	Average Price (eur)	Percent	
Capital Cost (eur)	-	509 200				
Tooling cost (dolars)	1039					
Relative cost index (eur/						

¹ The capital cost is the total cost of the equipment necessary to perform the process. The production rate is the output rate of the process. The tooling cost is the cost of the tooling (molds, dies, jigs, and fixtures) dedicated to producing a single product. The relative cost index approximates the cost of making a 'unit' or a component by the process. Its value is calculated with the 'Process Cost Model'.

4. CONTEXTUALIZATION OF THE CASE STUDY

4.1 Wind Turbine Operation

The function of a turbine is the generation of electrical energy from kinetic energy, which is produced by the action of the wind. Typically, a turbine is comprised of six modules, namely the hub, spinner, blades, nacelle, foundation, and miscellaneous components. In Figure 12, some constituents of a wind turbine are depicted.

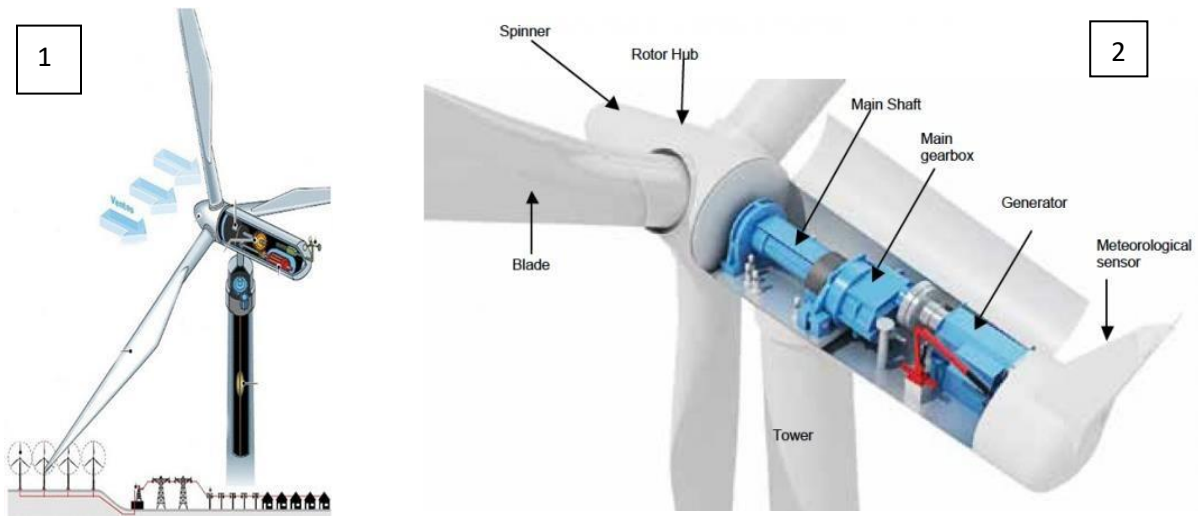


Figure 12 – (1) Representative image of a wind turbine [70] and (2) the interior of a wind turbine [71].

In this equipment, the blades rotate with the force of the wind, which in turn causes the rotor to spin, transmitting this rotation to the generator. The generator, typically coupled with a power converter, converts the received mechanical energy into electrical energy. Subsequently, the produced electrical energy is injected into a voltage grid within the wind farm, and through this grid, the energy reaches the collection station. Using a power transformer, voltage levels are raised to levels that allow the produced energy to flow through transmission lines, directed towards cities. Wind turbines also feature a brake mechanism, which allows the interruption of blade rotation when the generation of electrical energy is not necessary or feasible. Additionally, a control unit is incorporated, enabling the analysis of wind characteristics so that the equipment's blades can be positioned to efficiently harness the wind's potential [70].

The subject of study in this dissertation is the Mk1B spinner model of the EnVentus V162 onshore turbine, which is illustrated in Figure 13. The function of the spinner is to safeguard the interior of the hub from external aggressions, such as extreme weather conditions or impact from rotating objects, while concurrently minimizing aerodynamic resistance, thereby creating a more streamlined airflow. Presently, the panels comprising the spinner's cover are composed of a composite material, and the structural components forming the interface with the cover are constructed from structural steel [72].

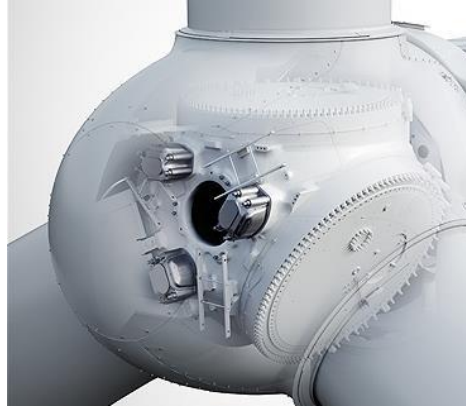


Figure 13 — Real image of the spinner of the Vestas EnVentus v162 turbine, Mk1B model. [73]

4.2 Spinner Specific Requirements

The spinner component presents requirements that primarily encompass mechanical and environmental criteria throughout the wind turbine's approximately 30-year lifespan, as well as its impact on the entire supply chain [72].

General Requirements

The degradation of exposed surfaces of this structure, due to environmental conditions should neither diminish the lifespan nor impair the original function of the component throughout its designated service life. The spinner should refrain from accumulating or absorbing water and other liquids, and its repair, in case of damage, must remain feasible throughout the entire component's lifespan. It is important to emphasize that these repairs must ensure the projected service life [72].

Environmental Requirements

The structure comprising this component should be capable of fulfilling its function both during storage and during the turbine's operation under the following environmental conditions: [72]

- Humidity levels of 100%, for 40% of the service life, and 90% humidity for the remaining 60% of the service life.
- Operating temperatures ranging from -40°C to 60°C.
- UV solar radiation with a maximum intensity of 1000 W/m² and 10,000 MJ/m²/year throughout the entire service life.
- Extreme wind situations with speeds of 58.1 m/s.

Mechanical Requirements

The mechanical requirements of the reinforcing fiber and matrix are depicted in Tables 8, 9, and 10:

Table 8 - Reference values to be used for UD fiber mat.[74]

Properties	Units	LSL Value	Nominal Value
Longitudinal modulus	MPa		37 045
Transverse modulus	MPa		10 192
Shear modulus	MPa		2880
Poisson ratio			0.3
Minimum Failure Strain	(%)	1.32	

Table 9 – Reference value to be used for CSM fiber mat.[74]

Properties	Units	LSL Value	Nominal Value
Longitudinal modulus	MPa		8872
Transverse modulus	MPa		7959
Shear modulus	MPa		3400
Poisson ratio			0.38
Minimum Failure Strain	(%)	1.32	

Table 10 – Reference values to be used for resin (generic).[74]

Properties	Standard	Units	LSL Value	Nominal Value
Young's modulus	ISO 527	MPa		3400
Shear modulus		MPa		1308
Poisson ratio		-		0.3
Density	ISO 2811	Kg/m3		1200
Tensile strength	ISO 527	Mpa		50
Heat deflection temperature	ISO 75-2 method A	°C	70	

Environmental Impact on the supply chain

In the realm of the environmental impact of the spinner across the entire supply chain, it is anticipated that a more sustainable alternative can be identified. This pertains not only to end-of-life considerations, whereby component recycling is encouraged to prevent landfilling, but also to the manufacturing stage. This involves exploring materials and processes that contribute to carbon emission reduction [74].

4.3 Spinner Material

4.3.1 Metallic Material

The metallic portion of the spinner is composed of S235 and S355 structural steels [74]. Structural steels are primarily characterized by their uniformity, which enables the anticipation of their behavior under stress, deformation, and fracture situations. They exhibit high yield strength, good weldability, and are easily worked on through activities like cutting and bending. These steels find wide application across various industries such as construction and automotive manufacturing [75]. Considering that recycling of steel and metallic materials, in general, is not a concern, these materials will not be the focus of the study, if the currently used metallic materials remain unchanged.

4.3.2 Composite Material

The materials used for manufacturing the Vestas spinner are currently produced from a thermoset unsaturated polyester resin matrix, reinforced with synthetic glass fiber and an interpenetrating polymer networks core. Spinner uses a specific type of commercial composite laminate, Combimat, which composed by different combinations of unidirectional ply (UD), polypropylene (PP) and chopped strand mat (CSM) fiber glass. Depending on the strength needed, additional Combinat plies can be assembled into one panel. Furthermore, there are certain areas that requires a higher strength and stiffness than the monolithic panels. Therefore, the solution is to add a foam core.

Incorporating a polypropylene mat into a single Combimat layup configuration serves several key purposes. Firstly, it is aimed at improving the bending stiffness of the composite fabric overall, all while keeping the added weight minimal. This is critical for preserving structural integrity and ensuring the composite material's optimal performance. Secondly, the polypropylene mat assists in facilitating the flow of resin during the manufacturing process. It ensures that the fiberglass is effectively saturated, allowing the resin to evenly distribute and bond with the fibers. Consequently, this results in enhanced adhesion and improved mechanical properties for the composite material.

Regarding the chopped strand mat (CSM) used in Combimat, it is a specific type of ply where the fibers are randomly oriented in both the 1-direction and the 2-direction. Typically, the strength is equal in these two directions, although technically, the 1-direction exhibits greater strength. Conversely, the 3-direction demonstrates considerably lower strength compared to the 1- and 2-directions. This random fiber orientation in CSM provides a balanced blend of strength and flexibility.

The unsaturated polyester resin, a class of polymer resin widely used in various industries due to its broad range of processing temperatures, good mechanical properties, corrosion resistance and cost-effectiveness. However, this resin also carries significant environmental drawbacks, which necessitates its replacement. The unsaturated polyester is a polymer derived from petrochemical products that contain high concentrations of hazardous air pollutants, such as styrene, a substance with significant environmental risks. Additionally, the recycling process for this polymer is quite intricate, as it belongs to the category of thermosetting polymers [64].

E-glass fiber, a type of glass fiber, is known for its good wear resistance, electrical properties, and cost-effectiveness compared to other types. It is the most used glass fiber type in structural applications. [32] While glass fibers are recyclable, the recycled product resulting from mechanical methods yields discontinuous fibers. These fibers cannot be reused in high-value products such as the spinner because they possess lower mechanical properties [22]. Recycled fibers from thermal and chemical processes also exhibit significantly lower tensile strength and other mechanical properties when compared to virgin fibers. This once again renders their use in structural applications unfeasible [76].

The core of the panel is composed, as mentioned earlier, of a network of interpenetrating polymers with a very high degree of cross-linking. The molecular structure is akin to cross-linked PVC foam, but with a thermoplastic based on polyester chemistry. This combination results in a material that offers both high hardness and good flexibility [77]. Interpenetrating polymers result from the combination of two or more polymer networks, wherein at least one polymer is cross-linked or synthesized in the presence of the other. This process does not involve the introduction of covalent bonds between the polymers as seen in copolymerization. This approach makes it possible to create materials with specific properties designed to achieve certain objectives, depending on the purpose of the product. The resulting properties depend on the original properties of the polymers used and how they are combined. Therefore, their recycling becomes a highly intricate process, as it would be necessary to disentangle these two polymer networks, besides the potential risk of cross-contamination [78].

4.4 Spinner Manufacturing Process

Currently, at Vestas, two manufacturing processes are accepted for spinner fabrication: vacuum infusion and resin transfer molding. These processes have been explained in sub-chapters 2.3.1 and 2.3.2.

Currently, the method used to produce the Spinner is vacuum infusion due to its lower cost when compared to RTM.

4.5 Alternative Materials and Selection Process

The need to explore alternative materials arose, as previously mentioned, due to the intricate recycling processes of the currently utilized materials and the fact that the recycled products are not suitable for reuse in high-value industries. This results in their deposition in landfills, posing a hazardous environmental threat. This chapter investigates and assesses various alternative materials, as presented in Chapter 2, that has the potential to replace the current materials and offer a lower environmental impact, both during processing and at the end-of-life stage. After a literature review, several aspects were considered for the selection of alternative materials.

4.5.1 Matrix

To simplify the discussion, Table 11 was constructed, presenting the aspects considered in the matrix selection.

Table 11 - Decision matrix table

Matrix	Biopolymers	Thermoplastics	Thermosets	Vitrimers
Advantages	Lower carbon foot print; Low price	Low price; Strong adhesion properties; Widely available in the market	Strong adhesion and mechanical properties	Unique self-repairing properties
Disadvantages	Fast degradation	Sensitives to variables such as UV, radiation and humidity	Higher price when compared to the other groups	Limited market availability; Still in the research and development phase
Manufacturing Process	Not suitable for vacuum infusion process	Not suitable for vacuum infusion process	Suitable for vacuum infusion process	Not suitable for vacuum infusion process
End of Life	Biodegradable	Recyclable	Not recyclable	Recyclable

Despite the low environmental impact of biopolymers, [79] their application in structures requiring high durability without degradation of mechanical properties needs careful consideration, as they are susceptible to degradation by external environmental agents. In the case of manufacturing the composite that constitutes the spinner, this might not be the most suitable alternative because the spinner structure must maintain its mechanical properties over the 30-year lifespan of the turbine.

Regarding thermoplastics, due to their sensitivity to variables such as heat, UV radiation, and humidity, their application in components like the spinner must be carefully assessed. This is particularly important since the spinner is exposed to these conditions for many years. Another constraint associated with using thermoplastic polymers is the current manufacturing process employed for the spinner, which cannot be adapted for producing a thermoplastic matrix composite. This would require a significant overhaul of the manufacturing process and a substantial initial investment.

The vitrimers, even though are a revolutionary group of polymers that should be taken into consideration due to their advantageous mechanical properties coupled with their easy recyclability, are still in the research and development phase, vitrimers have not yet been widely adopted in an industrial scale, which poses a challenge for their application in spinner manufacturing.

Finally, thermosets, given the appealing mechanical properties and the fact they are suitable for the vacuum infusion process, were the chosen group, despite being the most expensive group, which was calculated in Chapter 3. Within the same group, the bio-based epoxy resin was chosen since it exhibits equivalent mechanical and adhesive properties compared to a standard epoxy resin. Additionally, it offers the advantage of a lower carbon footprint.

4.5.2 Fiber

Table 12 simplifies the aspects considered in the fiber selection process.

Table 12 – Decision fibre table

Fiber Fiber Type	Basalt Natural	Flax Natural	Sisal Natural	Hemp Natural	Carbon Synthetic
Advantages	Abundance of raw material; Good mechanical properties when compared to glass	Biodegradable; Low carbon footprint; Low density	Biodegradable; Low carbon footprint	Biodegradable; Low carbon footprint	Higher mechanical properties, when compared to glass
Disadvantages	More expensive than glass	Lower mechanical properties, when compared to glass; Sensitive to humidity and temperature	Lower mechanical properties when compared to glass and flax; Sensitive to humidity and temperature	Low availability of raw materials; Lower mechanical properties, when compared to glass; Sensitive to humidity and temperature	Much more expensive than glass; Very high carbon footprint
End of Life	Recyclable (can maintain mechanical properties)	Recyclable (does not maintain mechanical properties)	Recyclable (does not maintain mechanical properties)	Recyclable (does not maintain mechanical properties)	Complex recycling process

Considering all the mentioned environmental advantages of natural fibers, such as their renewability, low CO₂ emissions, and biodegradability, [27] they cannot be overlooked as potential alternatives. Among the natural fibers, the basalt fiber was deemed the most promising, given its abundant raw material and mechanical properties that closely match those of E-glass fibers, as described on sub-chapter 2.1.2. Furthermore, basalt exhibits a slightly higher cost compared to glass, which is around 2.17%, a value calculated in Chapter 3.

Flax natural fibers also present a promising alternative, considering that despite the disadvantages presented on Table 12, their lower weight offers a significant advantage, once that allows for the use of a larger quantity of fibers to achieve better properties without compromising the final structure's weight. These fibers were also considered due to the lower cost calculated in Chapter 3 (26.1% less); however, it could not be practically employed in the study.

Sisal fibers were ruled out because of their lower mechanical properties when compared to other natural vegetable fibers. Carbon fibers were also ruled out due to their substantial carbon footprint generated throughout their processing, which goes against the objective of this study.

4.5.3 Core

Finally, Table 13 was also constructed to evaluate the best choice for the core material.

Table 13 – Decision core table

Core	Polypropylene	Cork	Polystyrene
Advantages	Low density; Good mechanical properties	Natural raw material; Good mechanical properties; Biodegradable	Low price
Disadvantages	Sensitive to variables such as UV, radiation and humidity	Higher density when compared to other cores	High toxicity
End of Life	Recyclable	Recyclable	Complex recycling process

Both cork and polypropylene were considered potential alternatives for replacing the currently used core material, as both materials are easily recyclable and possess good mechanical properties. Polystyrene was excluded from the practical work due to its poor recyclability and high toxicity.

Notably, that according to the analysis in Chapter 3, both materials demonstrate significantly lower costs compared to the material used, considering that cork is 61.5% cheaper and polypropylene is 91% cheaper. However, since the values of these two materials and the used material do not originate from the same source, the comparison is not the most plausible.

5. MATERIALS AND METHODS

In this chapter, the studied composites will be analyzed, with a focus on the materials and production process. We compared composites with the same polymer matrix but different fiber states, one composed of virgin fibers and the other made with recycled fibers. Subjected to various time and temperature cycles. Furthermore, sandwich panels with identical laminates but different cores, made from cork and polypropylene were compared. It is noteworthy that a Life Cycle Assessment (LCA) of these materials was conducted by *Cai* [1] in his dissertation.

5.1 Composites in study

5.1.1 Raw Materials

A 38% bio-based epoxy resin was used in the production of the laminates, namely the SR InfuGreen 810/SD 8825.2 from Sicomin. The fiber used was a multiaxial basalt fiber, the *Bas Bi 450* from *Castro Composites*. As for the cores used in panel manufacturing an expanded cork agglomerate from *Amorim Cork Insulation* and a *Hardex XPP Optima* polypropylene core from *Spur* were employed. Mechanical properties are represented on Table 14.

Table 14 - Mechanical properties of materials used in composite manufacturing.

	SR INFUGREEN 810/SD 8825.2	BAS BI 450	AMORIM CORK INSULATION	HARDEX XPP OPTIMA
TENSILE STRENGTH (MPa)	68	3000	-	0,82
ELASTIC MODULUS (MPa)	2700	87000	-	11
ELONGATION AT BREAK (%)	9,1	-	-	-
FLEXURAL STRENGTH (MPa)	112	-	-	-
FLEXURAL MODULUS (MPa)	2700	-	-	-
DENSITY (g/cm ³)	1,16	2,67	0,11	0,06
COMPRESSIVE STRENGTH (MPa)	95	-	-	0,07
IMPACT STRENGTH (KJ·M ⁻²)	80	-	-	-
GLASS TRANSITION TEMPERATURE (°C)	91	-	-	-
THERMAL CONDUCTIVITY (W·M ⁻¹ ·K ⁻¹)	-	-	0,039	0,043

5.2 Laminate Production Process

Composites with virgin fibers

All the developed laminates were produced through the vacuum infusion process. To produce laminates with virgin fiber, the initial step involved cutting the fibers to the desired dimensions, with a margin of approximately 10 mm, to later allow for adjustments. Technical fabrics were also cut: the peel ply, whose role is to aid in the demolding stage and to provide a rough surface finish, and the infusion mesh, which plays a role in facilitating resin flow and dispersion. It should be noted that the peel ply fabric should have a size similar to that of the fibers, while the infusion mesh should be shorter in the exit zone, ensuring that the resin front is uniform at the end of the process. Lastly, the vacuum bag was cut to

dimensions significantly larger than the work area to prevent tearing. The mold was then prepared on the infusion table, with the placement of paper tape to define a working area. The demolding agent LOCTITE®FREKOTE 770NC was applied to this area to assist in the composite removal at the end of the process. Subsequently, six layers of fiber were placed one by one in the center of the working area, with alternating orientations of 45°/-45°, as seen in Figure 14, featuring a total of 3 layers in the -45° direction and 3 layers in the 45° direction. For a clearer view of the construction of the various layers, please refer to Appendix B.

