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# Determining the Mechanical Properties of Various Types of Flax Fibre Cloths
## UAntwerp Solar Boat Team

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Master's thesis
**Master thesis to obtain the degree in Master of Science, Electromechanical Engineering**

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# Abstract

In recent years, interest in the use of ecological materials in the production of fibre-reinforced composites has increased enormously. This study investigates if the mechanical properties of different types of flax fibre cloth could act as a substitute for carbon fibre in composite materials. The study focuses on nine different flax fibre cloths, each with different weight classes and different patterns, combined with bio-epoxy resin to create fiber reinforced composites. The study compares the mechanical properties, such as tensile strength and elongation of these flax-based composites. The results indicate that flax fibre composites achieve similar strengths to carbon fibres composites, but due to the fact that they require more layers resulting in greater thickness and weight, their applications are limited, especially in weight-sensitive areas. Unidirectional (UD) flax fibres exhibit the highest tensile strength of all flax fibres tested. In addition, the research shows that the importance of the proper fibre-epoxy ratio is huge, variations in epoxy content will affect the mechanical properties enormously. Bio-epoxy resin, which contains up to 34% biodegradable material, is a good substitute for traditional epoxies. The only difference of bio epoxy is the fact that it is more ductile. Overall, the research highlights the potential applications of flax fibre as a sustainable alternative to synthetic fibres, like carbon or glass fibre.

# Glossary and Abbreviations

| Term | Explanation |
|---|---|
| Fibres | A thin thread made from natural or artificial substances, used in textile production and other materials. |
| Filava fiber | Natural fiber made from volcanic rock filament. |
| Flax fiber | This refers to the natural fibers extracted from the stem of the flax plant, used in textile production. |
| Carbon fiber | A lightweight, high-strength material composed of carbon atoms bonded together in a crystal alignment, exceptional strength-to-weight ratio. |
| Yarn | Combinations of multiple fibers. |
| Warp Yarn | Yarns or threads that are stretched lengthwise on the loom and held in tension. The warp yarns run vertically in the finished fabric. |
| Weft Yarn | The horizontal threads that are woven through the warp yarns, passing over and under them. |
| Twill | Twill pattern is a weaving technique where each weft thread passes over and under two warp threads, creating diagonal lines on the fabric. |
| TEX | TEX fibre is a type of twill 2x2 weaving pattern, where the fibers are less twisted (torsed). |
| Glass fiber | Material made from fine fibers of glass. |
| Epoxy | A type of thermosetting polymer commonly used as a matrix material in composite materials. |
| Bio Epoxy | An epoxy resin derived from renewable biological sources, offering environmental benefits over traditional epoxy resins. |
| FRC | Fiber-Reinforced Composite. |
| Composite | Composites are a combination of two or more constituent materials with distinct properties. |
| Peel Ply | A fabric used in composite laminates to create a textured surface, improving the adhesion of subsequent layers or coatings. |
| Breather | A type of textile used in the vacuum process to allow air and excess resin to escape, ensuring even pressure is maintained on the composite. |
| Laminating | The process of creating a composite material by bonding multiple layers of material together, with the application of heat, pressure, or adhesive. |
| Wet Lay-Up | Type of laminating (hand laminating) where layers of fabric are manually coated with liquid resin and then stacked to form a laminate. |
| Ultimate tensile strength | Ultimate tensile strength is the maximum stress that a material can withstand while being stretched or pulled before breaking. |
| TS | Tensile Strenght |
| EP | Epoxy |
| REF | Reference |
| WA | Water Absorption |
| PP | Production Process |
| Stress ($\sigma$) | Stress is a material property defined as the force applied on a material divided by the cross-sectional area over which the force is applied. Expressed in Mega Pascal (MPa). |
| Strain ($\varepsilon$) | Strain is a material property defined as the deformation or displacement of a material divided by its original length. |
| Modulus of elasticity (E) | The modulus of elasticity (E) is a measure of a material's ability to resist deformation under stress. |

# Acknowledgments

During the academic year 2023-2024 , I conducted research on the mechanical properties of flax fibre cloths. The success of my research is due to the help and support of many people.

First, I would like to thank my supervisor, Sam van der Jeught, for his guidance and great recommendations. His constructive criticism made me think deeply about specific topics.

I also want to thank Arne Aerts and Jolan Vanderstruyf from the FabLab at the University of Antwerp for their practical support. Special thanks to Mr. Aerts for assisting me in processing and testing the test specimens.

The Uantwerp Solar Boat team, a team of fifteen students, offered their assistance throughout my research. They were always available to answer my questions and help solve problems. I am especially grateful to Arne Janssens for his insights about composite and his practical support in the fiber laminating process.

My research would not been possible without the support of two companies, Flaxco and Vsure. These companies provided essential materials and information. Flaxco, a West Flemish company specializing in flax fiber weaving, supplied the flax fiber cloths needed for my experiments (figure 1 Left). Caroline Flipts from Flaxco was always available to answer my questions about flax. V-sure, based in Lier, provided both bio epoxy and conventional epoxy (figure 1 Right). Thanks to their bio epoxy, I was able to guide the solar team towards a more sustainable direction. Marc De Moor from V-sure provided assistance regarding bio epoxy and supported me with information trough my research.

Figure 1: Image of flax fiber cloth and bio-epoxy used in this research.

Lastly, I want to express my gratitude to my parents and sister for reviewing my thesis. Their constant support and encouragement kept me motivated throughout my experiments. My sister's critical feedback led to insightful questions that advanced my research. I also thank my girlfriend, Fleur, for her unwavering support during the thesis-writing process.

# Contents

# 1 Introduction

## 1.1 Background

The UAntwerp Solar Boat team is a team of fifteen bachelor and master students at the University of Antwerp that work together at a project to improve a boat on solar energy, the so called "Solar Boat". As a member of this team, I am responsible for the research on more sustainable composite materials in order to replace some parts of the boat. Currently, the boat's components are predominantly made out of carbon fibre impregnated with epoxy. The purpose of the study is to replace both the carbon fibres as well as the epoxy, with a more sustainable alternative. Therefore, the application of a natural fibre, flax and bio epoxy resin will be studied.

Previously, research was conducted within the UAntwerp Solar Boat team on different fibres that could serve as substitutes for carbon. Two different ecological fibres were tested: flax and filava[1]. Both fibres were processed with epoxy and then several tests were performed on them. The research only focused on replacing carbon fiber with another type of fiber. In previous research, the number of woven fibres and the fibre orientation were not taken into account. Moreover, all tests have been done with a non-durable epoxy variant.

The current research focuses on all types of flax fibres and how their mechanical properties can be improved. This can be done by looking at the fibre orientation as well as the woven fibres. A total of nine different fibre cloths are examined. These fibres can be woven in different ways, each leading to unique mechanical characteristics. In addition, epoxy will be replaced by bio-epoxy. These fibres are processed into a composite material in combination with bio-epoxy through hand lay up process. Subsequently, these various composites will go trough testing for determining the tensile strength. Based on these results, a method can be developed for applying these fibers in future projects of the UAntwerp Solar Boat.