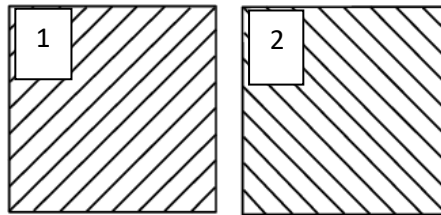


Figure 14 - Fiber orientation of (1) 45° and (2) -45°.

Following the fiber layers, peel ply fabrics and the infusion mesh were placed, and then spiral tubes, T-connections, and inlet/outlet tubes were also positioned. These components enable the entry and distribution of resin. The penultimate step involves sealing the vacuum bag, adhering the vacuum seal to the defined work area—starting from the edges and then moving towards the center until reaching the extremities. For the preparation of the resin mixture, it is necessary to first weigh the fiber layers to calculate the amount of the mixture, which should be about 1.5 times their weight. To create this mixture, 22g of hardener is used for every 100g of resin. It is worth noting that before the mixture is used, a vacuum chamber to remove any air bubbles, ensuring they do not negatively impact the composite fabrication process. Finally, the infusion process begins by connecting the outlet tube to the vacuum pump and submerging the inlet tube in the resin. Figure 15 illustrates the various steps of the vacuum infusion process:

1. Definition of the working area and application of the demolding agent
2. Placement of tapes and technical fabrics
3. Placement of spirals, inlet/outlet tubes, vacuum bag, and finally
4. Application of vacuum, resin infusion, and vacuum process. The composites were cured at 80°C for 10 hours.

Subsequently, the composites were cut to the desired dimensions for conducting mechanical tests.

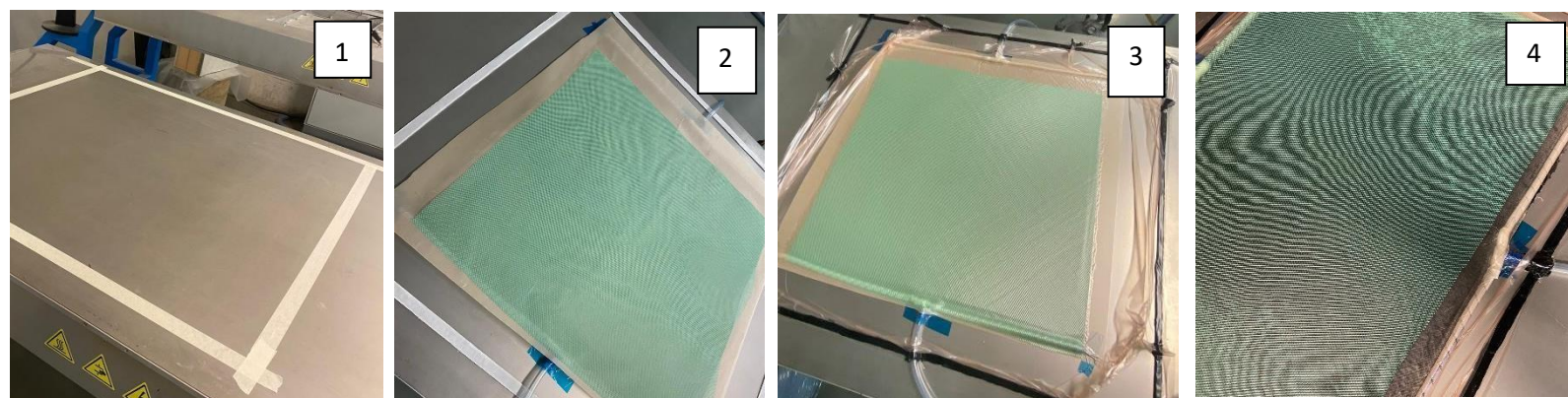


Figure 15 - Various stages of the vacuum infusion process for laminate production.

Composites with recycled fibers

To produce composites with the recycled fiber, it was necessary to first create composites with virgin fiber, which were later thermally recycled. This was the chosen recycling method, as it allows for the incineration of the polymer matrix while preserving the continuous fibers, which can be reused. The temperatures used were always below 700°C, as the recrystallization temperature of the basalt fibers varies between 700°C and 850°C. [80] This is not the desired phenomenon to achieve, as recrystallization results in a change in the physical and mechanical properties of the fibers.

Two laminates of virgin fiber were manufactured with the purpose of being incinerated and subsequently used in the production of four recycled laminates.

The time and temperature cycled are described in the Table 15:

Table 15 – Temperature and time cycled applied to different composites, inside muffle.

Composite	Temperature (°C)	Time (hours:min.)
1	625	1:30
2	425	6:00
3	375	10:00
4	350	7:00

After the composites were subjected to the muffle furnace, where the resin was burned off, only the fibers were retrieved, which were subsequently used in a new infusion. The infusion process for the recycled composites was the same as the process described before, with the difference that no virgin fibers were cut; the fibers that were removed from the muffle furnace were used directly. Subsequently, the composites were cut to the desired dimensions for mechanical testing.

5.3 Sandwich Panel Production Process

The two sandwich panels were also manufactured using the infusion process, although they had different preparations. For the panel with a cork core, a laminate measuring 200x150mm was first fabricated, which was subsequently cut into two parts to be placed on the upper and lower sides of the

core. The laminates were not produced together with the core because the cork used is a composite with numerous cavities that would absorb a significant amount of resin. The laminates were produced following the process described in the previous subchapter. After cutting the cork core to dimensions of 100mmx75mm, it was placed between the laminates on the infusion table, where the mold was already prepared with tape. It is worth noting that a layer of resin was also applied to the composite on the bottom side of the core and another layer on the top side of the core to ensure better adhesion between the layers. Before starting the infusion, a breather, a white "blanket," was placed to prevent the collapse of the vacuum bag. The resin-hardener mixture was calculated using the same method as for the laminates, adjusted for the panel's weight, and taken to the vacuum chamber. The rest of the process was carried out in the same manner as the laminate production process. In the production of the panel with an XPP core, there was no prior fabrication of laminates, as this core was not prone to absorbing a large amount of resin. The fibers and the core were both cut to dimensions of 100mmx75mm. The core thickness was 20mm. After preparing the mold on the infusion table, six layers of fiber were placed, followed by the core, and then another six layers of fiber. The technical fabrics of peel ply and the infusion mesh were placed on the top, following the same steps as described previously for the infusion process.

5.4 Characterization Methods

In this dissertation, physical characterization tests were conducted on a group of laminates, along with mechanical tests including tensile, flexural, and compressive testing on both laminates and panels.

5.4.1 Physical Characterization Tests

5.4.1.1 Density Test

One way to calculate the average density of an element, assess the degree of uniformity among various samples, and detect physical changes in a sample is by calculating the density of multiple samples of the same laminate.

To achieve this, an experimental test was conducted on the virgin composite following ASTM D792 standard, using the experimental setup depicted in the Figure 16:

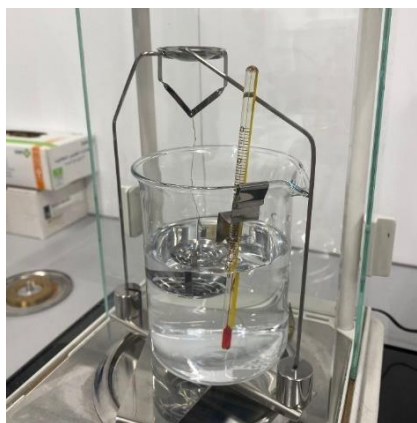


Figure 16 - Experimental setup used in density tests.

The procedure was initiated by weighing five dry samples, which were then immersed in water to obtain the apparent mass. In the end, the density of the samples was calculated (ρ) in g·cm⁻³ using Equation (3), where m_{dry} corresponds to the mass of the dry sample and m_{water} corresponds to the mass

of the sample in water, both measured in grams. The conversion factor values for 24°C are presented in Appendix C.

$$(3) \rho = \frac{m_{dry}}{m_{dry} - m_{water}} \times \text{conversion factor}$$

5.4.1.2 Fiber Content Test and Void Volume

The fiber content and void volume test was conducted on five samples of the virgin fiber composite, following ASTM D3171 standard. Initially, five samples of the composite were placed in appropriately labeled crucibles, which were then weighed. Subsequently, each crucible was also weighed to obtain the mass (g) of each one. The samples were then placed inside the crucibles and subsequently inside the muffle furnace, as shown in Figure 17, at 625°C for 1 hour and 30 minutes.



Figure 17 - Muffle furnace used in the fiber content and void volume test.

After the crucibles were removed from the muffle furnace, they were weighed again. The fiber content in mass percentage (W_{fiber}) and in volume percentage (V_{fiber}) were calculated using Equations (4) and (5) respectively. The resin content in volume percentage (V_{resin}) was calculated using Equation (7), a value that was necessary for the calculation of void volume (V_{voids}). In the equations described below, m_i and m_{fi} represent the initial and final mass of the sample respectively. In Equation (5) and (7), ρ_{sample} corresponds to the value calculated in Equation (3), as described in the above sub-chapter. For the fiber and resin densities, the values from the technical data sheets provided by the manufacturers were used, which are 2.67 g/cm³ and 1.16 g/cm³ respectively.

$$(4) W_{fiber} = \frac{m_{fi}}{m_i} \times 100$$

$$(5) V_{fiber} = \frac{m_{fi}}{m_i} \times \frac{\rho_{sample}}{\rho_{fiber}} \times 100$$

$$(6) V_{void} = 100 - (V_{resin} + V_{fiber})$$

$$(7) V_{resin} = \frac{m_i - m_{fi}}{m_i} \times \frac{\rho_{sample}}{\rho_{resin}} \times 100$$

5.4.2 Thermal Characterization Tests

5.4.2.1 Differential Scanning Calorimetry - DSC

Differential Scanning Calorimetry (DSC) was employed, following the ASTM D3418 standard, to characterize the thermal behavior as well as the thermal transitions of the studied resin. Figure 18 illustrates the equipment used for conducting the test, the Differential Scanning Calorimeter, model Q20 from *TA Instruments*.



Figure 18 - Photograph of the equipment used in the DSC tests - Model Q20 from *TA Instruments*®

This technique involves measuring the heat flow difference between the sample under analysis and a reference sample as a function of time and temperature, during heating, cooling, or under isothermal conditions. [81] This technique is highly versatile and allows for the study of various properties, such as glass transition temperature, curing behavior, and specific heat capacity. In this way, a transition is characterized by the absorption or release of energy by the sample, resulting in an endothermic or exothermic peak. The property under study was the glass transition temperature. It is noteworthy that in this assay, the presence of impurities can impact the outcome. Figure 19 presents several examples of the different thermal transitions that can be obtained through DSC.

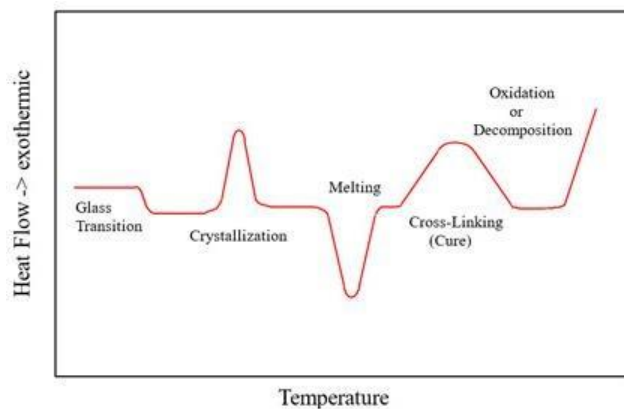


Figure 19 - Example of various transitions that can be obtained through DSC. [82]

5.4.3 Mechanical Characterization Tests

5.4.3.1 Flexural Test

The flexural test was performed on multiple samples, that were cut in different directions, which can be identified in the Table 16. The dimensions of all samples are provided in Appendix G for laminates and Appendix H for sandwich panels.

Table 16 – Specimens tested for flexural test.

Composite	0°/90° Direction	-45°/45° Direction
Virgin Fiber	7	7
Recycled Composite 1	4	6
Recycled Composite 2	5	5
Cork Core Panel	-	7
PP Core Panel	-	7

The ISO 14125 standard was used for monolithic laminates, and the ASTM C393/C393M standard was used for sandwich panels. The equipment used was a INSTRON 5900R and is depicted in the Figure 20:

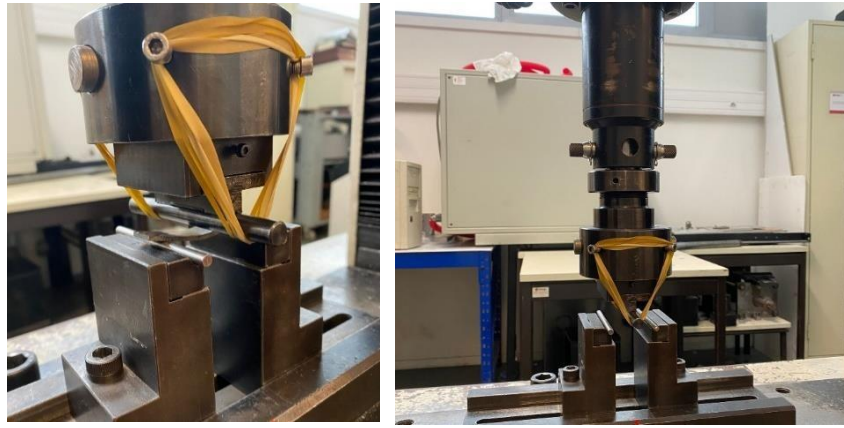


Figure 20 - Photograph of the equipment used in flexural tests.

To determine the flexural properties, the test was conducted at three points, with the samples subjected to a flexural deformation at a constant rate until sample fracture occurred. A 100 kN load cell was used, and the testing speed was set to 5 mm/min for both laminates and sandwich panels. For the monolithic laminates, Equation (8) below was utilized to calculate the flexural stress of the samples, where F_{max} represents the maximum force before failure in Newtons, L is the distance between the rollers in mm (with a value of 40 mm), and b and h denote the width and thickness of the sample, respectively:

$$(8) \sigma_f = \frac{3F_{max}L}{2bh^2}$$

For the panels, according to the previously mentioned standard, the maximum core shear strength (F_s^{ult}) and the flexural stress of the loaded laminate (σ_f) were calculated in MPa using Equations (9) and (10) respectively:

$$(9) F_s^{ult} = \frac{F_{max}}{(p+c)b}$$

$$(10) \sigma_f = \frac{F_{max}L}{2t(p+c)b}$$

In both equations, p represents the panel thickness and c represents the core thickness, both measured in mm; L is a fixed value of 150 mm for all tests, corresponding to the distance between the rollers, and t is the laminate thickness, in mm.

The flexural modulus (E_f) was also calculated in MPa for both laminates and sandwich panels using Equation (11), where m represents the tangent slope of the initial portion of the stress-strain curve, in N/mm^{-1} :

$$(11) E_f = \frac{L^3 m}{4bh^3}$$

5.4.3.2 Compressive Test

The compression test was conducted on 7 samples of the cork sandwich panel and 7 samples of the XPP sandwich panel, following the ASTM C364/C364M standard. The dimensions of all samples are provided in Annex I. The Figure 21 depicts the utilized equipment, the *INSTRON 5900R*, as well as one of the tested samples:



Figure 21 - Photograph of the equipment and sample used in the compression tests.

During the various tests, each panel was subjected to a compressive force parallel to the plane of its faces, and the force was measured using a 100kN load cell. The maximum compressive strength (σ_c), in MPa, was calculated using Equation (12):

$$(12) \sigma_c = \frac{F_{max}}{2tb}$$

5.4.3.3 Tensile Test

To determine the tensile properties, tensile tests were performed on the composite of virgin fibers, following the ASTM D3039/D3039M standard. Tensile tests were not conducted on the recycled fiber composites, as the samples used for these tests require specific dimensions that cannot be obtained due to the limitations imposed by the size of the muffle. The dimensions of all samples are provided in Appendix F. The equipment used was the *INSTRON 5900R*, which is depicted in Figure 22.



Figure 22 - Photograph of the equipment used in the tensile tests

A 100 kN load cell and specimens with dimensions of 25 mm x 250 mm x 2.5 mm were used. It should be noted that at least 5 valid results should be obtained. During the test, a tensile force was applied at a rate of 2 mm/min, where the maximum material strength was determined from the maximum force sustained before failure. It is also possible to obtain the stress-strain response, from which the maximum tensile strain, modulus of elasticity, and Poisson's ratio are determined.

Equations (13), (14), (15) and (16) were used for the calculation of tensile strength, tensile strain, tensile modulus of elasticity and Poisson's ratio by chord method respectively:

$$(13) F^{tu} = \frac{F_{max}}{Area}$$

$$(14) \epsilon = \frac{\delta_i}{L_g}$$

$$(15) E^{chord} = \frac{\Delta\sigma}{\Delta\epsilon}$$

$$(16) \nu = - \frac{\Delta\epsilon_t}{\Delta\epsilon_l}$$

5.4.3.4 Shear Test

The shear tests were performed only on specimens of the composite with virgin fibers, according to ISO 14129. Once again, the samples with recycled fibers were not tested for the same reason mentioned in the tensile test in subsection 5.4.3.3. In this test, the samples had fibers oriented at $\pm 45^\circ$ with respect to the applied tensile force. The equipment used was the INSTRON 5900R, depicted in Figure 22.

The dimensions of all samples are provided in Appendix F. Samples were tested with a speed of 2 mm/min. Through the equations presented below (17 and (18)), it was possible to calculate the in-plane shear strength τ_{12} and in-plane shear modulus, G_{12} respectively:

$$(17) \tau_{12} = \frac{F_{max}}{2bh}$$

$$(18) G_{12} = \frac{\tau_{12}'' - \tau_{12}'}{\gamma_{12}^{FF} - \gamma_{12}'}$$

5.4.3.5 Single Fibre Test

Two types of specimens were prepared for both fibre groups: resin-infused specimens and dry specimens, i.e., without resin. Note that for the resin-infused specimens a residual amount of resin was used solely to facilitate fibre bonding. The samples were cut, manually impregnated with bio-based epoxy resin, and cured for 10 hours at 80°C. Subsequently, composite tabs, measuring 25 mm × 25 mm, were applied to the ends of the samples using a structural bonding adhesive, as depicted in Figure 23. The tabs were used to enable the placement of the specimens in the testing machine. Finally, single fibre tests were conducted on both virgin and recycled fibres to compare their tensile strength and evaluate whether the recycled fibres, when isolated, exhibited a reduction in mechanical properties. Initially, the sizing treatment was manually removed from the virgin fibres to ensure a valid comparison with the recycled fibres, as this treatment is eliminated within the furnace. Subsequently, a composite was fabricated according to the procedure described in subsection 5.2, which was then placed in the furnace and heated to 425°C for 6 hours. This thermal recycling cycle was chosen as it yielded the best flexural properties for the specimens subjected to this cycle, in comparison to the other specimens from the remaining recycled composites.

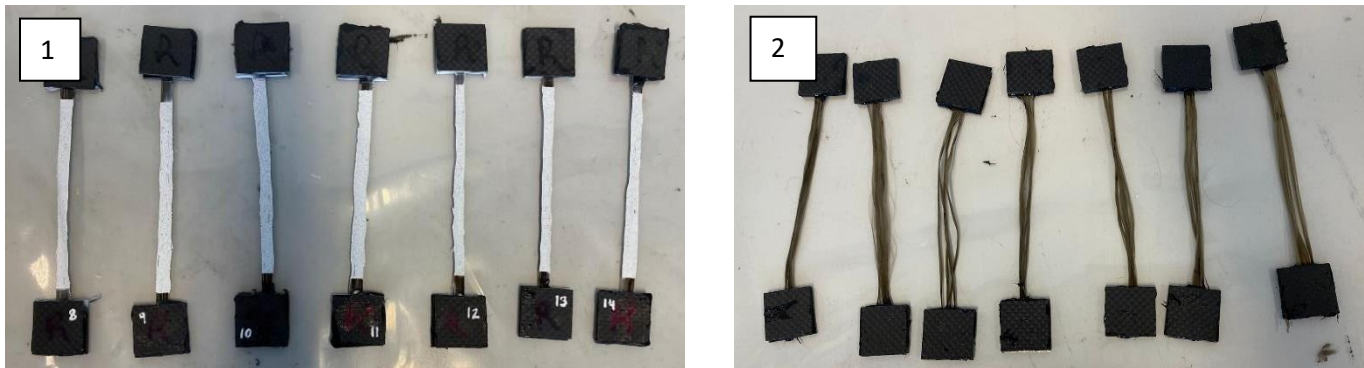


Figure 23 – (1) Impregnated recycled fibres and (2) dry recycled fibres used in tensile test.

For the dry specimens, for both virgin and recycled group, it was necessary to attach tabs with a width of approximately 5 mm. The ISO 10618 standard was employed, and the testing equipment used was the *INSTRON 5900R*, as depicted in Figure 22, equipped with a 100 kN load cell and operating at a testing

² τ_{12}' is the shear stress at a shear strain $\gamma_{12}' = 0.001$; τ_{12}'' is the shear stress at a shear strain $\gamma_{12}'' = 0.005$.

speed of 2 mm/minute. The initial gauge length between the grips was approximately 110 mm. Through the equations (19) it was possible to calculate the tensile strength (σ_f) for the four groups (virgin fibres with and without resin and recycled fibres with and without resin). For fibres with resin, it was also calculated the strain at maximum load (ϵ), by Equation (20):

$$^3(19) \sigma_f = \frac{F_f}{A_f} \times 10^{-6}$$

$$^4(20) \epsilon = \frac{L_u - L_o}{L_o}$$

5.4.3.6 Microscope

To assess and compare the diameter of the virgin and recycled fibres of composite 2, they were observed using the *Leica Zeiss* microscope, depicted in the Figure 24. The diameter was calculated using the *Microscope Imaging Software*.



Figure 24 –Photograph of the microscope Leica

6. RESULTS AND DISCUSSION

6.1 Density, Void Content and Fibre Content Test

Upon conducting both density and void content tests, it was possible to ascertain the true density of the specimen, as well as the mass and volume percentages of the resin and fibre components. The findings of the density test are elucidated in Table 17, which was computed following Equation (3). Comprehensive outcomes for individual samples from the density, void content, and fibre content tests are provided in Appendix D.

Table 17 - Density tests results

SAMPLE	CRUCIBLE MASS (g)	DRY MASS SAMPLE (g)	WET MASS SAMPLE (g)	DENSITY (g/cm ³)
AVERAGE	24.53 ± 0.82	2.28 ± 0.11	1.08 ± 0.02	1.90 ± 0.05

³ F_f is the maximum tensile force, in newtons; A_f is the cross-sectional area of the yarn, in square metres.

⁴ L_o is the extensometer gauge length, in millimetres; L_u is the extensometer reading, in millimetres, at maximum load.

The average density of the composite stands at 1.90 g/cm^3 , a value that falls within the range of density values for both the resin and the fibre, which is 1.16 g/cm^3 and 2.67 g/cm^3 respectively. Examining the density column and its coefficient of variation value in Appendix D, reveals nearly constant values, indicative of the homogeneity in the composite's density.

In Table 18, the represented variables were obtained to calculate the void volume and fibre content.

Table 18 – Information to calculate void volume and fibre content.

SAMPLE	CRUCIBLE MASS (g)	CRUCIBLE + SAMPLE MASS (g)	INITIAL MASS - MI (g)	CRUCIBLE + FIBER MASS (g)	FINAL MASS - MFI (g)
AVERAGE	24.53 ± 0.82	26.81 ± 0.83	2.29 ± 0.11	26.12 ± 0.83	1.59 ± 0.02

The mass and volume percentages of fibre and resin, along with the void percentage, were calculated using Equations (4), (5), (6), and (7) with the values provided in Table 18. The outcomes are illustrated in Table 19:

Table 19 - Fiber content test results.

SAMPLE	FIBER CONTENT (WEIGHT PERCENT)	FIBER CONTENT (VOLUME PERCENT)	MATRIX CONTENT (WEIGHT PERCENT)	MATRIX CONTENT (VOLUME PERCENT)	VOID VOLUME (%)
AVERAGE	69.80 ± 2.75	49.73 ± 3.20	30.20 ± 2.75	49.35 ± 3.05	0.92 ± 0.67

Considering that the composite exhibits an average void content of 0.92%, signifying a virtually negligible porosity, it can be inferred that the composite is compact, stemming from a strong fibre-matrix adhesion and a successful curing process. From a mechanical properties' standpoint, a low porosity content is desirable, as it adversely affects attributes such as strength and stiffness.

6.2 Differential Scanning Calorimetry – DSC Test

Upon analysing the virgin fibre composite, it was observed that the glass transition temperature of the utilized *InfuGreen 810/SD 8825.2* resin was approximately $92.36^\circ\text{C} \pm 1.8^\circ\text{C}$, a value that lies within the range provided by the supplier, as indicated in the technical datasheet found in Appendix A. Graphs detailing the conducted tests can be found in Appendix E. Notably, a higher glass transition temperature of a resin correlates with improved mechanical properties. It is evident that the bio-based resin employed in the fabrication of all composites exhibits a higher glass transition temperature than that one of the standard epoxy resin, the *Biresin CR83* by *Sika*, a resin widely used in the vacuum infusion composite manufacturing process, which in turn exhibits a glass transition temperature between 81°C and 84°C , as can be verified from its technical datasheet available in Appendix A.

6.3 Mechanical Tests of the Composite

6.3.1 Tensile and Shear Tests

In the initial phase, virgin fiber composites were subjected to mechanical tests involving tensile and shear evaluations. A total of 7 samples were tested for each assay, and the results of only 5 samples were selected due to their lower result variability. Graphs generated from these tests are provided in

Appendix F. Table 20 encapsulates the outcomes acquired from both assessments, featuring the average values of ultimate strength (maximum force that a material can withstand under ideal conditions before breaking) and tensile strength.

All the tensile and shear results presented in this sub-chapter were employed by Cai [1], in the Finite Element Method (FEM) program for a performance comparison of basalt fibers with glass fibers in the spinner.

Table 20 - Tensile and shear tests results

PROPERTIES	TENSILE TEST	SHEAR TEST
ULTIMATE STRENGTH (N)	30712 ± 805	6852 ± 62.03
TENSILE STRENGTH (MPa)	582 ± 21.5	-
IN-PLANE SHEAR STRENGTH (MPa)	-	66.81 ± 0.87

Analyzing the Table 20, it becomes apparent that higher values of ultimate strength and tensile strength were achieved on tensile test, when compared with the values of ultimate strength and in-plane shear strength on shear test, indicating that the composite it exhibits distinct mechanical properties in the various tested directions and have superior ability to withstand loads in the axial direction, where the forces act to elongate the material.

During fracture propagation, reinforcing fibres maintain structural integrity until the crack or series of cracks has grown too large, at which point material failure occurs. Notably, the fracture patterns observed in the tested specimens differed, as depicted in Figure 25. Specimens subjected to the tensile test displayed fractures of the "explosive at grip" and "explosive gage" types, occurring in varying regions (top, middle, and bottom) depending on the sample, according to the standard ASTM D3039/D30390M. This type of failure signifies that the fracture of the composite occurred suddenly and catastrophically, meaning that the material fractured without warning. Conversely, specimens from the shear test exhibited fractures of the "angled gage" type, either at the top or bottom, according to the standard ISO 14129. Fractured specimens are depicted in Figure 25.

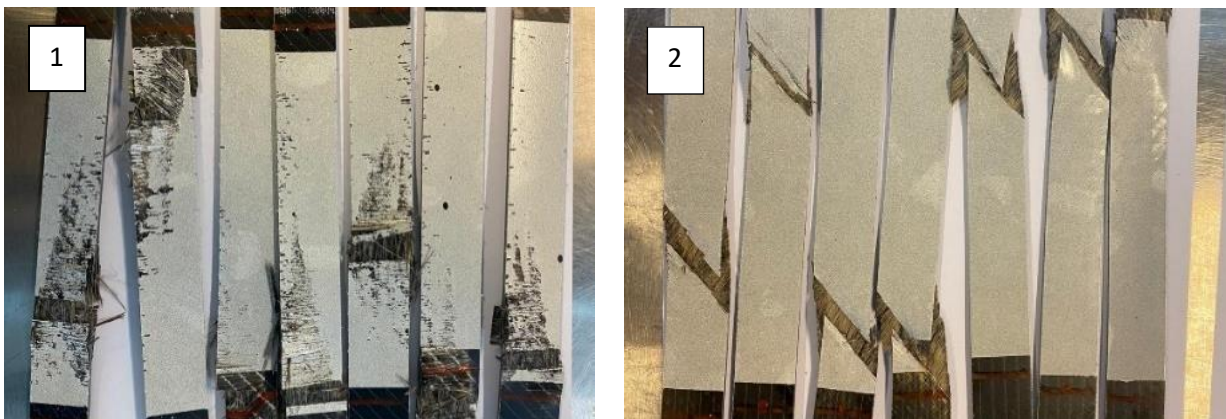


Figure 25 – Specimens after the tensile (1) and shear (2) test.

The remaining properties calculated from the tensile test are presented in Table 21:

Table 21 - Tensile test results

Tensile Strain (%)	3.26 ± 0.11
Tensile Chord Modulus of Elasticity (MPa)	17955.2 ± 2904.8
Poisson's Ratio by Chord Method (-)	0.14 ± 0.01

From the presented results, we can infer that the material underwent a deformation of 3.26%, showcasing the composite's remarkable rigidity and resistance to tensile deformation, as evidenced by its elastic modulus of 17955.2 GPa. Meanwhile, the Poisson's ratio, an adimensional proportion that relates the lateral (contraction) deformation of a material to the axial (elongation) deformation when subjected to uniaxial tensile or compressive forces, indicates that the material tends to laterally contract approximately 14% of the elongation value. This value is lower than expected, that should be between 0.2 and 0.3, which can be justified by a malfunction of the equipment used.

Lastly, another property was calculated from the shear test, as detailed in Table 22. Considering the shear modulus value, we can assert that the composite is rigid, as this parameter is a measure of the material's stiffness with respect to shear deformation.

Table 22 - Shear test results

Shear Modulus (MPa)	4820.11 ± 247.84
----------------------------	----------------------

6.3.2 Flexural Test

Subsequently, bending tests were conducted on the virgin composite, as well as on the recycled composites 1 and 2, which underwent cycles of 625°C for 1_5 hours, and 425°C for 6 hours, respectively. It should be noted that composites 3 and 4, subjected to cycles of 375°C for 10 hours and 350°C for 7 hours, were not tested due to their high level of fragility, which prevented the fibres from being used on the infusion table, as evident from the Figures 26:



Figure 26 - Photographs of composites 3 and 4 after being removed from the muffle.

The results of the bending tests, including maximum force and flexural stress, are presented in Figure 27. The corresponding graphs are in Appendix G.

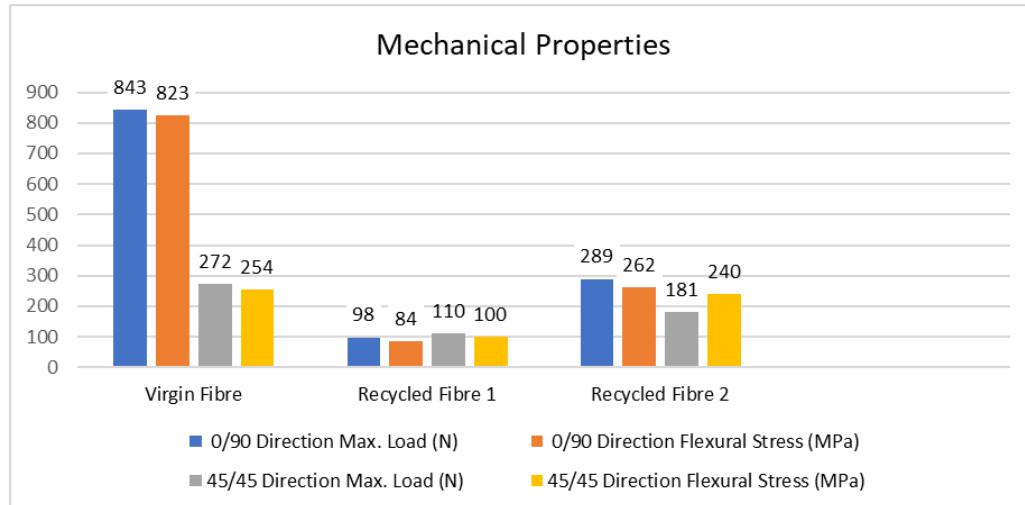


Figure 27 - Comparison of the results obtained in the bending test between different composites in the 0/90 and 45/45 direction.

After comparing the obtained results, it becomes evident that, in general, higher flexural strength and maximum force values are observed in the 0/90° direction compared to the 45/45° direction, except for composite 1. This phenomenon can be attributed to the fact that fibres in 0/90° direction (contrary to the -45/45° direction) were aligned with the direction of the applied load. In other words, the resistance of the composite becomes predominantly dependent on the fibre in 0/90° direction and predominantly dependent on the matrix in 45/45° direction, which results in a better stress distribution within the material in the 0/90° direction, consequently leading to greater resistance to deformation and fracture [83]. Recycled fiber 1 was an exception, as it exhibited significantly lower flexural stress values when compared to recycled fiber 2. This can be explained by the significant degradation of the fibers during the thermal recycling process at 625°C for 1.5 hours. Consequently, in the 0/90° direction, the fibre offered minimal resistance to the flexural force.

Regarding the virgin fibre composites in comparison with the recycled fibre composites, a significant difference in properties is observed. This disparity can be explained by the loss of sizing during the thermal recycling process. Sizing is a surface treatment applied to fibres that not only protects them but also improves the adhesion between the fibres and the composite matrix, acting as a lubricant to reduce interfacial friction. As the recrystallization temperature of basalt fibres is around 850°C, and the maximum temperature used during the thermal degradation cycles was 625°C for 1 hour and 30 minutes, this phenomenon likely did not contribute to the reduction in fibre strength [81].

Another potential cause for the diminished properties of the recycled fibres is the inherent degradation of the fibre due to the recycling process, something that was studied in greater detail in the chapter 6.3.3.

Another fact that can be observed from the graphs in Figure 27 is the similar flexural stress values between the virgin fibre composite and the recycled fibre 2. This can be explained by the fact that in this direction, this property is more dependent on the matrix than on the fibre and that the temperature used in this recycling cycle leads to less degradation of the fibres.

Finally, the flexural modulus was also analysed, revealing an increase in both in the 45/45 direction in both recycled composites and an increase in recycled composite 2 in the 0/90 direction. This trend is evident upon reviewing the graphs depicted in Figure 28.

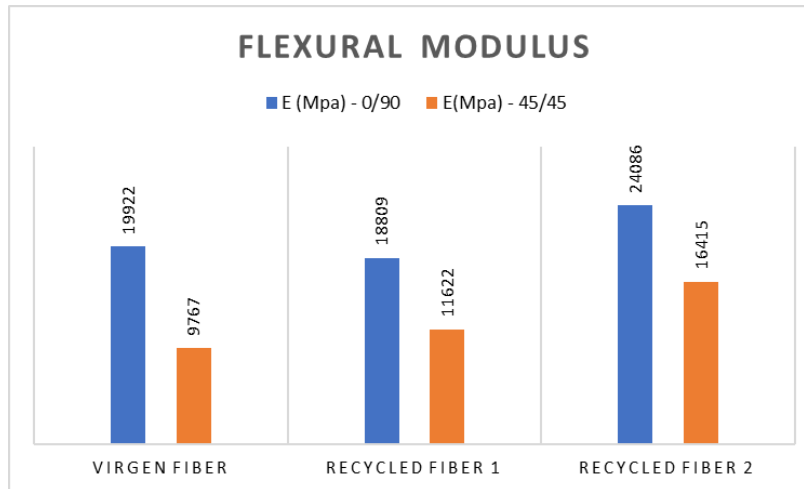


Figure 28 - Comparison between the flexural modulus of the different composites in the 0/90 and 45/45 directions.

This can be attributed to the fibers becoming more flexible, after the recycling process, as they lose the sizing treatment. This loss results in an increase in this property.

6.3.3 Fibre Testing and Optical Microscopy

Fibre tests were conducted on the fibers, like explained in 5.4.3.5 chapter, to assess whether the reduced mechanical properties observed in the composite with recycled fibre were solely a result of potential sizing treatment loss and poor adhesion between the fibre and matrix, or if the fibres underwent a state of fragility. In the 4 fibre groups (both dry fibers and impregnated fibers), there was a marked reduction in mechanical properties, signifying that the fibre became more brittle after the thermal recycling procedure. It is noteworthy that, for the calculation of these properties, the density provided by the fibre manufacturer was employed, both for the group of virgin fibres as well as for the group of recycled fibres. For enhanced result accuracy, a study of the density of the recycled fibres would be necessary. The results are represented in Figure 29.

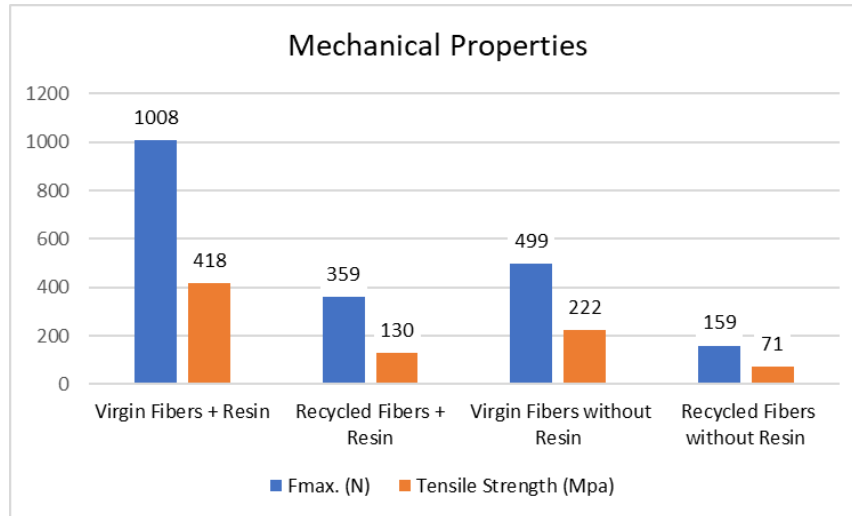


Figure 29 - Comparison of the results obtained in the fibre test, between virgin and recycled virgin fibres and virgin and recycled impregnated fibres.

Following the fiber testing, to gain a deeper understanding of the behavior of the recycled fibers and the loss of both properties, both the virgin and recycled fibers were examined under a microscope, as per description in 5.4.3.6 chapter, where their diameters were measured. The virgin fibers exhibited an average diameter of 0.01525 mm, whereas the recycled fibers showed an average diameter of 0.01075 mm. In other words, there was a reduction of approximately 30% in fiber size diameter, which can signify that there was a mass loss or that there was an increase in the length of the fibers. This phenomenon was not well understood and requires further future research, as an increase in the diameter of the fibers would have been expected, because of the relaxation of the recycled fibers, The images and measurements obtained through microscopy are provided in Appendix J.

6.4 Mechanical Tests of Sandwich Panels

6.4.1 Compression and Flexural Tests

As mentioned in Chapter 5, the sandwich panels were investigated through compression and flexural tests. The table below, denoted as Table 23, presents the compression strength values acquired for both cork and XPP panels. Corresponding graphs can be found in Appendix H for flexural tests and Appendix I for compression test.

Table 23 - Compression tests results for sandwich panels.

	σ_c (MPa)
XPP PANEL	37.75 ± 1.19
CORK PANEL	27.5 ± 6.12

The flexural test result (maximum core shear strength, flexural stress of the loaded laminate and flexural modulus are represented at Table 24:

Table 24 - Flexural tests results for sandwich panels.