## 1.2 Problem Statement

Over the past decade, the use of fibre-reinforced polymers has increased significantly, with carbon fibre being the most frequently chosen material [2]. Carbon fibres are indispensable across various industries due to their exceptional mechanical properties. However, despite their advantages, the environmental disadvantages of carbon fibres are often overlooked. Consequently, there is a need to explore more environmentally sustainable alternatives [2] [3].

In recent years, there has been growing interest in natural fibers as a replacement for synthetic ones, such as carbon. One of the reasons for this extraordinary growth are the good mechanical characteristics in combination with the light weight and the low cost. Apart from the mechanical advantages, this type of natural fibre also presents opportunities in ecological terms. Figure 1.1 gives an overview of all the different fibres, with one of these natural fibres being flax. Flax is recyclable and will not cause any pollution to the environment during the production phase [4]. Due to these advantages, flax fibres are now more utilized in different industries: for example, some canoes and scooters are already made from flax [5] [6].

[1] Janssens, Arne "Gewichtsreductie en materiaaloptimalisatie van de zonneboot." 2023. [1]

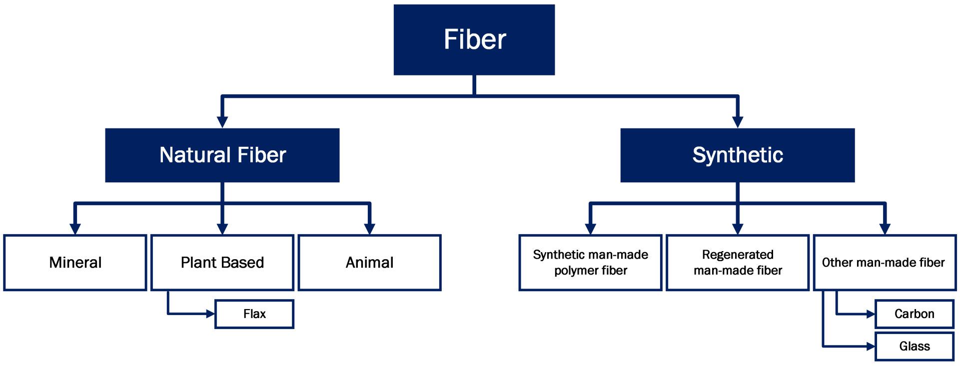



Figure 1.1: Classification of natural and synthetic fibres. [7]

## 1.3 Literary Review

### 1.3.1 Flax

Flax is a plant that originally grows in West-Europe and has been cultivated for thousands of years [8]. The plant is known for its fibres and seeds, which are extensively utilized in industrial applications and consumer products such as linen. An illustration of a flax field can be seen in Figure 1.2. The fibres are known for their strength and durability, making them suitable for use in composite materials. Over time, flax cultivation has declined due to competition from synthetic fibres. However, during the past years there has been a comeback in the use of natural fibres because of the combination of flax with synthetic fibres to combine the advantages of both materials [9] [10].

Figure 1.2: Picture of a flax field around Kortrijk, showing different plant stems used for fiber production [11].

The process of extracting fibres from the flax plant is relatively straightforward and an environmentally friendly process. When the plant has reached the appropriate size, the stems are harvested and pulled into fibres. The length of the plant stems, typically ranging from 0.9 to 1.2 meters, enables the extraction of long fibres in a single piece. After the initial harvesting, the flax fibres undergo several additional processing operations before they can be used as a finished product. These processing steps are crucial in transforming the raw fibres into a material that can be effectively woven into fabrics [10].

The long flax fibres are then woven into different fiber cloth patterns, each with its own unique specifications. The weaving process makes it possible to create various textile products that take advantage of the properties of the flax fibres, such as their strength and durability. The variety of flax as a raw material, combined with its various processing and weaving techniques, allows flax to be used in a variety of industrial and for commercial applications [12].

## 1.3.2 Properties of Flax Fibre Cloths

### 1.3.2.1 Fibre Orientation

A yarn consists of multiple fibres twisted together to form a continuous thread. In practice, the terms fibre and yarn are often used interchangeably. As show in Figure 1.3 two types of yarns are distinguish in textile fabrics: warp yarns and weft yarns [13].

Warp yarns are the yarns that are stretched lengthwise on the loom and held in tension. These warp yarns run vertically in the finished fabric cloth and are referred as yarns in the longitudinal direction. Perpendicular to the warp yarns are the weft yarns. These are the horizontal threads that are woven through the warp yarns, passing over and under them according to the weaving pattern. The yarns in the transverse direction are referred to as weft yarns [13] [14].

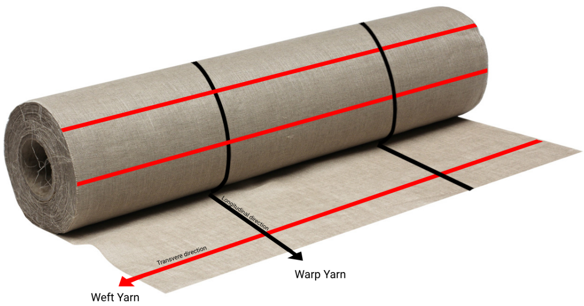



Figure 1.3: Picture of flax fibre cloth showing the difference between weft (red lines) and warp yarns (black lines) [15].

Understanding the properties of both warp and weft fibres is crucial for determining the direction in which the fibres should be used in their applications. According to Caroline Flipts from Flaxco[2], when considering different weight classes of the same weaving pattern, the yarns in the transverse (weft) direction will be different. This has an impact on the mechanical properties [12].

### 1.3.2.2 Microscopic Structure of Flax fibre

Flax fibre, at the microscopic level, exhibits a complex and hierarchical structure that significantly influences the mechanical properties. When examining flax fibre cloth, we observe that it comprises multiple yarns intertwined to form the fabric structure (see Figure 1.4 a). Each yarn itself is an assembly of numerous fibres, tightly twisted together to enhance strength (see Figure 1.4 b) [12].

Delving deeper, a closer inspection of an individual fibre reveals the intricate arrangement of cellulose chains within its structure (see Figure 1.4 c). These cellulose chains, known as microfibrils, which are only a few micro metres long, are the base for the fibre's tensile strength and flexibility [16] [17].

The spaces between these cellulose chains, as well as the voids between individual fibres within a yarn, play a crucial role in the performance of flax fibres composites. For optimal mechanical properties, these voids must be fully saturated with epoxy resin. Complete saturation ensures that all microscopic spaces are filled with epoxy, eliminating any potential weak points [12].

[2]https://flaxco.be/

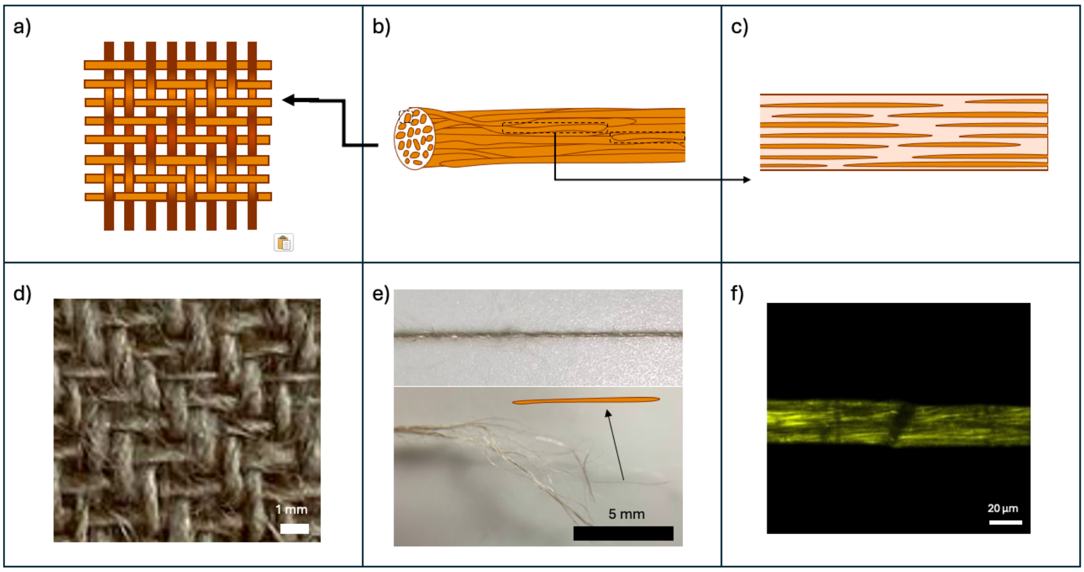



Figure 1.4: a) Illustration of a flax fibre cloth with multiple visible yarns b) an illustration showcasing a single yarn containing various fibres c) close-up drawing of one fibre revealing different cellulose chains within the fibre d) image of the a flax fiber cloth, twill 2x2 pattern e) image of a single yarn showing multiple fibers f) microscopic image of a single flax fibre from the article by Alessia Melelli et al. [17].

**Torsion of Fibre**

Figure 1.5 illustrates the difference between yarns with varying degrees of fiber twist. On the left, the yarn shows multiple fibers twisted tightly together, forming a densely packed structure. On the right, the yarn has less torsion, resulting in more space between the fibers.

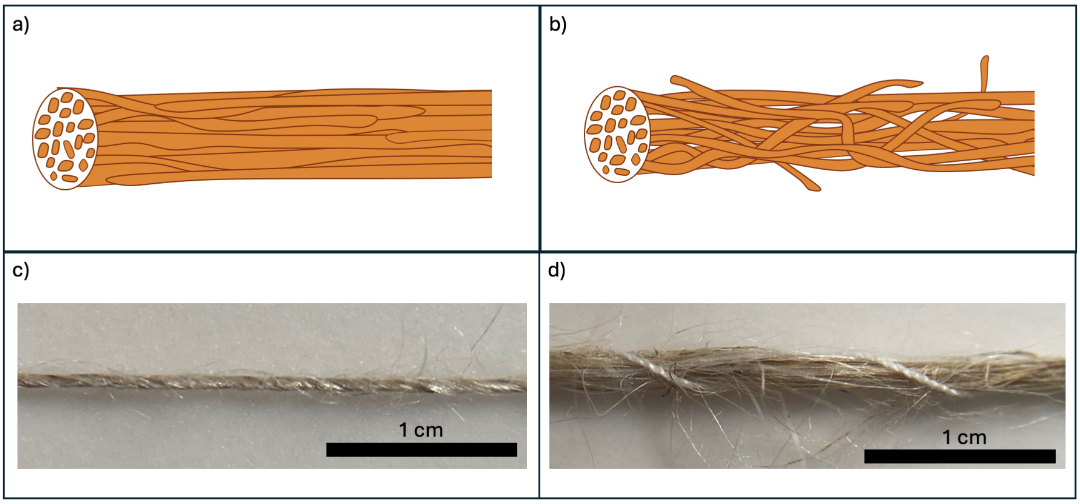



Figure 1.5: Illustration of two yarns a) yarn showing multiple fibres packed together b) yarn with less torsion showing looser fiber arrangement.

In Figure 1.6, we see two images of different flax fibre cloths. The left image shows a 2x2 twill weave, while the right image shows the same pattern but TEX variant. The TEX fibre has less yarn in the same area because the fibres are less twisted, making them thicker [12].

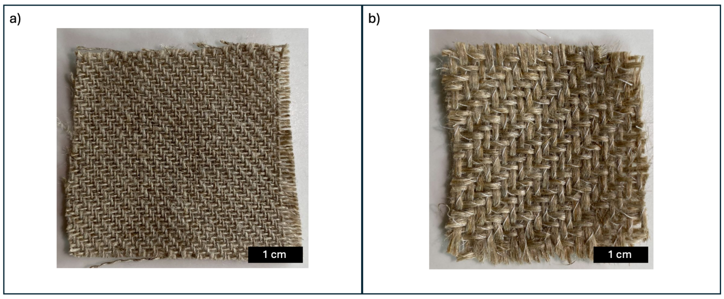



Figure 1.6: Two different fibre cloths, left twill 2x2 300 g/m$^2$, right twill 2x2 TEX 315 g/m$^2$.

#### 1.3.2.3 Weaving Patterns

Before the flax fibres can be used in the production of composites, these fibres must be woven into fibre cloths. In weaving techniques, two or more yarns (multiple fibres) are woven perpendicular to each other to create a fabric. The specific pattern in which these yarns are woven together, known as the weaving pattern, has a significant impact on the overall appearance, texture and properties such as tensile strength or elongation of the resulting fabric. In Figure 2.1, the three most commonly used patterns in the application of fibre cloths are described [18].

Plain weave is the most fundamental and simple weaving pattern, where the weft yarn is passed over and under each individual yarn in an alternating, perpendicular pattern. This results in a uniform, checkerboard pattern appearance on the fabric surface [19].

Twill weaving pattern is one of the most widely used weaving patterns in textile production. It is characterized by a diagonal ribbing pattern created by running the weft yarn alternately over and under several warp yarns. This results in a distinct diagonal line or ”twill” effect on the surface of the fabric. The diagonal pattern forms a more complex weave structure, which often shows higher mechanical properties than other weave patterns. Twill pattern is often indicated by the number of warp and weft yarns. For example, a ”2x2 twill” means that the weft yarn goes over two warp yarns and then under two warp yarns, with this pattern shifting by one warp yarn in each successive row. In contrast, in a ”4x4 twill weave,” the weft yarn passes over four warp yarns and then under four warp yarns, with the pattern shifting by one warp yarn each row [20].

Basket weave is a variation of the plain weave, where two or more warp yarns and two or more weft yarns are woven together as a single unit. This creates a more pronounced, textured appearance compared to a standard plain weave [19].