	F_s^{ULT} (MPa)	σ_F (MPa)	E_f (MPa)
XPP PANEL	0.64 ± 0.01	27.59 ± 0.52	657.17 ± 43.02
CORK PANEL	0.41 ± 0.17	15.44 ± 0.72	331.42 ± 49.09

As discerned from the analysis of both test results, the panel with a polypropylene core exhibited considerably superior mechanical properties in comparison to the cork-core panel. In essence, the polypropylene core endows the panel with heightened capacity to withstand compressive and flexural, loads, concurrently rendering it more rigid. The polypropylene core also exhibits a higher maximum core shear strength, meaning it demonstrates a greater shear stress when subjected to cutting deformation forces. Additionally, it is notable that polypropylene boasts a lower density compared to that of cork—a particularly significant attribute considering the core constitutes the bulk of the panel's composition.

7. Conclusion

The wind energy industry is currently experiencing significant growth, making it essential to invest in the use of more sustainable materials and processes in the manufacturing of various turbine components, as well as to practice sustainable waste management for the generated waste after their end-of-life.

After a literature review, where various polymeric matrices were evaluated, the decision was made to use a bio-based epoxy resin, a thermosetting material. This choice is due to its excellent mechanical properties, lower carbon footprint compared to other thermosetting materials, and the added benefit of not requiring a change in the spinner manufacturing process. Various types of fibers were also analyzed, with the ones considered most promising being basalt and flax fibers. Basalt fibers were chosen due to the abundance of raw materials, good mechanical properties, and the ability to recycle and reuse them. On the other hand, flax fibers were chosen because they also exhibit good mechanical properties (although not as high as basalt) and are biodegradable. In the process of choosing a different core material, the materials considered were polypropylene and cork, as they are both 100% recyclable materials.

The chosen materials were tested in the laboratory, except for flax, due to external constraints. In the first step, the fabrication of a composite with bio-based epoxy resin and basalt fibers was successful, as evidenced by its low void content, indicating good adhesion between the fibers and the matrix. A DSC analysis was also performed on the composite, revealing that the bio-based epoxy resin exhibited a glass transition temperature like that of a standard epoxy resin.

Subsequently, tensile and shear tests were conducted on the manufactured composite, demonstrating its higher strength in the axial direction. As for the structural feasibility of BFRP alternative material on the spinner design is further studied by Cai [1].

Two additional composites were manufactured with the aim of evaluating different time and temperature cycles in a process simulating thermal recycling. Thus, four different cycles were tested, resulting in dry fibers without the polymer matrices. These same fibers were subsequently used to manufacture new composites. It was determined that the optimal cycle was 425°C for 6 hours, as this resulted in the recycled composite with the best properties in the bending test, when compared to the 625°C for 1_5 hours. Cycles of 375°C for 10 hours and 350°C for 7 hours visibly degraded the fibers, making it impossible to manufacture a new composite.

Following the flexural tests on the composites with both virgin and recycled fibers, it was observed that the composite with recycled fibers exhibited significantly lower bending stress values. There was a decrease in the flexural stress of approximately 90% in composite 1 and 67% in composite 2. This might be partly due to the loss of sizing and by the degradation of the recycled fibers themselves. Tensile tests on the fibers confirmed the loss of fiber properties, which is hypothesized that might contribute to the results obtained in the flexural tests. Although the recycling process is not yet fully optimized, the mechanical properties obtained by the composite recycled at 425°C for 6 hours are still promising. There is the possibility of using the recycled fibres in other components of the spinner that do not have such high mechanical requirements. In terms of costs, the proposed solution would be 65% more expensive. However, it is necessary to consider long-term objectives from a sustainability standpoint rather than just costs.

Lastly, different cork and polypropylene cores were studied and compared through bending and compression tests. It was concluded that the polypropylene core sandwich panels exhibited a 27% higher

compression resistance, a 36% higher maximum core shear strength, a 44% higher flexural stress, and a 50% higher flexural modulus, along with lower density, making it a better choice for mechanical performance than cork cored sandwich panels. The results of structural comparisons, obtained through Finite Element Method (FEM) analysis, between these both core materials and the core currently in use can be referenced in *Cai's* dissertation [1].

In conclusion, the materials studied and tested have been deemed promising alternatives for replacing those currently utilized in the manufacture of the spinner. Nevertheless, a more in-depth study of these materials is required to assess their practical suitability effectively.

8. Limitations and Future Work

One of the limitations encountered during this present dissertation was the delayed arrival of flax fiber, which had been considered for the practical work and was intended to be employed in the manufacturing of composites for subsequent testing and comparison with tests conducted on basalt fiber composites. Another constraint was the unfeasibility of conducting scanning electron microscopy (SEM), which would have enabled the assessment of the adhesion between the fibers and the matrix of the recycled fiber composites, thereby determining any potential impact. The analysis in the SEM would also be essential to accurately determine the diameter of the recycled and virgin fibers.

For future work, it would be recommended using flax fibers with the same polymer matrix used in this laboratory study to test the composites and evaluate their mechanical properties alongside basalt fiber composites. Additionally, I would suggest employing SEM for the analysis of recycled basalt fibers to gain a deeper understanding of their characteristics and further investigation into the properties of the recycled fibres is warranted since the issue has not been fully understood.

For future endeavors, it would also be advisable to subject the manufactured composites and panels to accelerated degradation tests. These tests are employed to simulate natural degradation processes of materials, products, or systems, such as elevated temperatures, humidity, precipitation, among others. This enables an assessment of material reactions to these conditions within a short time span. Given that the turbine component under study, the spinner, must maintain mechanical properties over a period of approximately 30 years while being exposed to various climatic conditions, these tests would offer an advantage in selecting the materials to be employed.

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Appendix A – Technical sheet of raw materials

Biologically Based Epoxy Resin – SR InfuGreen 810



InfuGreen / E 1649.8 / SD 882x2 SD 477x E 1616
Page 1 / 9
Version 01/03/2017

SR InfuGreen 810

Green Epoxy systems for Injection and Infusion

The **InfuGreen 810** is a two-component epoxy system. It has been specially formulated for resin transfer processes, such as injection or infusion.

This system has a very low viscosity at ambient temperature.

The different hardeners allow the production of small to very large parts.

The cured system gives a temperature resistance up to 100°C (Tg onset)

The hardeners SD 4770 and 4771 are designed for very thick laminates by infusions.

SR InfuGreen 810 Epoxy resin is produced with about 38 % of carbon from plant origin and has a lower environmental impact than standard Epoxy systems.

The bio-based Carbon content of our resin is certified by an independent laboratory using Carbon 14 measurements (ASTM D6866 or XP CEN/TS 16640).

This percentage is function of the carbon origin contained in the epoxy molecule.

SR InfuGreen 810 is DNV-GL Maritime approved 



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Epoxy resin **SR InfuGreen 810**

Aspect		Clear liquid
Color Gardner		1 maximum
Viscosity (± 20 % mPa.s)	@ 15 °C @ 20 °C @ 25 °C @ 30 °C @ 40 °C	2 200 1200 750 470 210
Carbon Green content (± 3 %)		38 %
Density Pycnometer (± 0.01) Helium (± 0.005)	@ 20 °C	1.16 1.152
Refractive index (± 0.0020)	@ 25 °C	1.5491
Storage stability	24 Months @ ambient temperature Can crystallize at low temperature or after a long storage. If SR InfuGreen 810 develops a haziness or crystallizes during storage, warming it @ 50 to 60 °C, with stirring, will restore it to its original state	

Hardeners **SD 882x SD 477x**

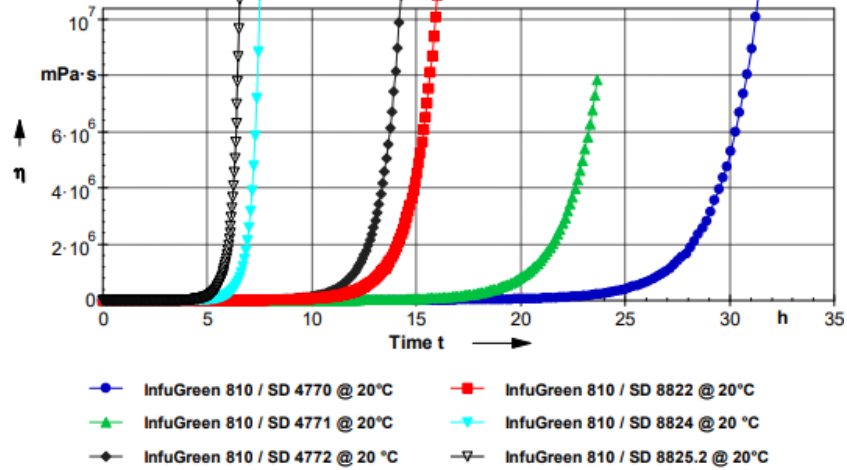
Reference		SD 8825.2	SD 8824	SD 8822	SD 4772	SD 4771	SD 4770
Reactivity type		Fast	Standard	Slow		Ultra-slow	Mega slow
Aspect / colour		Light yellow liquid					
Color Gardner		3 maximum	4 maximum	5 maximum	3 maximum		
Viscosity (+ 20 % mPa.s)	@ 15 °C	9	7	27	13		
	@ 20 °C	7	6	20	11		
	@ 25 °C	6	5	16	9		
	@ 30 °C	5	4	13	7		
	@ 40 °C	4	3	9	5		
Carbon Green content	%	none					
Storage stability	AT	24 months					
		Hardeners react with carbon dioxide and moisture. Keep tightly closed packaging, minimize maximum contact with the air.					
Density Pycnometer (+0.010)	@ 20 °C	0.915	0.944	0.935	0.927	0.944	0.944
Refractive index (± 0.002)	@ 25 °C	1.4785	1.4982	1.4712	1.4822	1.4594	1.4604

SR InfuGreen 810 / SD 8822 SD 477x Mixes

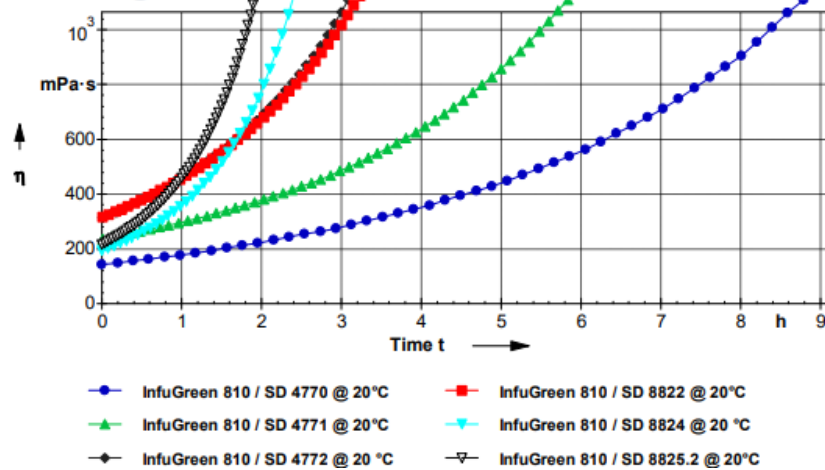
References		SD 8825.2	SD 8824	SD 8822	SD 4772	SD 4771	SD 4770
Mixing ratio by weight		100 / 22	100 / 22	100 / 31	100 / 29		
Mixing ratio by volume		100 / 28	100 / 27	100 / 39	100 / 36		
Initial mix viscosities	@ 20 °C	230	200	320	330	235	142
	@ 30 °C	130	100	120	90	115	100
Time to reach 300 cps	@ 20 °C	28'	44'	/	/	60'	3 h 20'
" Optimal infusion time"	@ 30 °C	40'	50'	67'	90'	130'	160'
Carbon Green content maximum Calculated (+/- 3 %)		31	31	29	29	29	29

Viscosities increase on 1 mm film thickness

@ 20 °C



Zoom initial @ 20 °C



Mechanical properties on cast resin

		SR InfuGreen 810 / SD 8825.2			SR InfuGreen 810 / SD 8824		
Curing cycle		AT + 24 hrs 40 °C	AT + 16 hrs 60 °C	AT + 8 hrs 80 °C	AT + 8 hrs 40 °C	AT + 16 hrs 60 °C	AT + 8 hrs 80 °C
Tension							
Modulus of elasticity	N/mm ²	3000	2700	2600	3000	2800	2600
Maximum resistance	N/mm ²	69	68	67	68	65	60
Resistance at break	N/mm ²	55	53	64	57	57	52
Elongation at max.load	%	3.8	4.8	5.7	3.6	4.4	5.0
Elongation at break	%	5.9	9.1	8.0	5.3	5.9	9.5
Flexion							
Modulus of elasticity	N/mm ²	3000	2700	2600	3100	2800	2600
Maximum resistance	N/mm ²	113	112	108	109	107	101
Elongation at max.load	%	4.9	6.1	6.6	4.6	5.7	6.0
Elongation at break	%	12.6	11.6	11.9	12.6	9.3	13.4
Shear strenght							
Maximum resistance	N/mm ²	46	45	45	43	42	41
Compressive							
Compressive yield strength	N/mm ²	98	95	93	91	87	82
Offset compressive yield	%	11.7	15.1	15.7	12.3	13.0	14.9
Impact Choc Charpy							
Resilience	KJ/m ²	80	80	70	100	90	90
Glass Transition							
Tg1 onset	°C	72	91	96	69	83	82
Tg1 onset maximum	°C			94			82

		SR InfuGreen 810 / SD 8822			SR InfuGreen 810 / SD 4770		
		AT + 24 hrs 40 °C	AT + 24 hrs 40 °C	AT + 16 hrs 60 °C	AT + 8 hrs 80 °C	AT + 16 hrs 60 °C	AT + 8 hrs 80 °C
Curing cycle							
Tension							
Modulus of elasticity	N/mm ²	3000	2900	2700	3160	3100	2700
Maximum resistance	N/mm ²	66	67	61	71	74	70
Resistance at break	N/mm ²	55	60	53	70	68	69
Elongation at max.load	%	3.5	4.4	4.9	3.1	4.2	5.0
Elongation at break	%	4.3	6.1	8.0	3.2	5.1	5.6
Flexion							
Modulus of elasticity	N/mm ²	2900	2800	2700	3250	3000	2770
Maximum resistance	N/mm ²	99	106	101	116	116	115
Elongation at max.load	%	4.4	5.6	6.0	4.6	5.4	6.4
Elongation at break	%	15.5	13.6	13.6	9.8	7.4	7.8
Shear strenght							
Maximum resistance	N/mm ²	43	43	41	47	47	45
Compressive							
Compressive yield strength	N/mm ²	91	91	84	104	100	95
Offset compressive yield	%	11	12	13	11.3	12.8	14.6
Impact Choc Charpy							
Resilience	KJ/m ²	85	88	75	85	83	80
Glass Transition							
Tg1 onset	°C	63	74	85	69	84	97
Tg1 onset maximum	°C			84			98

Biresin® CR83 Composite resin system

Product Description

Biresin® CR83 is an epoxy resin system with extremely low viscosity designed specifically for the infusion process for the production of high performance fibre reinforced composites parts and moulds. The system has thermal properties up to 80°C. Biresin® CR83 epoxy resin has a low tendency to crystallise.

Application Areas

Biresin® CR83 is especially suited to the infusion and injection processes due to its low viscosity range. It can be used in the marine and general industrial composite areas. Due to its good wetting properties it is particularly suited for use with carbon fibre reinforcement.

Features / Advantages

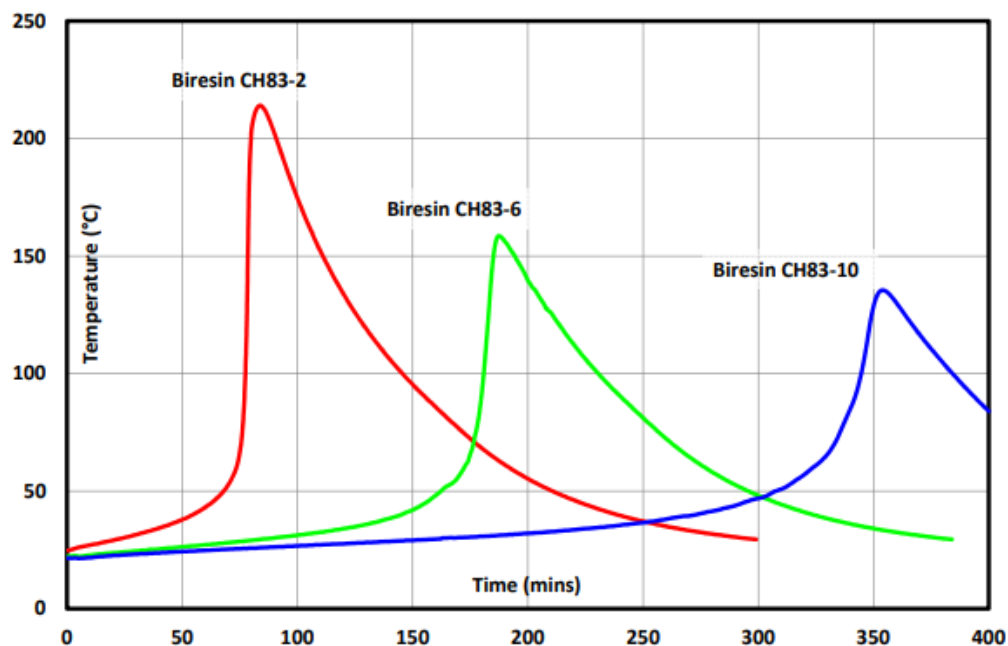
- 3 hardeners (B) give a wide range of processing times
- The reactivity can be adapted by mixing the hardeners
- Fast infusion and good wet-out of fabrics and non-wovens due to low viscosity and good wetting characteristics even at low temperatures
- All systems DNV GL approved, Certificate No. TAK000019Z
- Glass transition temperatures up to 80°C dependent on curing conditions
- Biresin® CR83 resin (A) has a low tendency to crystallise

Physical Data		Resin (A)		Hardener (B)	
Individual Components		Biresin® CR83	Biresin® CH83-2	Biresin® CH83-6	Biresin® CH83-10
Mixing ratio, parts by	weight	100	30		
Mixing ratio, parts by	volume	100	36		
Colour		translucent	colourless to yellowish		
Viscosity, 25°C	mPa.s	~610	<10	<10	< 10
Density, 25°C	g/ml	1.14	0.95	0.94	0.95
		Mixture			
Potlife, 100 g / RT, approx. values	min		60	180	300
Mixed viscosity, 25°C, approx. values	mPa.s		155	170	155

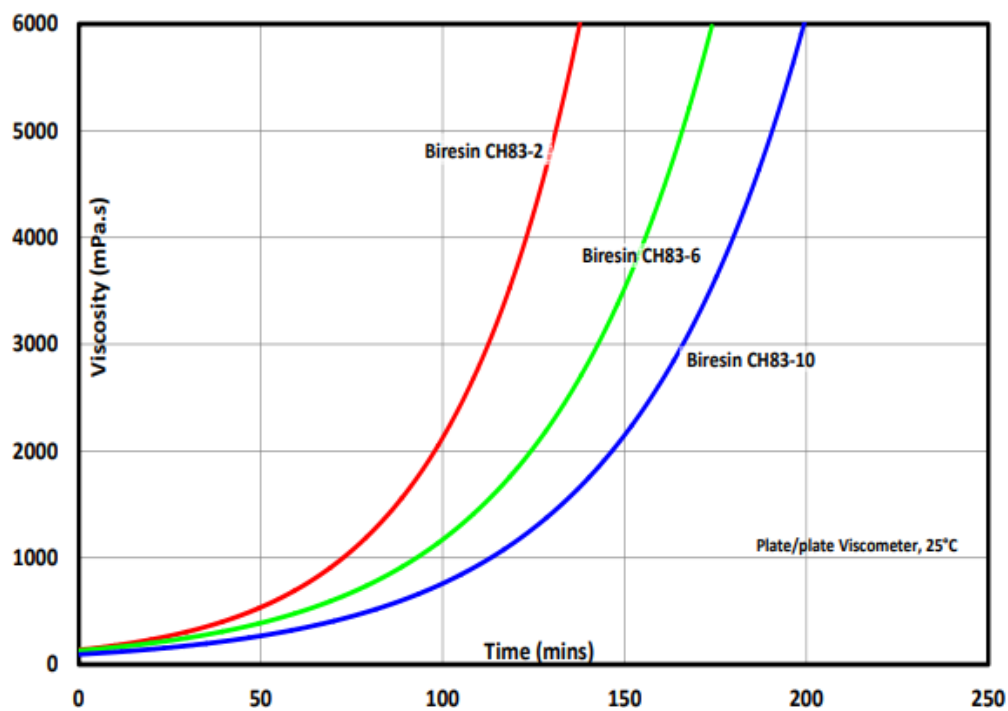
Processing

- The material and processing temperatures should be in the range 18 - 35°C.
- The mixing ratio must be followed accurately to obtain best results. Deviating from the correct mix ratio will lead to lower performance.
- The final mechanical and thermal values are dependent on the applied postcuring cycles.
- It is recommended to clean brushes or tools immediately after use with Sika Reinigungsmittel 5.
- Additional information is available in "Processing Instructions for Composite Resins".