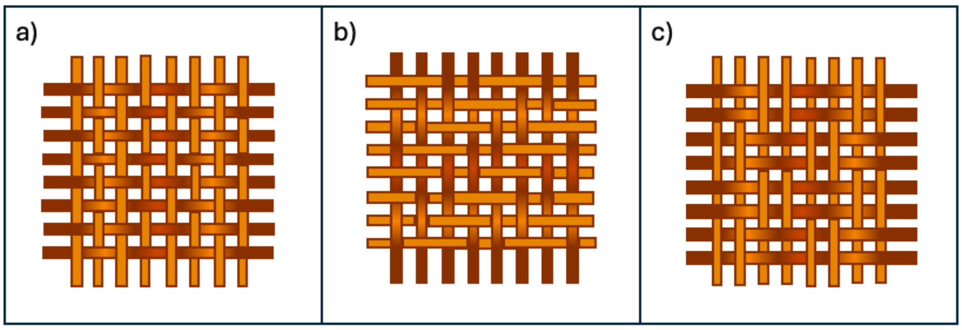



Figure 1.7: Plain weave (a), Twill 2x2 weave (b) and Basket weave (c) [18]

### 1.3.3 Comparison of Flax, Glass and Carbon fibres

Comparing the production process of flax to some synthetic fibres, like carbon or glass, flax fibres offer significant advantages. The production of glass fibre involves a heating process, contributing to its total energy consumption of 54.7 MJ/kg [4] [21]. Comparatively, the production of carbon fibres requires about 460 MJ/kg [1] [22] [23], significantly higher than the energy needed for glass fibre production. In contrast, flax fibres offer a more energy-efficient alternative, with a total energy consumption of 9.55 MJ/kg during the production process. According to Joshi et al., the energy needed for production is therefore 50 times lower [4].

Based on cost considerations, flax outperforms carbon and glass fibre as well. The cost per unit weight for flax is significantly lower compared to carbon and glass fibres. On average, the cost of carbon fibre stands at around $9.5 per kg, while glass fibre costs approximately $2.5 per kg, whereas flax is approximately $1 per kg. This cost difference positions flax as a more economical option, making it an attractive choice for various applications [24].

The main disadvantage is that flax performs less optimally in terms of mechanical properties, shown in Table 1.1. However, research indicates a promising future for flax applications, with the potential to come closer to the results achieved by carbon fibre. Better result can be obtained by using other weaving patterns. Despite its current limitations, ongoing developments suggest that fax holds significant promise for achieving the same mechanical properties as carbon fibre in the future.

Table 1.1: Mechanical properties of flax, glass and carbon fibre [24].

| fibre type | Density ($g/cm^3$) | Tensile Strength (MPa) | Young's Modulus (GPa) | Elongation at failure (%) | Moisture Content (wt%) |
|---|---|---|---|---|---|
| Flax | 1.4–1.5 | 343–2000 | 27.6–103 | 1.2–3.3 | 8–12 |
| Glass | 2.53 | 4600 | 89 | 5.2 | — |
| Carbon | 1.7 | 4000 | 235 | 1.4–1.8 | — |

The values presented in the above table represent the tensile strengths of individual fibres. When calculating the tensile strength of fibre-reinforced composites (FRC), the stress can be significantly lower than the tensile strength of the individual fibres. This is because the cross sectional area of one fiber is much smaller then from a FRC, resulting in a lower overall strength of the material. Furthermore, the choice of matrix material used to combine the fibres together plays a significant role in influencing the strength characteristics of the composite material [25] [26].

The tensile strength of fibre-reinforced composites can vary significantly depending on the type and proportion of fibres used. For example, a study on the mechanical properties of flax-epoxy composites and carbon fibre-epoxy found that the tensile strength of plain flax-reinforced composite was approximately 68 MPa, while the tensile strength of plain carbon composite was approximately 759 MPa [27].

### 1.3.4 Effect of water absorption

Since flax is a natural fibre, it is hydrophilic making it high sensitive to moisture [28]. This hydrophilic nature implies that the fibre gradually dissolves in water over time. As several components of the Solarboat are exposed to water or used in a humid environment, it is necessary to investigate the influence of moisture. Studies have shown that flax composite materials follows to the Fickian diffusion model during the absorption of water [29]. This model illustrates how water molecules move through the fibres. The Fickian diffusion model can help predicting how quickly and how much moisture the material will absorb [30]. The model is based on the principles of diffusion, offering insights into how the concentration of a particular substance in a material change over time due to diffusion. [28-30]

Secondly, flax fibres inherently contain a specific moisture content. Various techniques exist to extract this moisture from the fibres. As outlined in the paper by E. Muñoz and J. A. García-Manrique, a method involves heating the composite material in an oven at 40°C for 24 hours to eliminate the moisture [29]. This procedure needs to be repeated until the test specimen reaches a constant weight.

Lastly, there are several methods of applying additional moisture to composites. Studies have shown this additional moisture can have a beneficial effects on flexural strength [29]. In the paper by E. E. Muñoz and J. A. García-Manrique, they submerge the composite material in water. At regular intervals, typically every 24 hours, the samples are carefully removed from the water bath, subjected to drying, and then reweighed. It becomes possible to accurately calculate the percentage of moisture in the composite material by using Formula 1.1 [28] [29] [31].

$$M_t(\%) = \frac{W_t - W_0}{W_0} \cdot 100 \tag{1.1}$$

### 1.3.5 Bio Epoxy

Bio epoxy refers to a type of epoxy resin that incorporates bio-based or renewable materials in its composition. Unlike traditional epoxy derived from petrochemical sources, bio epoxy incorporates plant-based or other renewable resources, making it more environmentally friendly. The goal is to reduce dependence on fossil fuels and minimize the environmental impact associated with traditional epoxy production. [32]

To make bio epoxy, scientists use different methods to create resins from renewable materials. One way is to use a process called liquefaction [33], which turns plant-based oils into a liquid that can be used to make epoxy resin. This liquid, called bio-oil, can be mixed with regular epoxy resin to make it stronger and more heat-resistant. Another method uses materials left over from making other products, like lignin (a part of plants) and glycerol (a type of alcohol). These materials are combined in a specific way to create a completely natural epoxy resin [34].

One of these biobased epoxy resins made out of liquefaction is Biobased Diglycidyl Ether Diphenolate (DGEDP) [35]. It is a type of bio-based epoxy resin that is synthesized from diphenolate esters and plays a crucial role in the formulation of sustainable epoxy materials. DGEDP is known for its promising properties, including enhanced mechanical strength and thermal stability, making it a valuable alternative to traditional petrochemical-based epoxy resins like “bisphenol A (DGEBA)” [36] [37].

# 2 Methods

## 2.1 Materials

For this study, various composite materials are created. Composites are a combination of two or more materials with different properties. This often results in a better and stronger product with unique properties. Composites consist of two different parts: the matrix and the fibre. The matrix forms the main material, while the fibre provides reinforcement. Besides the matrix and fibres, composites can also include core materials such as foam, but this will not be the focus in this research. In this thesis, their will be referred to a fibre-Reinforced Polymer (FRP), where the fibre, in this instance flax, serves as the reinforcing material, and the bio-epoxy acts as the polymer matrix. As reinforcement fibres, the following will be used: carbon fibre(as a reference), glass fibre (as a reference), and flax fibres from Flaxco, Belgium. Three different epoxy resins are used as matrix materials: bio-epoxy and epoxy resin from V-sure (located in Lier), and epoxy resin from Sicomin. This comprehensive selection of matrix and fibre materials will allow for a thorough investigation of the properties and performance of the resulting composite materials.

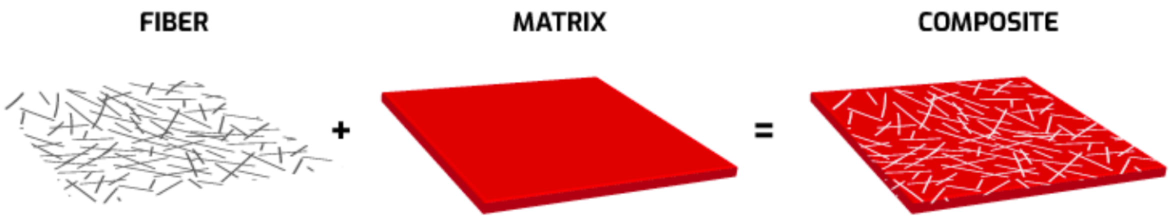



Figure 2.1: Structure of composite materials [38].

### 2.1.1 Fibres

Three different fibers were investigate: Carbon, Glass and Flax fibre. The carbon and glass fibres are woven according to the plain weave type. The flax fibre fabrics were produced by Flaxco located in West-flanders, Belgium. A total of nine different flax fibre cloths were employed in the study. Table 2.1 presents all the fibre cloths with their corresponding patterns, quality labels, and weight classes.

Table 2.1: Type of fibre, weaving patterns, quality labels, and weights.

| Fibre | Weaving Pattern | Quality Label | Weight (g/m$^2$) |
|---|---|---|---|
| Carbon | Twill 2/2 | CF-22-210PRO-100 QTY 10M | 210 |
| Glass | Plain | 31111018 10QM | 350 |
| Flax | Twill 2/2 | 171209 26Nm | 200 |
| Flax | Twill 2/2 | 171209-04 | 250 |
| Flax | Twill 2/2 | 171209 9.5Nm | 300 |
| Flax | Twill 4/4 | 171209 26Nm | 200 |
| Flax | Twill 4/4 | 171209-04 | 250 |
| Flax | Twill 4/4 | 171209 9.5Nm | 300 |
| Flax | Twill 2/2 TEX | LTW-TDL 300TEX 5555 | 340 |
| Flax | Twill 2/2 TEX | LTW-TDL 200TEX 7075 | 315 |
| Flax | UD | 2642 3 UD | 160 |

### 2.1.2 Epoxy Resin

In the study, three types of epoxy were used. Sicomin epoxy from 2020, which was used as a reference because previous boat components were made with this epoxy. A regular, non-sustainable epoxy variant delivered by V-sure was also used. Lastly a bio-epoxy resin also deliverd from V-sure was used. All specifications can be found in Table 2.2. Specific compositions can be found on the manufacturer's website.

Table 2.2: Epoxy types and corresponding specifications.

| Type | Manufacturer | Resin (A-component) | Harder (B-component) | Mix Ratio |
|---|---|---|---|---|
| Epoxy | Sicomin | sr8500 | 870x | 100A-35B |
| Epoxy | V-sure | Epoxy BK A | Epoxy BK B | 100A-60B |
| Bio-Epoxy | V-sure | 2500A | 2009 HSF | 100A-50B |

The bio-composite matrix consists of two main components: the A-component (resin) and the B-component (hardener). The A-component is a combination of epoxy monomers and a bio-based cashew nut derivative, providing a partially renewable matrix material. In contrast, the B-component contains a cycloaliphatic amine. This hardener component reacts with the epoxy in the resin to form the crosslinked polymer.

In table 2.3 more details about the compositions of these components are displayed. It is important to note that this bio-epoxy formulation does not contain any n-alkyl diphenolate esters, which are sometimes used in conventional epoxy resins. The absence of these petroleum-derived components ensures that the Solar boat team is heading towards a more sustainable future. The use of this partially bio-based epoxy matrix, in combination with natural fibre reinforcements such as flax, has the potential to create environmentally-friendly composite materials with reduced environmental impact compared to traditional petroleum-based composites.

Table 2.3: Composition of the different components in the Bio-Epoxy.

| Component | Composition |
|---|---|
| A-component (resin) | 80-90% CAS 1675-54-3:<br>2,2-bis[4(2,3-epoxypropoxy)phenyl]-propane<br>10-20% CAS 68413-24-1:<br>Cashew, nutshell liquid, polymer with epichlorohydrin |
| B-component (hardener) | 25% CAS 2855-13-2:<br>3-Aminomethyl-3,5,5-Trimethylcyclohexylamine |

## 2.2 Mechanical Properties

The tensile testing of the composite samples was carried out using a two different testing machines (Tinius Olsen 300 ST [39] and Lloyd LRX Plus [40]). The test specimens were prepared using two different cutting methods, 72 samples were cut using a waterjet cutter (Wazer [41]), while the remaining samples were cut using a laser cutter (BRM 90130 [42]) from the composite plates.

The test specimen dimensions are 170mm x 20mm, according to EN ISO 527-4 standard, shown in Figure 2.2 [43]. The thickness of the samples varied depending on the type of flax fibre cloth used and the amount of epoxy resin present in the composite [44]. The crosshead displacement rate was set at 5 mm/min during the tensile testing. All strength and modulus values were calculated by taking the average of three samples for each type of flax fibre cloth [45].

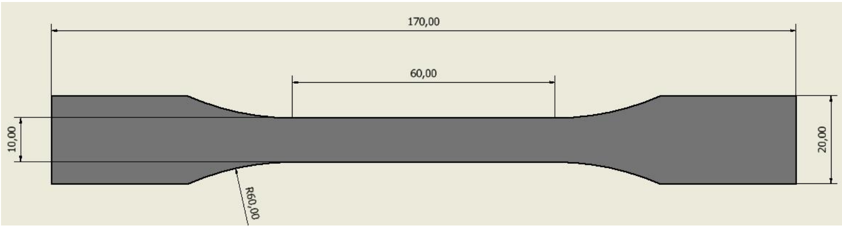



Figure 2.2: Sample Dimensions according to ISO527-4 [43].

The standardized test samples were clamped at both ends, and a force was applied to pull the sample apart. The resulting stress-strain data was measured to determine the crucial properties of the flax fibre composite material, including tensile strength, elongation, and elastic modulus.