Development of Exotherm of Biresin® CR83-Resin (A)-Hardener (B)-Mixtures, 100g / RT, insulated



Development of Viscosity of Biresin® CR83 (A)-Resin-Hardener (B)-Mixtures, 25°C



Postcuring

The suitable cure cycle and the attainable mechanical and thermal values depend on various factors, such as laminate thickness, fibre volume, reactivity of the resin system etc.

An appropriate cure cycle could look as follows:

- Heat-up rate of ca. 0.2°C/Minute until approx. 10°C below the required glass transition temperature (T_g)
- Followed by a dwell at that temperature of between 2 and 12 hours.
- Part(s) should then be cooled at ~0.5°C per minute

The specific postcure should be adapted to the required technical and economic requirements.

To measure the mechanical performance of the resin system a Sika Advanced Resins standard cycle is used to ensure that the full T_g potential of the system in question is reached.

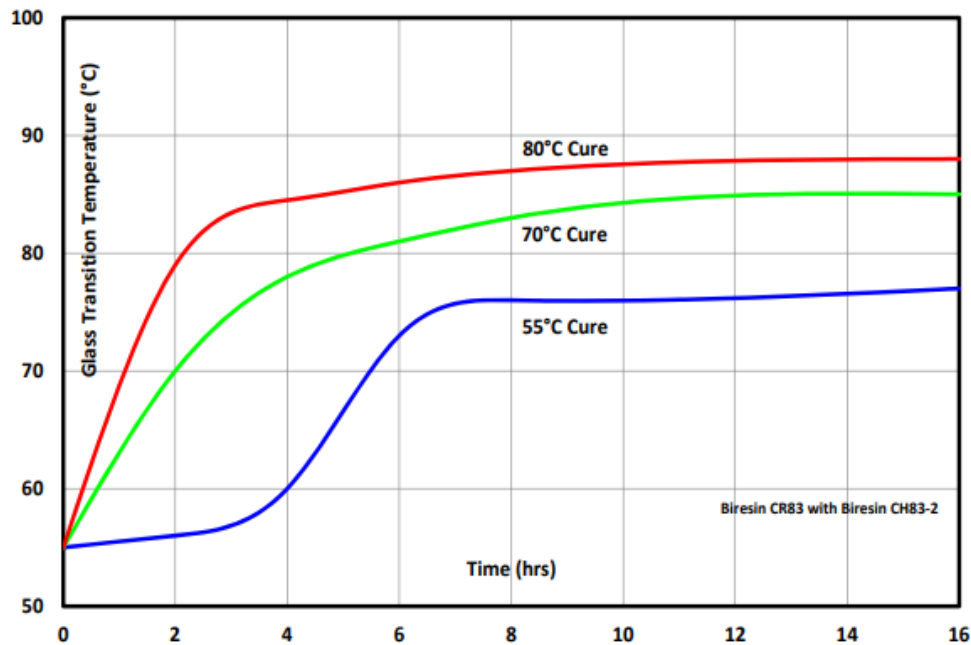
Typical Mechanical Properties of Fully Cured Neat Resin

Biresin® CR83 resin (A)	with hardener (B) Biresin®		CH83-2	CH83-6	CH83-10
Tensile strength	ISO 527	MPa	84	91	86
Tensile E-Modulus	ISO 527	MPa	2,960	3,200	3,100
Elongation at break	ISO 527	%	6.7	8.4	7.9
Flexural strength	ISO 178	MPa	129	134	131
Flexural E-Modulus	ISO 178	MPa	3,125	3,360	3,340
Compressive strength	ISO 604	N/mm ²	107	111	109
Density	ISO 1183	g/cm ³	1.15	1.15	1.15
Shore-hardness	ISO 868		D 85	D 85	D 85
Impact resistance	ISO 179	kJ/m ²	93	84	83

Typical Thermal Properties of Fully Cured Neat Resin

Biresin® CR83 resin (A)	with hardener (B) Biresin®		CH83-2	CH83-6	CH83-10
Heat distortion temperature	ISO 75B	°C	79	79	78
Glass transition temperature	ISO 11357	°C	84	80	81

Glass Transition Temperature vs. Cure Cycle



Packaging (net weight, kg)				
Biresin® CR83 resin (A)	1,000	200		10
Biresin® CH83-2 hardener (B)		180	20	3.0
Biresin® CH83-6 hardener (B)		180	20	3.0
Biresin® CH83-10 hardener (B)		180	20	3.0

Storage

- Minimum shelf life of Biresin® CR83 resin (A) is 24 month and of Biresin® CH83-2, CH83-6 and CH83-10 hardeners (B) is 12 month under room conditions (18 - 25°C), when stored in original unopened containers.
- The tendency to of crystallise with this system is very low. However, if crystallisation of the resin (A) component appears, it can be easily removed by warming up the resin for a sufficient time to at least 60°C.
- Containers must be closed tightly immediately after use. The residual material needs to be used up as soon as possible.

Health and Safety Information

For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Safety Data Sheet (SDS) containing physical, ecological, toxicological and other safety related data.

Disposal considerations

Product Recommendations: Must be disposed of in a special waste disposal unit in accordance with the corresponding regulations.

Packaging Recommendations: Completely emptied packagings can be given for recycling. Packaging that cannot be cleaned should be disposed of as product waste.

Value Bases

All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

Legal Notice

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

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Technical Data Sheet



Basalt Multiaxial Fabric

BAS BI 450

Identification & Application

Multiaxial basalt fabric is made of 100% BCF (basalt continuous filament) roving. It is primary used as reinforcement of epoxy composites.

Property	Standard/Method	Unit	Value
Base material			
Density of unsized filament		kg/dm ³	2,67
Moisture content of basaltic rock		%	0,1
Melting point*		°C	1350
Fabric			
Specific surface weight	ISO 3374:2000	g/m ²	464
Weave type			biaxial
Yarn density:			
- -45°		g/m ²	228
- 0°		g/m ²	0
- +45°		g/m ²	228
- +90°		g/m ²	0
- stitching		g/m ²	8
Sizing type			
			Silane
Continuous max temperature			
		°C	-250°C – 550°C
			1200°C fire blocking
Width	ISO 5025:1997	mm	1270
Thickness	ISO 4603:1993	mm	0,45
Moisture content (fabric)	ISO 3344:1997	%	<0,3
LOI, also sizing content	ISO 1887:1995	%	0,4-0,6
Combustibility	NF P92-503:1995	M0	Pass
UV stability	ISO 105-B02		>7

* after drying according ISO 3344:1997

Packaging

Standard fabric length: 50lm (Other lengths on request)

Fabric roll has support cardboard tube (ID 76mm), identification label with piece and batch number. Wrapping of roll in PE-foil, tape sealed. Rolls are arranged on a pallet with secure strapping.

Product Stability

All evidence obtained to date indicates that the performance should not significantly change over a significant period of time when basalt products are not subjected to excessive heat, wear and abrasion.

It is the responsibility of the developer of the end-product to test its performance in the end-application.

Updated: feb 20

Aglomerado de cortiça expandida

Materiais naturais para soluções técnicas

Descrição

O AGLOMERADO DE CORTIÇA EXPANDIDA é um material sustentável para a construção sustentável. Processo 100% natural no qual se utiliza apenas cortiça como matéria prima. Solução de elevada performance em isolamento térmico, acústico e anti-vibrático, especialmente adequado para isolamento de paredes exteriores e interiores, lajes e pisos, coberturas e tetos.

Vantagens

- 100% natural e reciclável
- Baixa Energia incorporada
- Sumidouro de CO₂ (carbono negativo)
- Excelente isolamento térmico, acústico e anti-vibrático
- Estabilidade mecânica
- Durabilidade praticamente ilimitada, mantendo as características técnicas
- Promove o atraso térmico
- Qualidade do ar interior A+
- Permeabilidade ao vapor de água

Linhas de produto

- Dimensão de placa: 1000 x 500 (mm)
- Espessura até 300 (mm)
- Opção: Sistema meia-madeira

Especificações do produto

- Densidade: +/- 110 Kg/m³
- Condutividade térmica: 0,039 W/m.K
(declarada 0,040 W/m.K para certificação ACERMI)



AMORIM CORK INSULATION

Principais sistemas de aplicação

Coberturas



Pisos



Paredes exteriores



Divisórias interiores



Tetos



CARACTERIZAÇÃO TÉCNICA

Performance declarada: ICB - EN 13170 - L2 - W2 - T2 - CS(10)100 - TR50 - WS - MU20 - CC(0,8/0,4/10)5 - AFR35

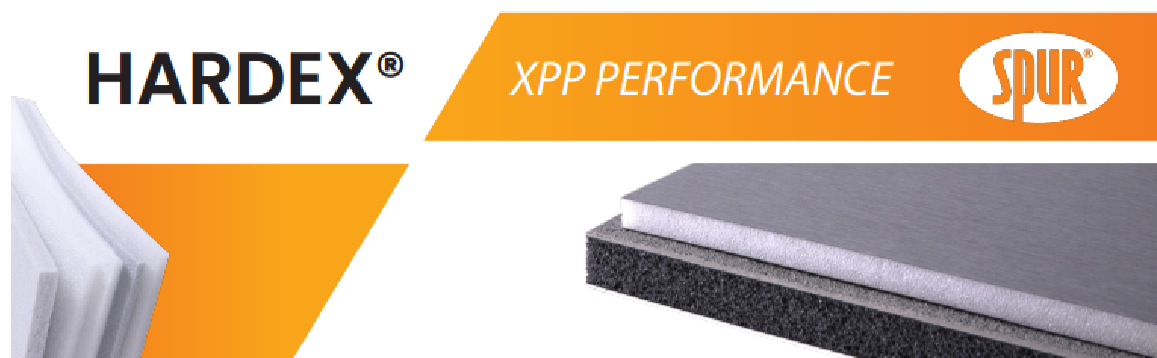
Características essenciais	Performance	Especificação técnica harmonizada EN 13170:2012
Reação ao fogo, Euroclasse	Reação do fogo	Euroclasse E
Resistência térmica	Resistência térmica	ver Tabela A
	Condutividade térmica	0,039 W/m.K
	Espessura, d_L	T1 - T2 ($d > 50\text{mm}$)
Permeabilidade à água	Absorção de água	WS
Vapor de água	Transmissão do vapor de água	MU20
Resistência à compressão	Resistência à compressão a 10% deformação	CS(10)100
Durabilidade da reação ao fogo com o calor, agentes atmosféricos, envelhecimento/degradação	Características de durabilidade	Satisfaz
	Resistência térmica e condutividade térmica	Satisfaz
	Características de durabilidade	Satisfaz
Resistência à tração / flexão	Resistência à tração perpendicular às faces	TR50
Durabilidade da resistência à compressão com o envelhecimento/degradação	Deformação compressiva	CC(0,8/0,4/10)5

Tabela A

Resistência térmica (R) Segundo a Norma EN 13170:2012+A1:2015

Espessura, d_L [mm]	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
Resistência térmica [$\text{m}^2 \cdot \text{K/W}$]	0,50	0,60	0,75	0,85	1,00	1,10	1,25	1,35	1,50	1,60	1,75	1,85	2,00	2,10	2,25	2,35
Espessura, d_L [mm]	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
Resistência térmica [$\text{m}^2 \cdot \text{K/W}$]	2,50	2,75	3,00	3,25	3,50	3,75	4,00	4,25	4,50	4,75	5,00	5,25	5,50	5,75	6,00	6,25

Polypropylene Core – Hardex XPP Performance



SPUR HARDEX XPP PERFORMANCE is a thermoplastic structured foam made of polypropylene (PP). The structure of the foam is made up of 95-98% closed cells. It offers excellent mechanical properties in shear and compression, impact strength, and is resistant to fatigue stress. It also offers excellent chemical resistance, water resistance, organic solvents resistance and health safety. It can be produced with higher resistance to burning and emits significantly lower toxic fumes when burning compared to other materials. It can be produced with higher resistance to UV radiation. It can be produced with recycled content and is recyclable.

Compared to materials made from foamed PET or PS, **SPUR HARDEX XPP PERFORMANCE** offers better mechanical properties.

SPUR HARDEX XPP PERFORMANCE can be used as a core for a composite sandwich structure with excellent mechanical properties combined with low weight. It is used in areas where the lightness and mechanical resistance of the product is required, e.g.: furniture boards, structural boards/profiles, the construction industry, the automotive industry – interior equipment (caravans, trucks, ...). It can be processed and cut similarly to wooden materials and can be joined with screws, nails, and glues, by fusion welding and hot air welding. The material can be processed by thermoforming. Also, the material can be laminated with functional surface layers by reactive or hot-melt glues, or in case of good compatibility without glues by heat only.

MECHANICAL PROPERTIES

Tensile properties (all values in tolerance ± 7,5%)										
Type of test		Norm	Units							
Bulk Density		EN 1602	kg.m ⁻³	40	60	80	100	120	150	200
Thickness wise	Strength	ASTM C297	MPa	0,83	1,29	1,78	2,31	2,87	3,77	5,42
	Modulus			17	30	47	67	90	131	217
Compressive properties (all values in tolerance ± 7,5%)										
Thickness wise	Strength	EN 826	MPa	0,31	0,75	1,21	1,70	2,21	3,03	4,50
	Modulus			16	24	32	39	47	58	76
Screw retention (all values in tolerance ± 7,5%)										
Resistance to the axial withdrawal of screws		EN 320	N	45	65	95	130	170	210	295
Determination of withdrawal capacity of fasteners		EN 13446	N.mm ⁻²	0,9	1,1	1,5	2,1	2,5	3,4	4,7

THERMAL PROPERTIES

Type of test	Norm	Units							
Bulk Density	EN 1602	kg.m⁻³	40	60	80	100	120	150	200
Thermal conductivity	EN 12667	W.m. ⁻¹ K ⁻¹	0,043	0,043	0,042	0,041	0,040	0,040	0,040
Coefficient of linear thermal expansion	ISO 11359-2	(10 ⁻⁵) K ⁻¹	16	14	9,9	5,2	4,1	3,5	1,9
Max. process temperature without thickness loss	-	°C	155						
Short-time operating temperature	-	°C	-40 to +130						
Continuous operating temperature	-	°C	from -30 to +100						
Laminating temperature *	-	°C	Recommended 160-200						
Thermoforming temperature *	-	°C	130-170						

* During the use of high temperatures above 160 °C, the thickness loss depends on setting, time, and properties of the laminated layer.

FIRE PROPERTIES

Type of test	Norm							
Bulk Density	EN 1602	40	60	80	100	120	150	200
Fire classification of buildings and constructions	EN 13501-1	Class E, D, C						
	DIN 4102-1	Class B3, B2, B1						
	UL94	Class HBF, HF1, HF2, V0, V1, V2						

OTHER PROPERTIES

Type of test	Norm	Units							
Bulk Density	EN 1602	kg.m⁻³	40	60	80	100	120	150	200
Type of structured foam									
Closed cell content	EN 4590	%	95-98						
Diffusion for water vapor	EN 13469	-	MU 2000						

DIMENSIONS OF THE PRODUCT*

Type of test	Norm	Units							
Bulk Density	EN 1602	kg.m⁻³	40	60	80	100	120	150	200
Length	mm		2440 ± 10						
Width			1220 ± 10						
Thickness			3 - 40 ± 0,5						

* at room temperature 23°C

Appendix B - View of the construction of the various layers

In the manufacturing of the composites, the layers of basalt fibers were arranged in the 0/90 direction, as observed in the figure below.

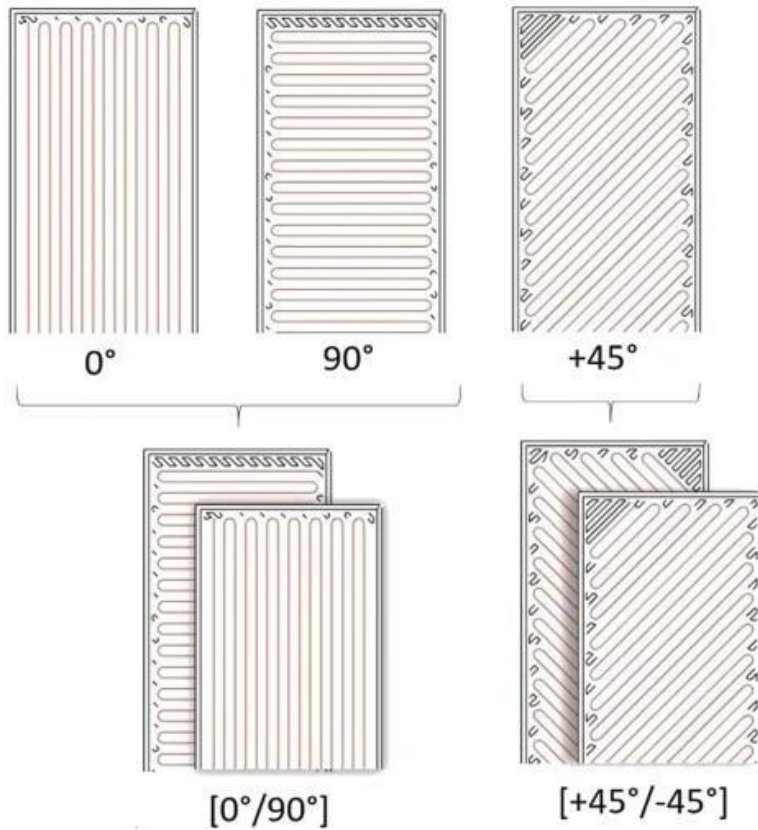


Figure B.1 – Layers' construction

Appendix C – Conversion Factor for Density Test

Table C.1 – Conversion Factor Values

Density of Water (g/mL) vs. Temperature (°C)

(from Handbook of Chemistry and Physics, 53rd Edition, p. F4)

Whole degrees are listed down the left hand side of the table, while *tenths of a degree* are listed across the top.

	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
15	0.999099	0.999084	0.999069	0.999054	0.999038	0.999023	0.999007	0.998991	0.998975	0.998959
16	0.998943	0.998926	0.998910	0.998893	0.998877	0.998860	0.998843	0.998826	0.998809	0.998792
17	0.998774	0.998757	0.998739	0.998722	0.998704	0.998686	0.998668	0.998650	0.998632	0.998613
18	0.998595	0.998576	0.998558	0.998539	0.998520	0.998501	0.998482	0.998463	0.998444	0.998424
19	0.998405	0.998385	0.998365	0.998345	0.998325	0.998305	0.998285	0.998265	0.998244	0.998224
20	0.998203	0.998183	0.998162	0.998141	0.998120	0.998099	0.998078	0.998056	0.998035	0.998013
21	0.997992	0.997970	0.997948	0.997926	0.997904	0.997882	0.997860	0.997837	0.997815	0.997792
22	0.997770	0.997747	0.997724	0.997701	0.997678	0.997655	0.997632	0.997608	0.997585	0.997561
23	0.997538	0.997514	0.997490	0.997466	0.997442	0.997418	0.997394	0.997369	0.997345	0.997320
24	0.997296	0.997271	0.997246	0.997221	0.997196	0.997171	0.997146	0.997120	0.997095	0.997069
25	0.997044	0.997018	0.996992	0.996967	0.996941	0.996914	0.996888	0.996862	0.996836	0.996809
26	0.996783	0.996756	0.996729	0.996703	0.996676	0.996649	0.996621	0.996594	0.996567	0.996540
27	0.996512	0.996485	0.996457	0.996429	0.996401	0.996373	0.996345	0.996317	0.996289	0.996261
28	0.996232	0.996204	0.996175	0.996147	0.996118	0.996089	0.996060	0.996031	0.996002	0.995973
29	0.995944	0.995914	0.995885	0.995855	0.995826	0.995796	0.995766	0.995736	0.995706	0.995676
30	0.995646	0.995616	0.995586	0.995555	0.995525	0.995494	0.995464	0.995433	0.995402	0.995371

Example: to find the density of water at 16.1 °C, you would first find the whole degree by searching down the left hand column until you reach '16'. Then you would slide across that row until you reach the column labeled '0.1'. The density of water at 16.1°C is 0.998926 g/mL.