## 2.3 Construction of Composite Samples

### 2.3.1 Laminating process

Various techniques are available to manufacture fibre Reinforced Polymers (FRP), with vacuum infusion being recognized as the most efficient and standardized approach [46]. This method is employed to ensure uniform resin distribution while minimizing waste. It is crucial to carefully manage the infusion pressure because any variations from the ideal level can cause resin buildup, which can affect the final results. Alternatively, hand lamination offers a more simple but less precise method for processing test samples. Achieving good epoxy distribution is a challenge with this technique.

In the context of this thesis, hand lamination (wet lay-up) is selected for evaluating the strength of composite materials intended for use in a Solar Boat. Most components of the Solar Boat use the wet lay-up method, making it the best choice for ensuring a precise evaluation of the strength of flax fiber with bio epoxy. The results obtained through Vacuum Infusion do not accurately reflect the strength of the current components in the Solar Boat.

### 2.3.2 Testing Samples

The dimensions of the individual test specimens are 170 mm x 20 mm as described in section 2.2. By including safety margins, the overall plate dimensions are 210mm x 240mm as illustrated in Figure 2.3. These dimensions were chosen based on the size of the test specimen and the required number of test samples, including the necessary margins.

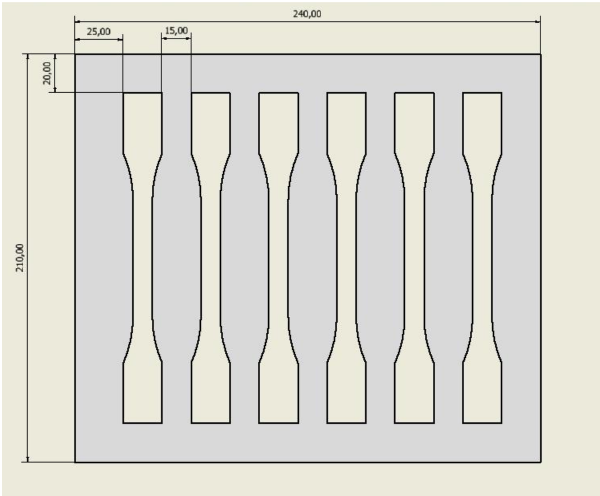



Figure 2.3: Overview of the dimensions of the flax plate showing all the margins.

From each plate, six test specimens can be obtained. The choice of six specimens is to enable the calculation of an average from the obtained results, as natural fibres may exhibit variations in properties due to potential defects in the fibres, which can affect the tensile strength. Therefore, it is important to produce multiple specimens from the same fibre cloth. Out of the six specimens from each plate, three specimens will be tested during the tensile tests. The remaining three specimens will be kept as reserves in case one of the results is out of the expected range or if something goes wrong during the manufacturing process.

It is also important to note that the specimens are distinguished by their position on the plate. The specimens are numbered from one to six, from top to bottom. Specimens one and six are located at the outer edges of the plate, while specimens three and four situate in the central region. Test specimens one, two, and tree will be tested to ensure a variation in the sample locations, from the outer edge to the center of the plate. This sampling strategy allows for a comprehensive evaluation of the material properties across different regions of the composite plate.

### 2.3.3 Processing Samples

The process of preparing the test plates for the flax fibre reinforced composite samples involved several key steps. Firstly, the flax fibre sheets were carefully cut to the required dimensions of 210 mm x 240 mm, ensuring that the fibre orientation was taken into account during the cutting process. To prevent any potential creases or wrinkles in the fibre cloths, which could influence the test results, the flax sheets were flattened using a steam iron. Additionally, any loose fibres along the edges of the sheets were trimmed off, as these loose fibres could also impact the final properties of the test samples.

The epoxy resin and hardener were then thoroughly mixed for a few minutes to ensure a homogeneous blend. The weight of the prepared epoxy mixture was recorded for later reference. The epoxy was then applied layer by layer onto the flattened flax sheets, with the application continuing until a visually saturated state was achieved. This saturated state was characterized by the flax sheets being fully soaked with the epoxy, indicating that no further epoxy could be absorbed.

After the flax sheets are fully saturated with epoxy, they are positioned between a single sheet of peel ply. The peel ply ensures that the flax plates can be easily removed after curing. Subsequently, the flax sheets with peel ply are placed between two aluminum plates, which are wrapped with breather fabric. The breather fabric facilitates the absorption of excess epoxy. These plates are then inserted into a vacuum bag, afterwards the air is evacuated using a vacuum cleaner.

## 2.4 Water Absorption

Water tests were conducted on twill 2x2 fibre-cloths across three distinct weight classifications as well as on unidirectional (UD) fibre specimens. Prior to immersion in water, the samples were thoroughly dried in an oven. Six samples from each plate were placed in the oven at 40°C, this is shown in Figure 2.4. The samples were weighed every 24 hours until their weight remained constant, indicating they had reached a relative zero point.

Figure 2.4: Pictures showing the testing setup in the oven to dry all the different samples.

Afterwards, three of the dried samples were placed in a vacuum bag to maintain their dry condition before tensile testing. The remaining three samples were used to conduct the water absorption test. The water absorption was measured by immersing the test samples in water at room temperature. The specimens were simultaneously removed from the water, dried to remove moisture, and then weighed using an digital scale precise to 0.05g. During the first two days, the samples were measured every six hours, and then the measurement frequency was reduced to every 12 hours for the remaining test duration of three days. By using formula 1.1, the percentage of moisture in the composite can be determined.

## 2.5 Overview of test plates

Table 2.4 provides a comprehensive overview of the various composite plates that were fabricated to determine the different material properties.

The majority of the tests were conducted to calculate the tensile strength (TS) and the directions (DIR) of the different yarns. Additionally, tests were performed to evaluate the differences between the various epoxy systems (EP) used.

Furthermore, reference plates were manufactured using carbon and glass fibre materials (REF) to establish benchmark strength values.

Investigations were also carried out on the different layers of flax fibre cloths to determine if the strength increased with the addition of more layers (TS).

Plates were also produced specifically for the water absorption tests (WA), as described in the previous section.

Finally, three extra composite plates were manufactured to validate the production process (PP) and confirm the same results can be obtained.