Appendix D – Density, Void and Fiber Content Tests Results

The presented tables depict the results obtained from each of the conducted tests, for the various samples.

Table D.1 – Density test results

SAMPLE	CRUCIBLE MASS (G)	MASS DRY SAMPLE (G)	MASS WET SAMPLE (G)	DENSITY (G/CM3)
1	26.13	2.25	1.08	1.92
2	24.14	2.49	1.11	1.79
3	24.17	2.24	1.07	1.90
4	24.33	2.23	1.08	1.93
5	23.84	2.18	1.06	1.93

Table D.2 – Void test results

SAMPLE	CRUCIBLE MASS (G)	CRUCIBLE + SAML E MASS (G)	INICIAL MASS – MI (G)	CRUCIBLE + FIBER MASS (G)	FINAL MASS – MFI (G)
1	26,13	28,39	2,26	27,74	1,61
2	24,14	26,64	2,49	25,75	1,60
3	24,17	26,42	2,24	25,78	1,60
4	24,33	26,57	2,24	25,92	1,58
5	23,84	26,04	2,19	25,41	1,56

Table D.3 - Fiber content test results

SAMPLE	FIBER CONTENT (WEIGHT PERCENT)	FIBER CONTENT (VOLUME PERCENT)	MATRIX CONTENT (WEIGHT PERCENT)	MATRIX CONTENT (VOLUME PERCENT)	VOID VOLUME (%)
1	71,18	51,39	28,82	47,89	0,72
2	64,32	43,34	35,68	55,33	1,33
3	71,48	51,09	28,52	46,91	1,99
4	70,68	51,12	29,32	48,82	0,06
5	71,34	51,69	28,66	47,81	0,50

Appendix E - Differential Scanning Calorimetry Test Results

The following graphs are representative of Differential Scanning Calorimetry (DSC) tests conducted on four samples of the same virgin fiber composite. Through these graphics, it was possible to ascertain the glass transition temperature of each of the samples, with the aim of averaging the obtained results and attaining the glass transition temperature of the utilized resin.

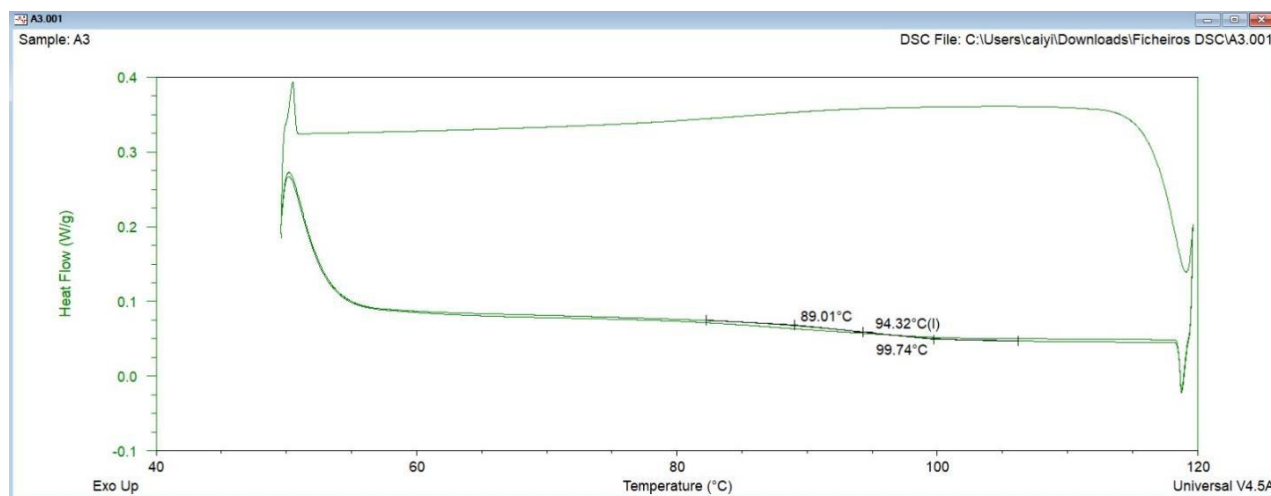


Figure D.1 – DSC Test Result for Sample 1

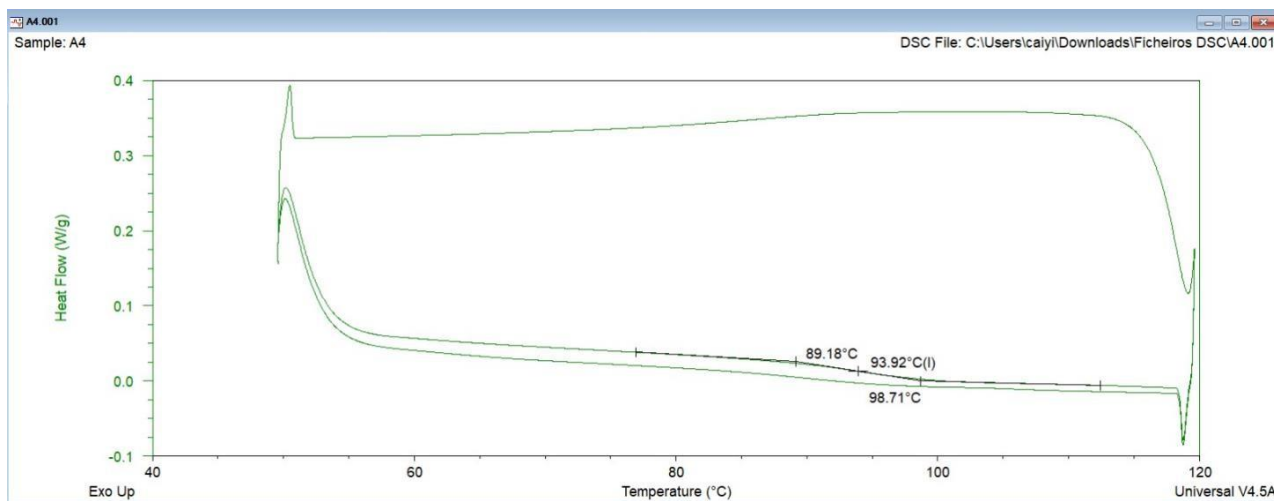


Figure D.2 – DSC Test Result for Sample 2

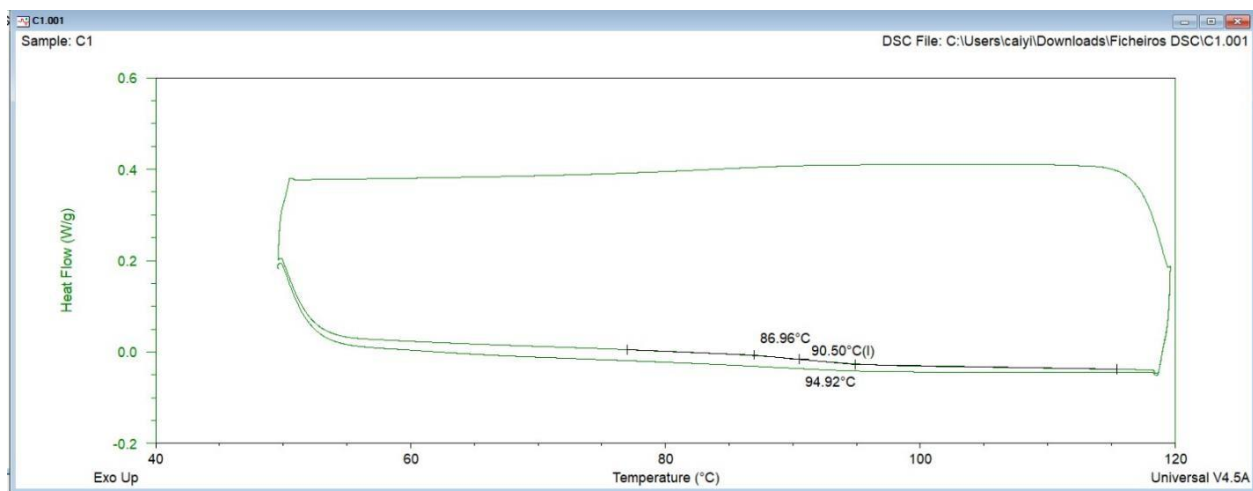


Figure D.3 – DSC Test Result for Sample 3

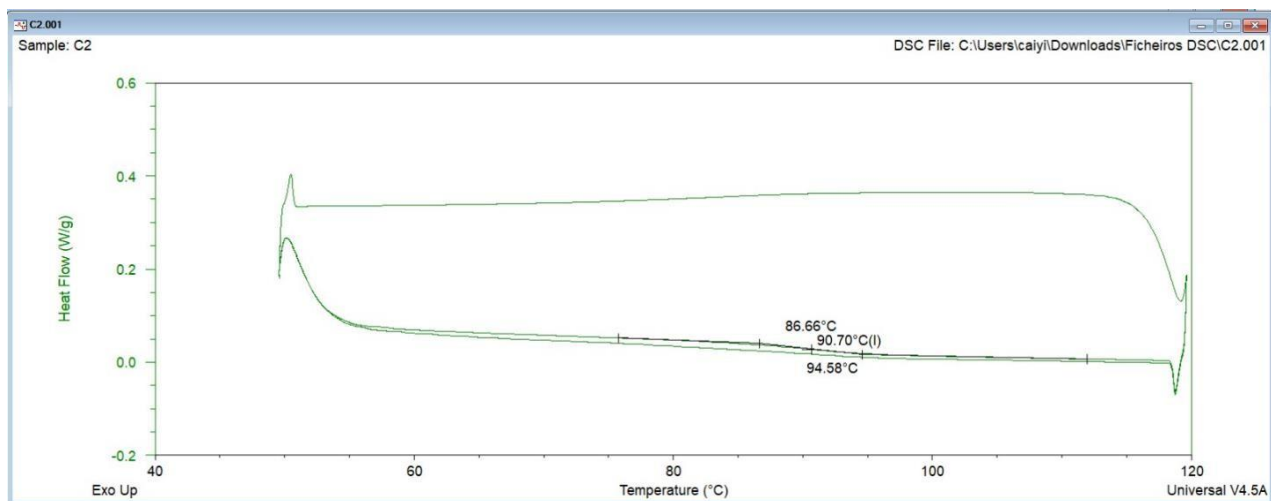


Figure D.4 – DSC Test Result for Sample 4

Appendix F – Tensile and Shear Tests Results

The measurements of all the specimens tested in the shear and tensile test are presented in Table F.1. and F.2 respectively. Three measurements were taken for each dimension (length, height, and width), along with their respective averages, all in millimeters.

Table F.1 - Measurements of the shear-tested samples.

Samples	Length 1	Length 2	Length 3	<u>Average Length</u>	Width 1	Width 2	Width 3	<u>Average Width</u>	Thickness 1	Thickness 2	Thickness 3	<u>Average Thickness</u>
1	248	248	248	248	24.53	24.56	24.30	24.46	2.22	2.03	2.20	2.15
2	247	247	247	247	24.29	2.24	24.46	17.00	2.10	2.19	2.26	2.18
3	248	248	248	248	23.85	24.17	24.00	24.01	2.05	2.16	2.17	2.13
4	248	248	248	248	24.57	24.49	24.38	24.48	2.01	2.13	2.18	2.11
5	249	249	249	249	24.45	24.09	23.87	24.14	2.22	2.04	2.08	2.11
6	248	248	248	248	24.36	24.44	24.21	24.34	2.09	1.97	2.26	2.11
7	248	248	248	248	24.70	24.09	24.06	24.28	2.14	2.07	2.01	2.07

Table F.2 - Measurements of the tension-tested samples.

Samples	Length 1	Length 2	Length 3	<u>Average Length</u>	Width 1	Width 2	Width 3	<u>Average Width</u>	Thickness 1	Thickness 2	Thickness 3	<u>Average Thickness</u>
8	247	247	247	247	24.31	24.75	24.20	24.42	2.25	2.24	2.17	2.22
9	248	248	248	248	24.38	24.34	24.15	24.29	2.18	2.08	2.06	2.11
10	248	248	248	248	24.31	24.41	24.47	24.40	2.11	2.18	2.16	2.15
11	248	248	248	248	24.42	24.27	24.26	24.32	2.25	2.14	2.18	2.19
12	248	248	248	248	24.34	24.37	24.36	24.36	2.09	2.15	2.08	2.11
13	249	249	249	249	24.27	24.23	24.40	24.30	2.01	2.18	2.16	2.12
14	249	249	249	249	23.84	24.19	24.63	24.22	1.92	2.02	2.06	2.00

The presented graphs pertain to specimens of the composite with virgin fiber, which underwent both tensile and shear testing.

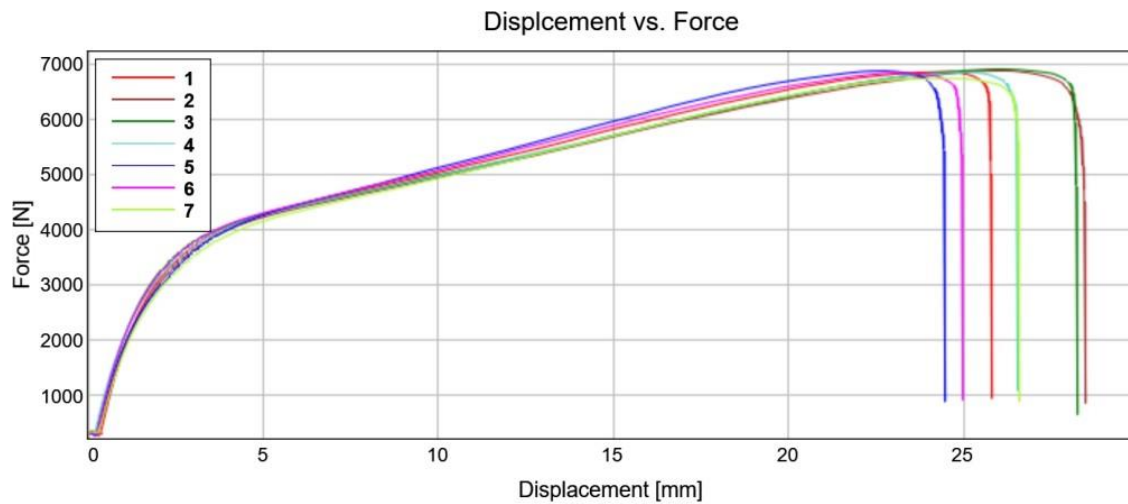


Figure E.1 - Force-displacement graphs of the specimens of virgin fiber tested for shear.

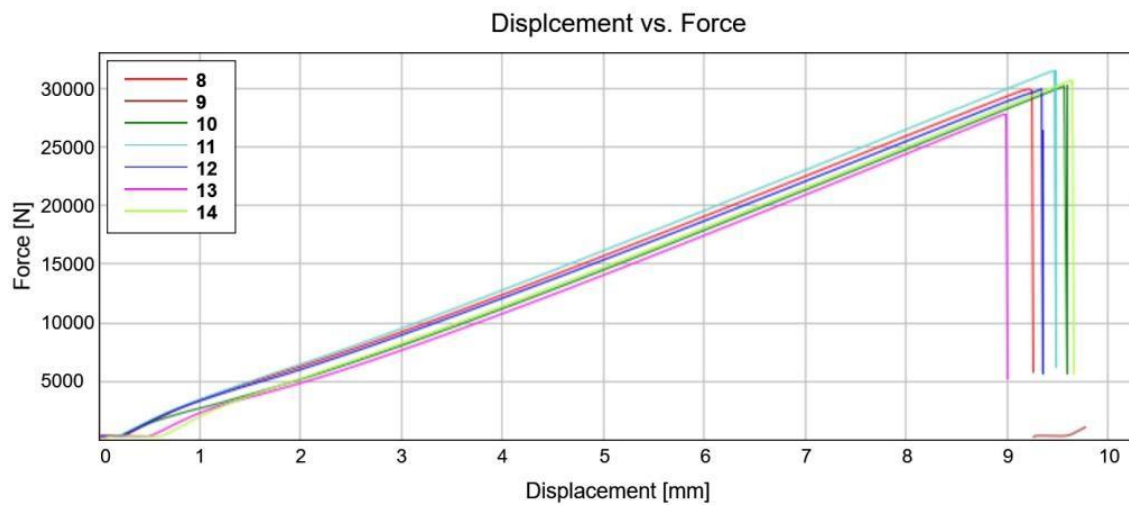


Figure E.2 - Force-displacement graphs of the specimens of virgin fiber tested for tensile.

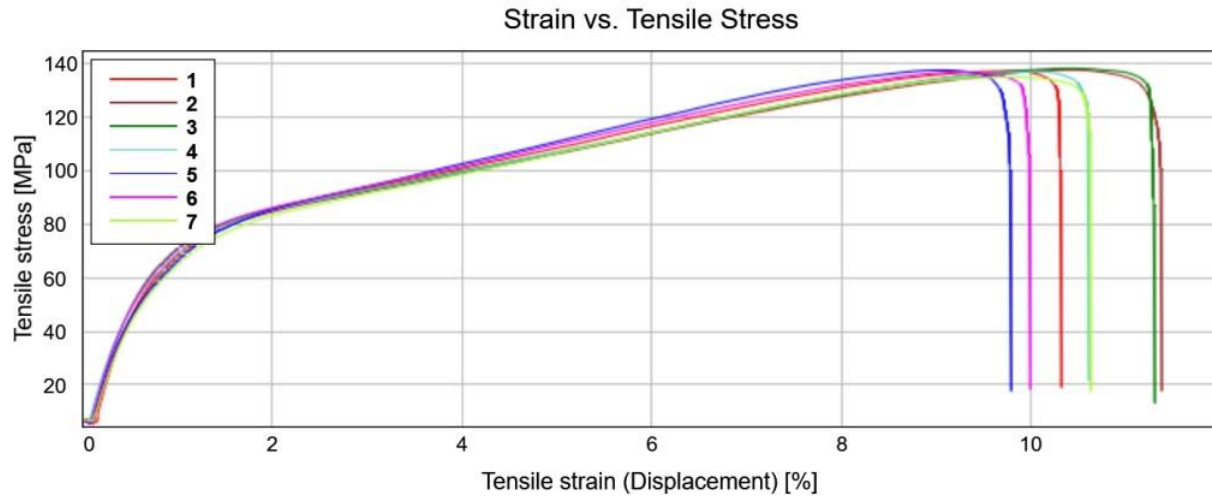


Figure E.3 – Strain-tensile stress graphs of the specimens of virgin fiber tested for shear.

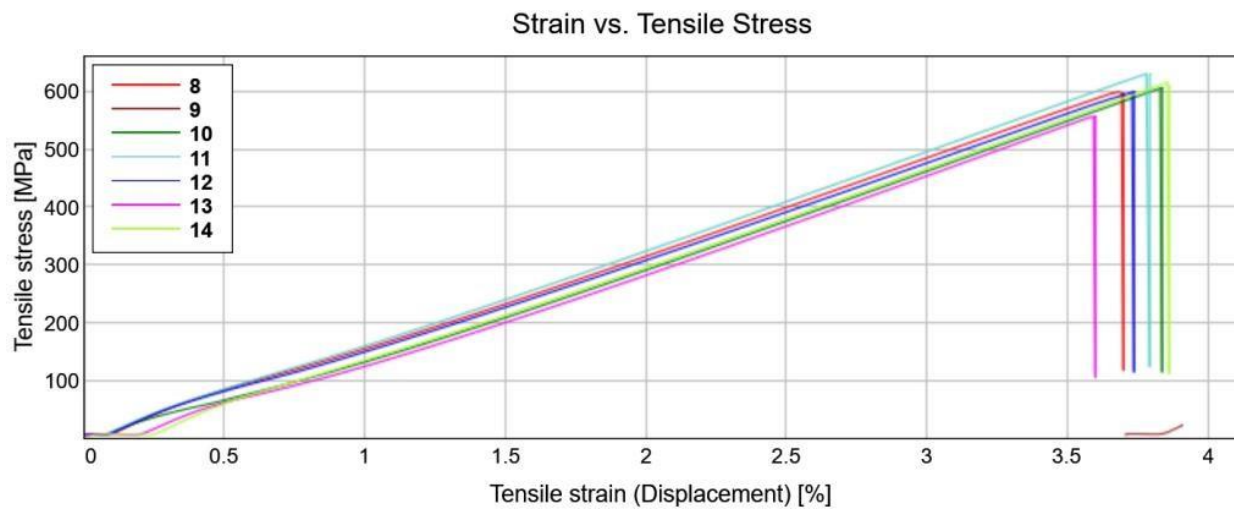


Figure E4 – Strain-tensile stress graphs of the specimens of virgin fiber tested for tensile.

Appendix G – Flexural Test - Laminates

The measurements of all the laminates specimens tested in the flexural test are presented in Table G.1A and G.1B, G.2A and G.2B, G.3A and G.3B for the virgin composite, recycled composite 1 and recycled composite 2, respectively. Three measurements were taken for each dimension (length, height, and width), along with their respective averages, all in millimeters.

Table G.1A - Measurements of the flexural-tested samples, for virgin composite in -45/45 direction

Samples	Length 1	Length 2	Length 3	<u>Average Length</u>	Width 1	Width 2	Width 3	<u>Average Width</u>	Thickness 1	Thickness 2	Thickness 3	<u>Average Thickness</u>
1	59.64	59.78	59.61	59.68	14.11	13.76	13.06	13.64	2.11	2.10	2.17	2.13
2	58.54	58.58	58.61	58.58	13.52	13.68	14.03	13.74	2.26	2.08	2.01	2.12
3	58.13	58.08	58.30	58.17	13.74	13.63	13.82	13.73	2.14	2.09	2.22	2.15
4	58.81	58.82	58.97	58.87	13.58	13.63	13.75	13.65	2.06	2.16	2.26	2.16
5	58.32	58.21	58.48	58.34	13.69	13.71	13.68	13.69	2.26	2.09	2.21	2.19
6	57.96	57.92	57.94	57.94	13.61	13.71	13.77	13.70	2.26	2.29	2.21	2.25
7	58.38	58.42	58.46	58.42	13.66	13.82	13.73	13.74	2.15	2.17	2.19	2.17

Table G.1B - Measurements of the flexural-tested samples, for virgin composite in 0/90 direction

Samples	Length 1	Length 2	Length 3	<u>Average Length</u>	Width 1	Width 2	Width 3	<u>Average Width</u>	Thickness 1	Thickness 2	Thickness 3	<u>Average Thickness</u>
8	58.72	58.56	58.65	58.64	13.99	14.08	13.88	13.98	2.22	2.19	2.25	2.22
9	59.28	59.22	59.30	59.27	13.86	13.84	13.77	13.82	2.22	2.10	2.12	2.15
10	59.24	59.22	59.20	59.22	13.91	13.90	13.85	13.89	2.12	2.16	2.14	2.14
11	58.87	58.68	58.71	58.75	13.88	13.81	13.82	13.84	2.17	2.14	2.15	2.15
12	59.21	59.15	59.10	59.15	13.85	13.71	13.68	13.75	2.04	2.05	2.12	2.07
13	58.69	58.61	58.59	58.63	13.63	13.70	13.67	13.67	2.07	2.03	2.02	2.04
14	59.19	59.60	59.05	59.28	13.70	13.79	13.74	13.74	2.07	2.01	1.99	2.02

Table G.2A - Measurements of the flexural-tested samples, for recycled composite 1, in -45/45 direction

Samples	Length 1	Length 2	Length 3	<u>Average Length</u>	Width 1	Width 2	Width 3	<u>Average Width</u>	Thickness 1	Thickness 2	Thickness 3	<u>Average Thickness</u>
15	59.81	59.53	59.32	59.55	15.16	15.21	15.22	15.20	2.05	1.95	2.03	2.01
16	59.88	59.92	59.79	59.86	14.90	15.13	15.07	15.03	2.13	1.98	2.09	2.07
17	58.69	58.37	58.10	58.39	15.13	14.98	15.07	15.06	2.37	2.03	2.17	2.19
18	58.83	58.81	58.58	58.74	15.20	15.06	15.21	15.16	2.10	2.04	2.07	2.07
19	59.85	59.91	59.76	59.84	15.24	15.12	15.19	15.18	2.26	2.14	2.06	2.15
20	59.10	58.93	59.04	59.02	15.20	15.02	15.26	15.16	2.05	2.13	2.19	2.12

Table G.2B - Measurements of the flexural-tested samples, for recycled composite 1, in 0/90 direction

Samples	Length 1	Length 2	Length 3	<u>Average Length</u>	Width 1	Width 2	Width 3	<u>Average Width</u>	Thickness 1	Thickness 2	Thickness 3	<u>Average Thickness</u>
21	60.69	60.63	60.08	60.47	14.97	15.06	15					
22	60.34	60.29	60.35	60.33	1							
23	60.60	60.70										
24												

Table G.3A - Measurements of the flexural-tested samples, for recycled composite 2, in 0/90 direction

Samples	Length 1	Length 2	Length 3	<u>Average Length</u>	Width 1	Width 2	Width 3	<u>Average Width</u>	Thickness 1	Thickness 2	Thickness 3	<u>Average Thickness</u>
1	61.61	61.44	61.45	61.50	14.23	14.36	14.39	14.33	2.02	2.04	2.13	2.06
2	60.49	60.55	60.43	60.49	14.47	14.48	14.38	14.44	1.90	1.95	1.93	1.93
3	61.25	61.36	61.56	61.39	13.93	13.88	14.54	14.12	1.88	1.92	1.94	1.91
4	62.18	62.21	62.16	62.18	14.35	14.38	14.36	14.36	1.93	1.88	1.89	1.90
5	60.71	60.75	60.64	60.70	12.16	12.08	11.55	11.93	1.88	1.96	1.91	1.92

Table G.3B - Measurements of the flexural-tested samples, for recycled composite 2, in -45/45 direction.

Samples	Length 1	Length 2	Length 3	<u>Average Length</u>	Width 1	Width 2	Width 3	<u>Average Width</u>	Thickness 1	Thickness 2	Thickness 3	<u>Average Thickness</u>
6	59.08	59.04	59.23	59.12	13.95	14.09	14.31	14.12	1.91	1.99	1.88	1.93
7	59.44	59.36	59.65	59.48	14.33	14.39	14.36	14.36	1.78	1.74	1.80	1.77
8	59.48	59.42	59.64	59.51	14.32	14.28	14.30	14.30	1.81	1.87	1.88	1.85
9	59.46	59.51	59.54	59.50	14.44	14.14	14.21	14.26	1.82	1.83	1.88	1.84
10	59.44	59.35	59.48	59.42	12.51	12.22	11.88	12.20	1.75	1.69	1.66	1.70
11	58.37	58.46	58.39	58.41	14.27	14.30	14.43	14.33	1.74	1.72	1.71	1.72

The displayed graphs correspond to specimens of three distinct composites: the composite with virgin fiber, recycled composite 1 (subjected to a muffle cycle at 625°C for 1_5hour), and recycled composite 2 (subjected to a muffle cycle at 425°C for 6 hours).

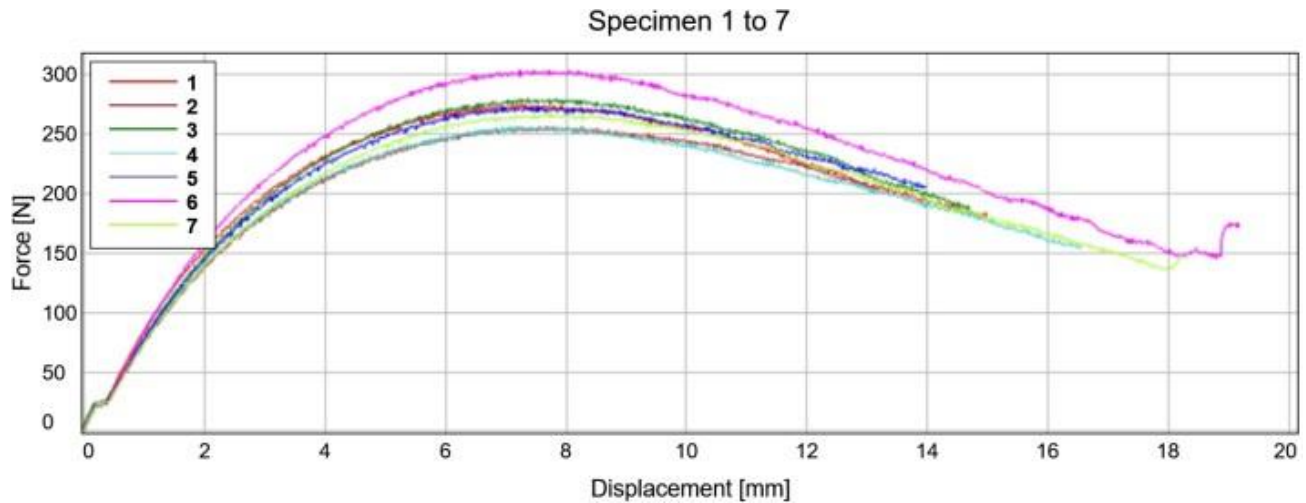


Figure F.1 - Force-displacement graphs of the specimens of virgin fiber in -45/45 direction, tested for flexural.

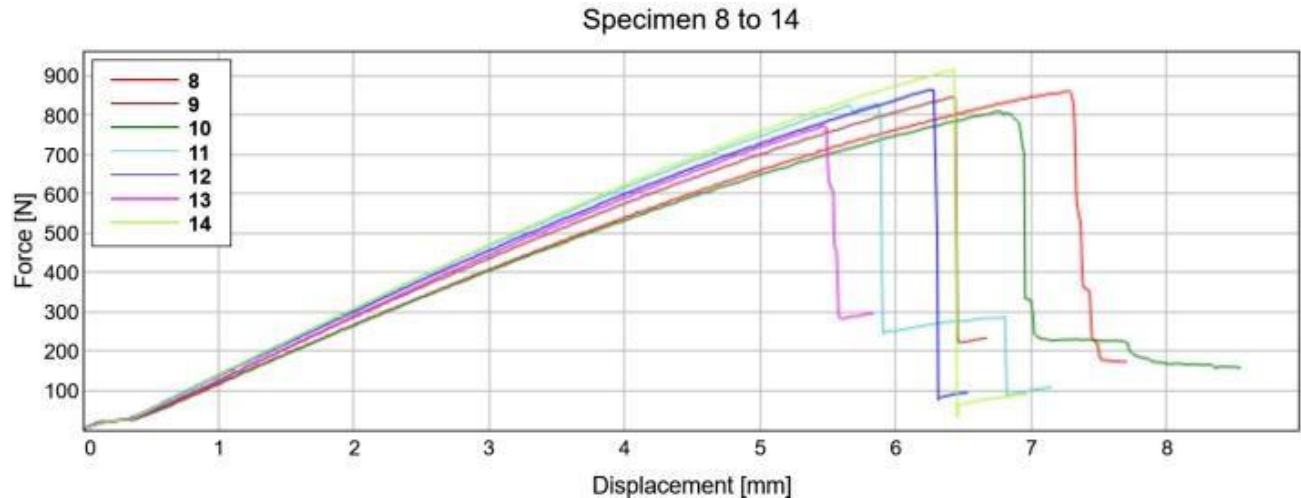


Figure F.2 - Force-displacement graphs of the specimens of virgin fiber in 0/90 direction, tested for flexural.

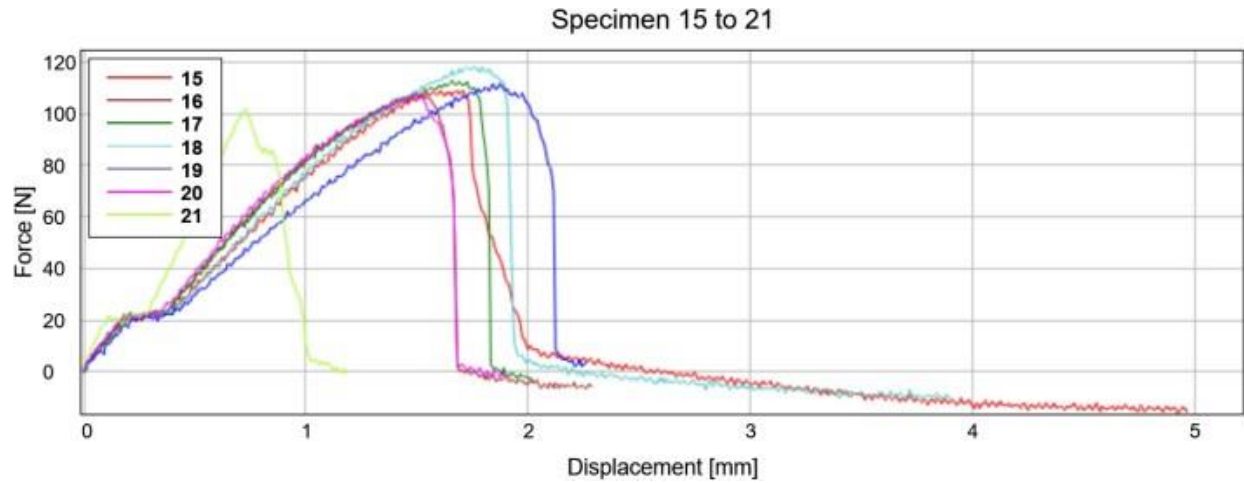


Figure F.3 - Force-displacement graphs of the specimens of recycled fiber (composite 1) in -45/45 direction, tested for flexural.⁵

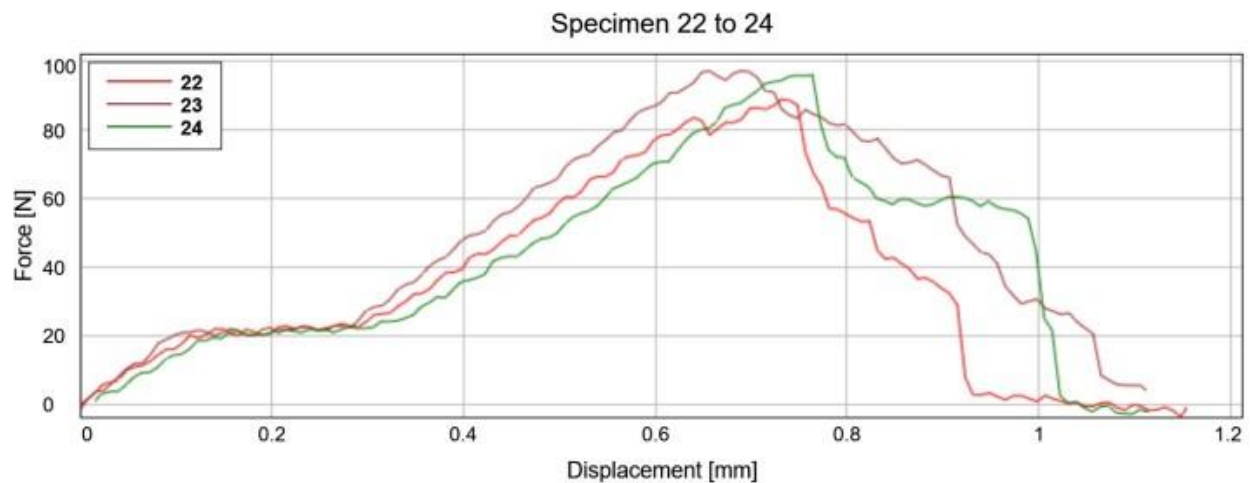


Figure F.4 - Force-displacement graphs of the specimens of recycled fiber (composite 1) in 0/90 direction, tested for flexural.

⁵ By default, the equipment settings place Curve 21 within this graph, however, it belongs to the graph F.4

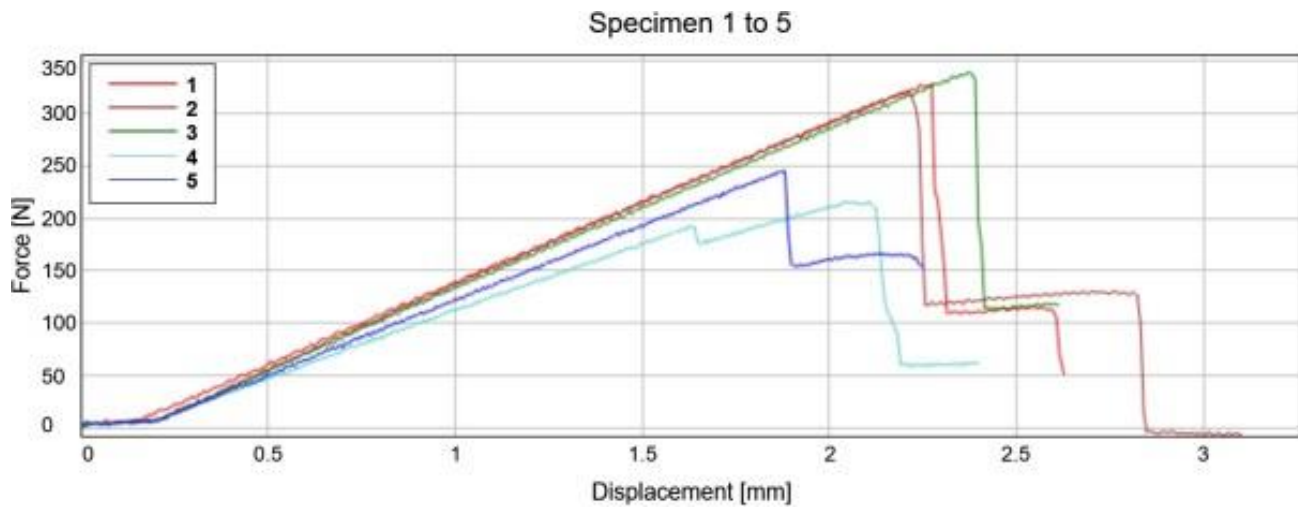


Figure F.5 - Force-displacement graphs of the specimens of recycled fiber (composite 2) in 0/90 direction, tested for flexural.

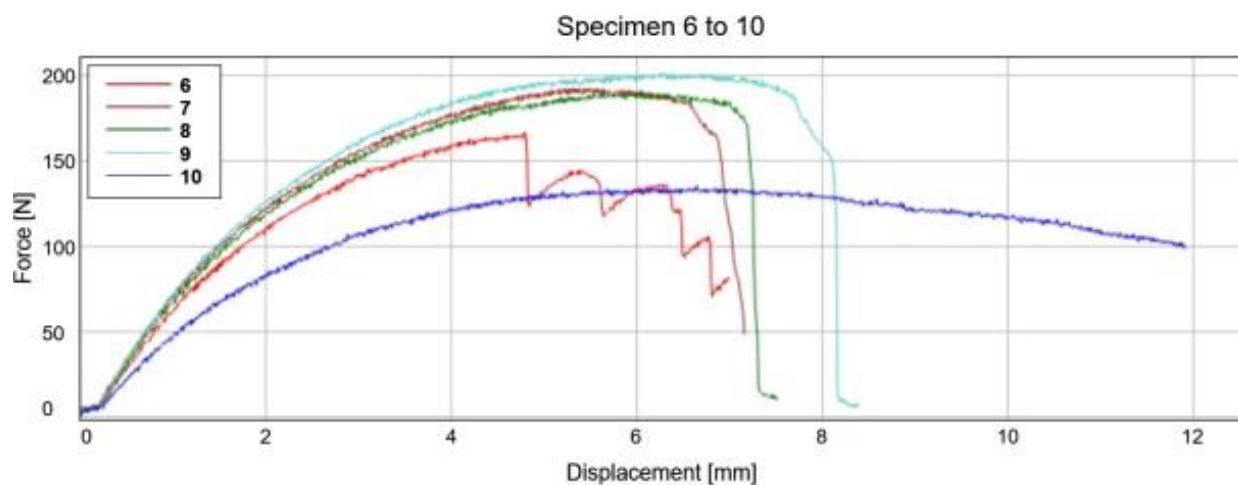


Figure F.6 - Force-displacement graphs of the specimens of recycled fiber (composite 2) in -45/45 direction, tested for flexural.