Table 2.4: Overview of test plates with dates and purposes.

| **Overview test plates** | | | | **Date** | **Purpose** |
|---|---|---|---|---|---|
| **Pattern** | **Weight Class** | **Type of Epoxy** | **Direction** | | |
| UD | 160 g/m$^2$ | Bio Epoxy | Longitudinal | 7/03/2024 | TS and DIR |
| Twill 4x4 | 300 g/m$^2$ | Bio Epoxy | Transverse | 7/03/2024 | TS and DIR |
| Twill 4x4 | 300 g/m$^2$ | Sicomin Epoxy | Transverse | 7/03/2024 | EP |
| Twill 4x4 | 300 g/m$^2$ | Vsure Epoxy | Transverse | 7/03/2024 | EP |
| Twill 2x2 | 200 g/m$^2$ | Bio Epoxy | Transverse | 17/03/2024 | TS and DIR |
| Twill 2x2 | 250 g/m$^2$ | Bio Epoxy | Transverse | 17/03/2024 | TS and DIR |
| Twill 2x2 | 300 g/m$^2$ | Bio Epoxy | Transverse | 17/03/2024 | TS and DIR |
| Twill 4x4 | 200 g/m$^2$ | Bio Epoxy | Transverse | 17/03/2024 | TS and DIR |
| TEX | 315 g/m$^2$ | Bio Epoxy | Transverse | 17/03/2024 | TS and DIR |
| TEX | 340 g/m$^2$ | Bio Epoxy | Transverse | 17/03/2024 | TS and DIR |
| Twill 4x4 | 250 g/m$^2$ | Bio Epoxy | Transverse | 17/03/2024 | TS and DIR |
| Twill 4x4 | 250 g/m$^2$ | Bio Epoxy | Longitudinal | 17/03/2024 | TS and DIR |
| Twill 4x4 | 200 g/m$^2$ | Bio Epoxy | Longitudinal | 5/04/2024 | TS and DIR |
| Twill 4x4 | 300 g/m$^2$ | Bio Epoxy | Longitudinal | 5/04/2024 | TS and DIR |
| Carbon | 210 g/m$^2$ | Bio Epoxy | - | 5/04/2024 | REF |
| UD | 160 g/m$^2$ | Bio Epoxy | Longitudinal | 5/04/2024 | LAY |
| UD | 160 g/m$^2$ | Bio Epoxy | Longitudinal | 5/04/2024 | LAY |
| UD | 160 g/m$^2$ | Bio Epoxy | Longitudinal | 5/04/2024 | LAY |
| Twill 4x4 | 200 g/m$^2$ | Sicomin Epoxy | Transverse | 5/04/2024 | EP |
| Twill 4x4 | 200 g/m$^2$ | Vsure Epoxy | Transverse | 5/04/2024 | EP |
| UD | 160 g/m$^2$ | Bio Epoxy | Longitudinal | 7/04/2024 | WA |
| UD | 160 g/m$^2$ | Bio Epoxy | Transverse | 7/04/2024 | DIR |
| Glasvezel | 350 g/m$^2$ | Bio Epoxy | - | 7/04/2024 | REF |
| Twill 2x2 | 200 g/m$^2$ | Bio Epoxy | Transverse | 7/04/2024 | WA |
| Twill 2x2 | 250 g/m$^2$ | Bio Epoxy | Transverse | 7/04/2024 | WA |
| Twill 2x2 | 300 g/m$^2$ | Bio Epoxy | Transverse | 7/04/2024 | WA |
| TEX | 315 g/m$^2$ | Bio Epoxy | Longitudinal | 7/04/2024 | TS and DIR |
| TEX | 340 g/m$^2$ | Bio Epoxy | Longitudinal | 7/04/2024 | TS and DIR |
| Twill 4x4 | 200 g/m$^2$ | Bio Epoxy | Transverse | 24/04/2024 | PP |
| Twill 4x4 | 250 g/m$^2$ | Bio Epoxy | Transverse | 24/04/2024 | PP |
| Twill 4x4 | 300 g/m$^2$ | Bio Epoxy | Transverse | 24/04/2024 | PP |

| | |
|---|---|
| TS | Tensile Strenght |
| EP | Epoxy |
| REF | Reference |
| WA | Water Absorption |
| PP | Production Process |

# 3 Results

## 3.1 Materials

### 3.1.1 Ratio Fibre to Epoxy of Different Fibre Groups

Figure 3.1 illustrates the proportions of flax and epoxy within a specific fibre group. The average weight of all the samples within a specific fibre class is used in the graph. This graph is categorized into the six groups: Carbon, Glass, Flax twill 2x2, Flax twill 4x4, Flax twill TEX and Flax UD fibre. On the left side of the graph, synthetic fibres are depicted, indicating that less epoxy is required when working with synthetic fibres. The graph shows a relatively consistent epoxy usage in twill 2x2 and twill 4x4 patterns due to the uniformity in fibre application, exactly the same fibre is used in this fibre cloth. In contrast, TEX fibres demand the highest epoxy amounts due to their looser fibre arrangement. On the right side, the weight of the UD fibre is displayed. The weight of the UD fibre is lower than the other flax fibre groups, resulting in a lower amount of epoxy used.

On the other side the graph also illustrate the calculation of the flax-to-epoxy ratio, crucial for determining mechanical properties. Subsequently, results will show how a ratio with less epoxy than the ideal ratio can have a negative effect on the tensile strength.

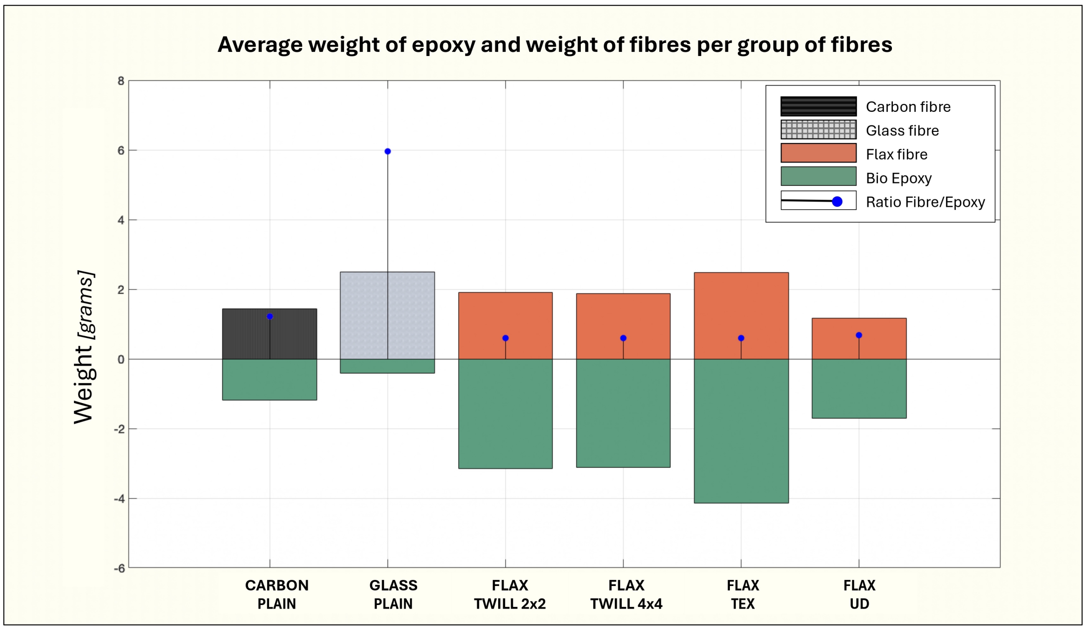



Figure 3.1: Overview of average weight flax and epoxy used in the different test samples and the flax-to-epoxy ratio.