Appendix H - Flexural Tests Graphs - Sandwich Panels

The measurements of all the sandwich panels specimens tested in the flexural test are presented in Table H.1A and H.1B, Table H.2A and H.2B for cork and XPP core, respectively. Three measurements were taken for each dimension (thickness, width, core thickness and laminates thickness) and length, along with their respective averages, all in millimeters.

Table H.1A - Measurements of the flexural-tested samples, for cork core sandwich panel

Sample	Thickness 1	Thickness 2	Thickness 3	<u>Average Thickness</u>	Width 1	Width 2	Width 3	<u>Average Width</u>	Length 1	Length 2	Length 3	<u>Average Length</u>
1	20.89	20.73	20.69	20.77	73.73	72.7	73.77	73.40	201	202	201	201.33
2	20.35	20.01	19.75	20.04	75.53	74.65	75.34	75.17	200	201	201.5	200.83
3	21.02	21.54	21.69	21.42	74.63	73.75	74.55	74.31	205	201	201.5	202.50
4	19.73	19.76	19.55	19.68	72.99	71.35	72.93	72.42	201	201	201.5	201.17
5	19.37	18.4	18.36	18.71	73.08	73.03	73.7	73.27	197	201	200	199.33
6	19.4	19.15	18.88	19.14	72.64	72.07	73.85	72.85	197	198	198.5	197.83
7	19.9	19.75	19.8	19.82	75.63	73.24	75.38	74.75	196.5	197.5	197	197.00

Table H.1B - Measurements of the flexural-tested samples, for cork core sandwich panel

Sample	Core Thickness 1	Core Thickness 2	Core Thickness 3	<u>Average Core Thickness</u>	Laminates Thickness
1	15.69	14.99	15.5	15.39	2.69
2	14.94	14.9	14.51	14.78	2.63
3	16.16	15.25	16.67	16.03	2.70
4	15.92	15.25	15.6	15.59	2.05
5	13.27	13.68	13.2	13.38	2.50
6	14.54	14.6	14.63	14.59	2.28
7	15.39	15.67	14.68	15.25	2.29

Table H.2A - Measurements of the flexural-tested samples, for XPP core sandwich panel

Sample	Thickness 1	Thickness 2	Thickness 3	Average Thickness	Width 1	Width 2	Width 3	Average Width	Length
1	23.42	23.46	23.48	23.45	73.29	73.17	73.07	73.18	199.00
2	23.29	23.48	23.38	23.38	74.97	74.53	73.65	74.38	200.00
3	23.43	23.58	23.38	23.46	72.83	74.02	76.02	74.29	200.00
4	23.45	23.66	23.53	23.55	71.36	71.27	71.3	71.31	199.00
5	23.43	23.03	23.01	23.16	73.49	73.89	73.09	73.49	199.50
6	23.47	23.46	23.4	23.44	75.11	74.72	74.65	74.83	199.00
7	23.7	23.74	23.9	23.78	75.01	75.09	75	75.03	200.00

Table H.2B - Measurements of the flexural-tested samples, for XPP core sandwich panel

Sample	Core Thickness 1	Core Thickness 2	Core Thickness 3	Average Core Thickness	Laminates Thickness
1	19.88	19.9	20.2	19.99	1.73
2	19.71	19.89	19.91	19.84	1.77
3	20.3	20.01	19.95	20.09	1.69
4	19.79	20.2	19.8	19.93	1.81
5	19.89	19.87	20.21	19.99	1.58
6	20.2	20.1	19.93	20.08	1.68
7	19.96	19.98	20.1	20.01	1.88

The presented graphs are related to sandwich panels with cores made of cork and polypropylene.

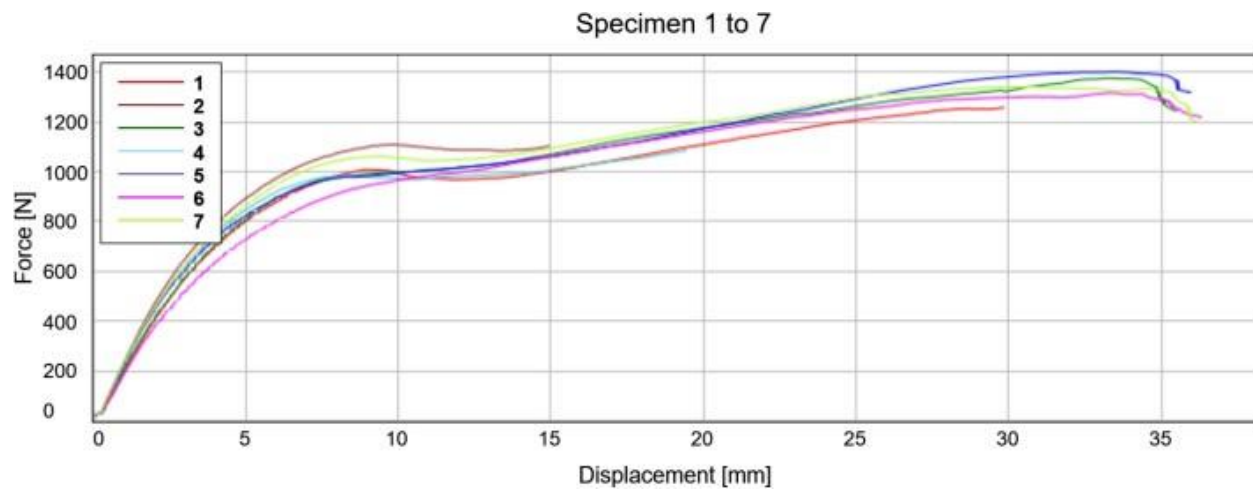


Figure G.1 - Force-displacement graphs of the cork core specimens tested for flexural.

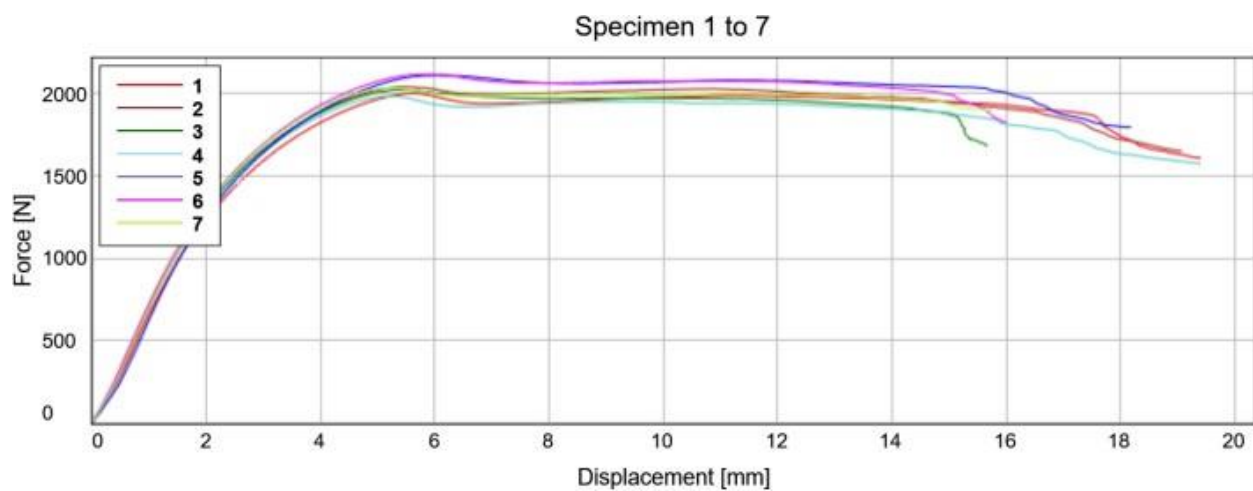


Figure G.2 – Force-displacement graphs of the polypropylene (XPP) core specimens tested for flexural.

Appendix I – Compressive Tests Graphs Results - Sandwich panels

The presented graphs are related to sandwich panels with cores made of cork and polypropylene.

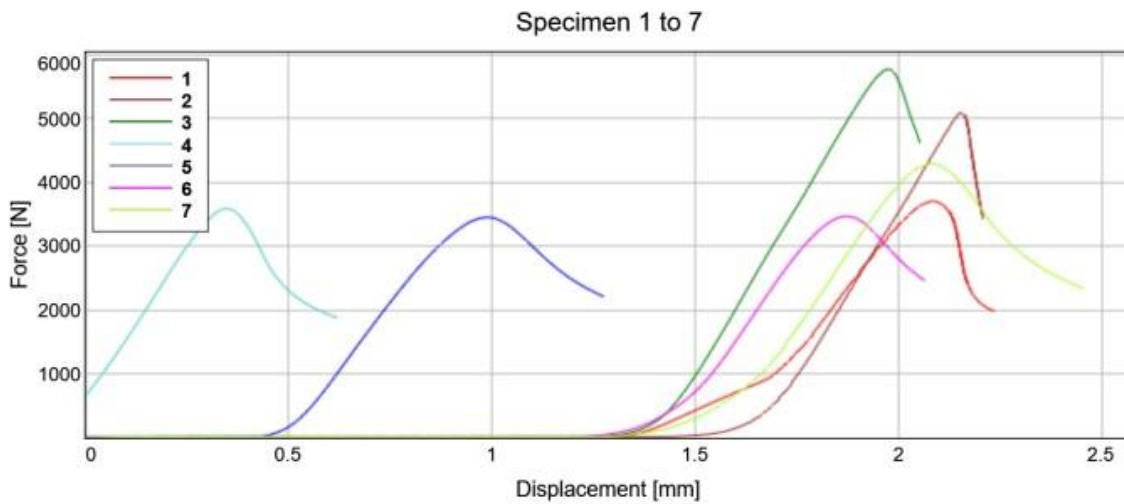


Figure H.1 - Force-displacement graphs of the cork core specimens tested for compression.

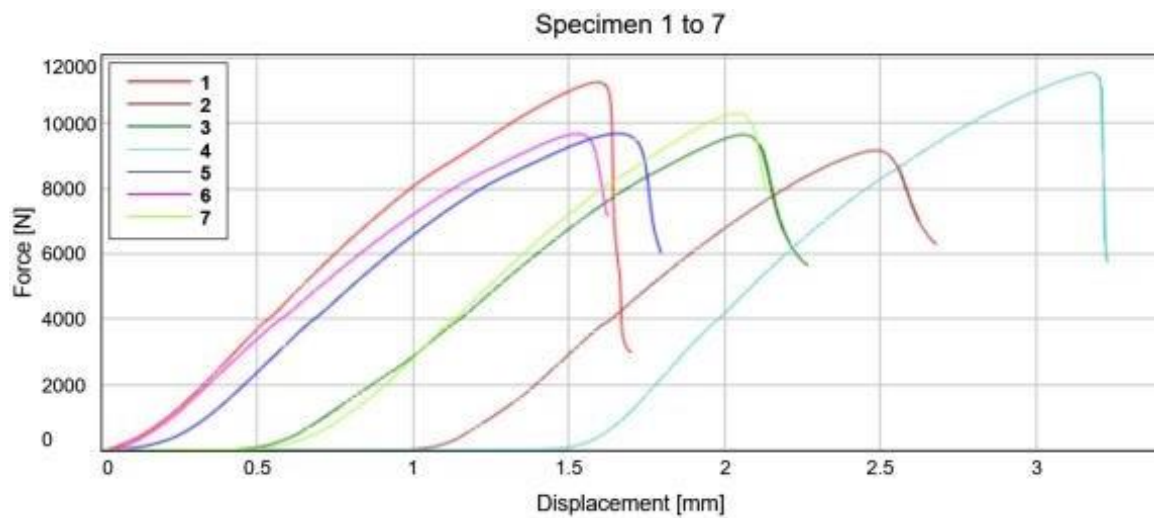


Figure H.2 - Force-displacement graphs of the polypropylene (XPP) core specimens tested for compression.

Appendix J - Microscopic images obtained.

The images presented below were obtained with the purpose of evaluating the diameter of both virgin and recycled fibers.

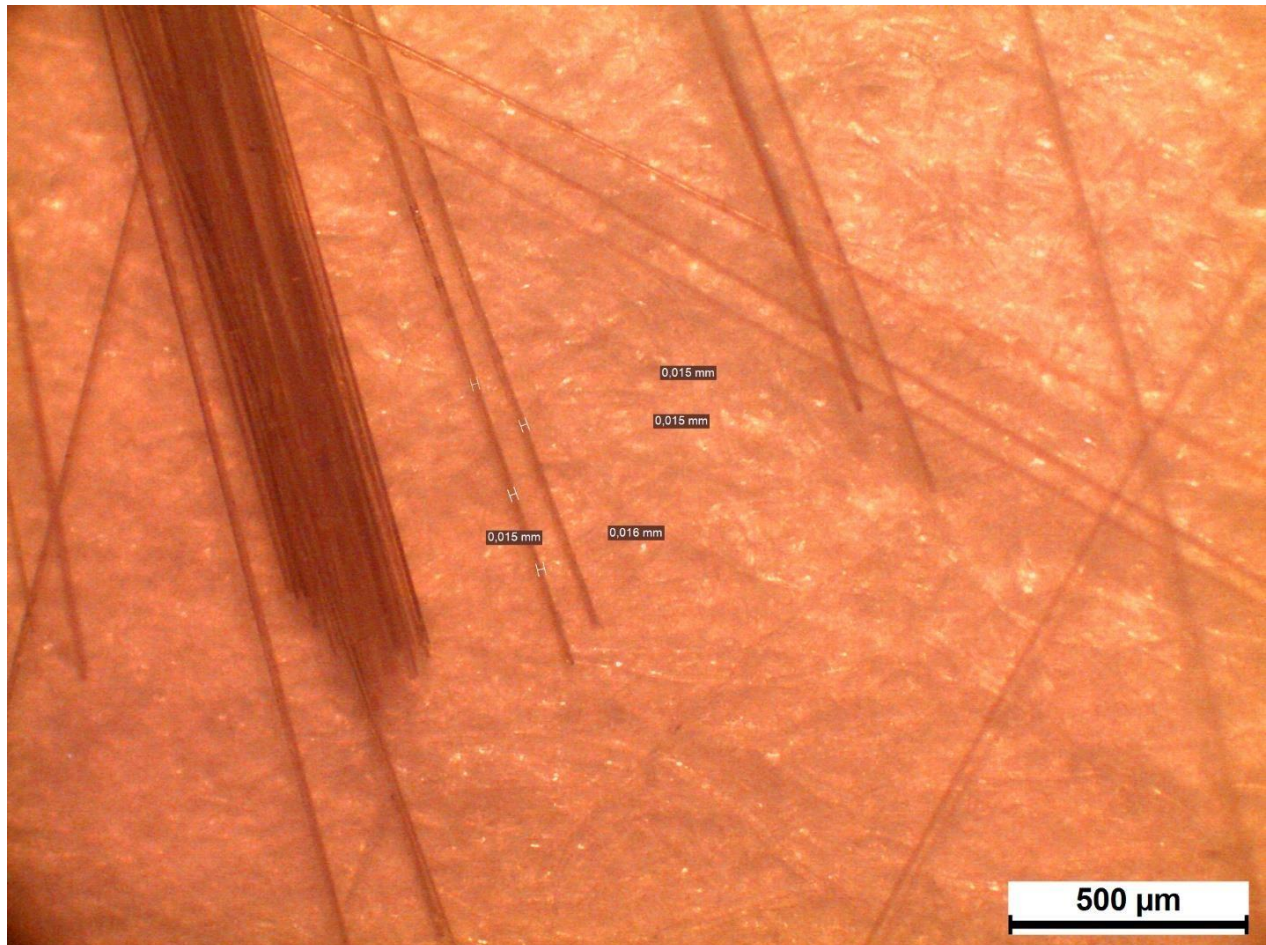


Figure J.1 – Virgin fibers

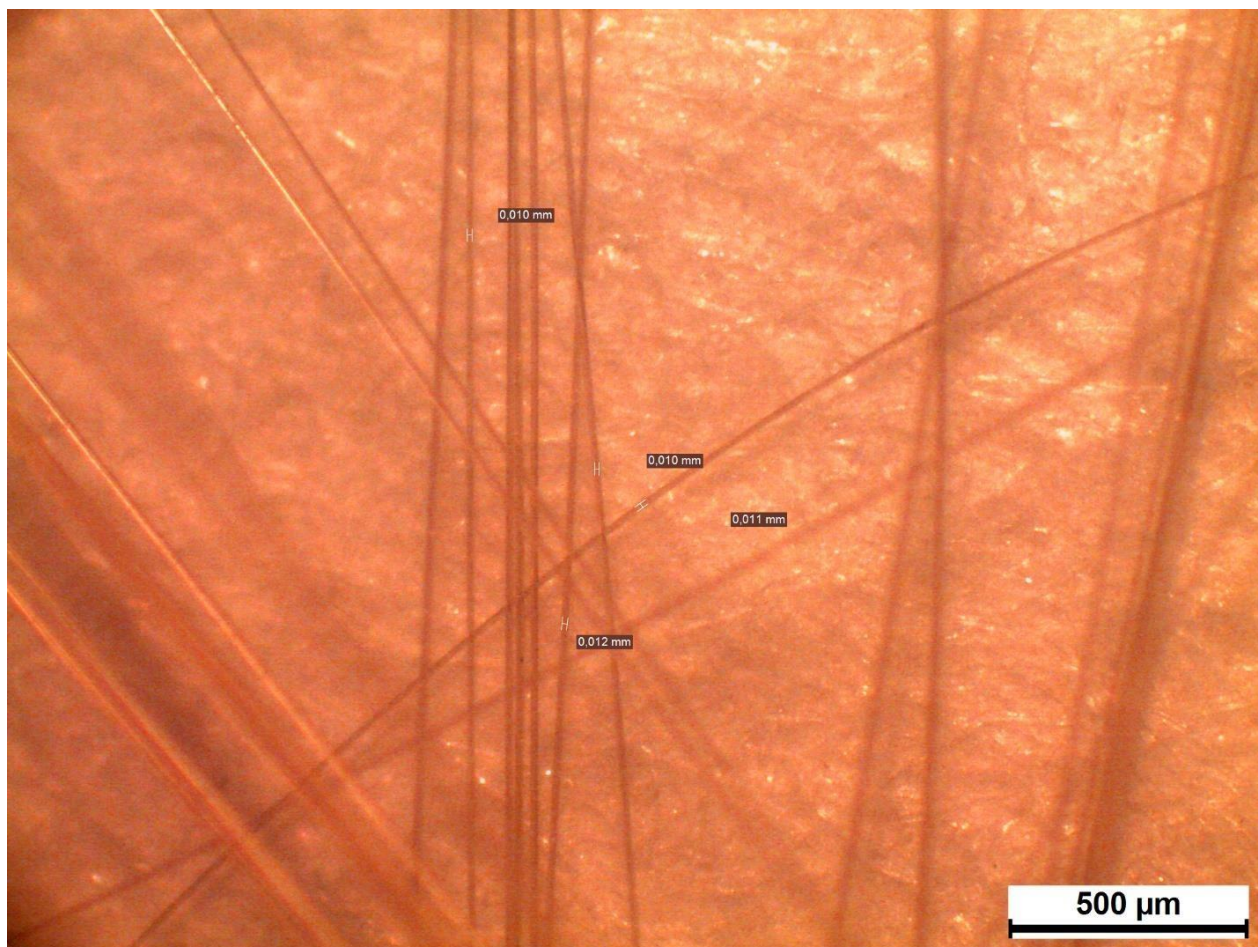


Figure J.2 – Recycled Fibers (425°C for 6 hours)