### 3.1.2 Comparison between Different Epoxy

The usage of bio epoxy is an import step towards a sustainable composite future. Tests have been conducted to examine differences in strength and elongation when utilizing bio epoxy. For these tests, twill 2x2 fabrics were used in two distinct weight classes. After sample processing, each sample was weighed to determine the weight of fibre and epoxy in each plate. From these results, illustrated in Figure 3.2a), the percentage of epoxy to total weight is then calculated. Figure 3.2b) shows the thickness of different plates along with the tensile strength of the samples. It demonstrates that the thickness of certain plates within the same weight class is constant. Despite the constant thickness, the twill 2x2 200 g/m$^2$ exhibits significant variations in tensile strength. These differences can be explained by plotting the percentage of epoxy against the stress. In Figure 3.2c), the different percentages with the corresponding stress and strain are plotted. Following this, some differences are noted among different types of epoxies in the twill 2x2 fabric, 200 g/m$^2$. This variation can be attributed to the disparate epoxy quantities within the fabric. It can be seen in this test that the sample with the highest epoxy-to-total-weight ratio has the highest tensile strength.

In Figure 3.2d), the stress strain curves are displayed of six tested plates. The strain of the twill 2x2, 300 g/m$^2$ fibres are aligned. This implies that the use of bio epoxy will not impact the tensile strength. Beside the constant value for stress, the graph illustrates the variations in elongation values. From this data, we can calculate the modulus of elasticity, which quantifies the stiffness of a material.

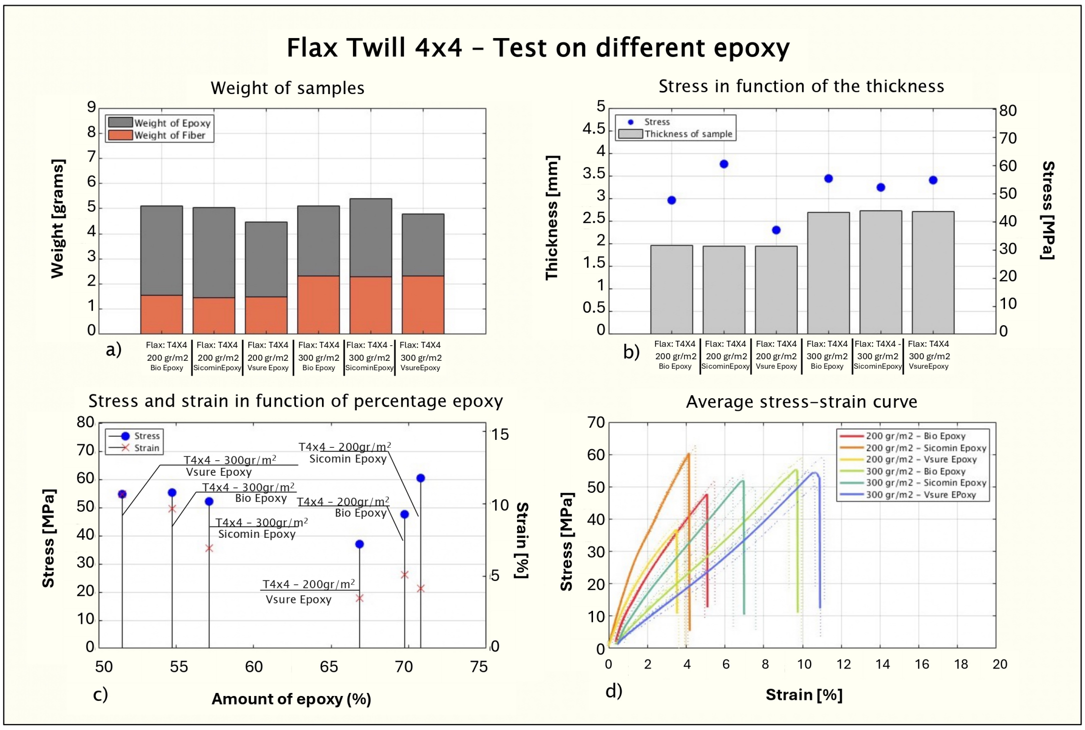



Figure 3.2: Overview of the properties of various plates using different types of epoxy.

**E-modulus** The Elasticity Modulus, is a critical measure of a material's stiffness, reflecting its ability to resist deformation under stress. In comparing different types of epoxy, Figure 3.3 shows that bio-epoxy exhibits the lowest E-Modulus. This is due to its higher strain results, which allows for greater flexibility and deformation under stress. This can be advantageous depending on the specific application requirements. Conversely, the Sicomin epoxy has the highest E-modulus, indicating the greatest stiffness and resistance to deformation. Vsure epoxy falls between these two, offering a moderate level of stiffness and flexibility. This range of E Modulus values is crucial for selecting the appropriate epoxy based on specific application requirements, ensuring optimal performance in different mechanical environments.

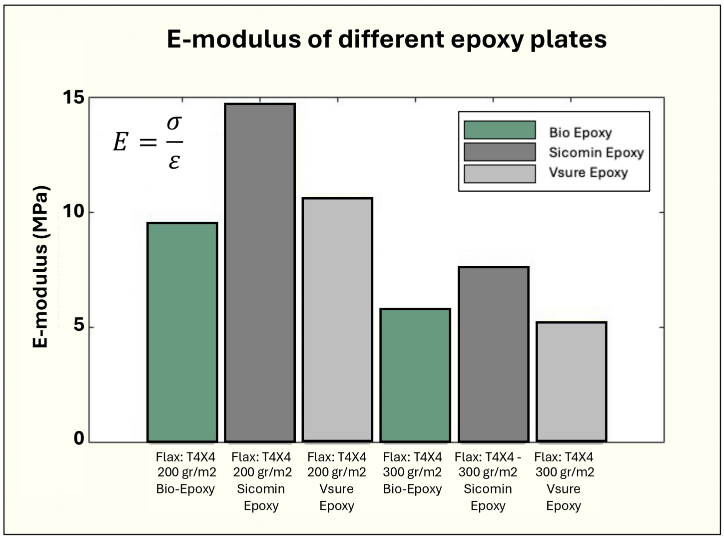



Figure 3.3: Comparison of E-modulus among three epoxy types paired with twill 2x2 fibre. The Sicomin epoxy exhibits the highest E-modulus, while the bio epoxy demonstrates the lowest.

## 3.2 Mechanical Properties

### 3.2.1 Unidirectional Fibre

**Different Layers**

The findings from the experimental investigation involving the tensile testing of unidirectional Fibre-Reinforced Polymer Composites are shown in Figure 3.4. In graph a) we see the amount of fibre and epoxy used in the different plates. the weight of flax in the different plates increases properly as the number of layers increases. This is not the case when looking at the amount of epoxy. The amount of epoxy between UD one layer and UD two layers doubles what was expected, but the amount of epoxy in UD three layers is exactly the same as UD two layers. This is also confirmed in Figure 3.4 c) where it is shown that the percentage of epoxy on the total weight of three layers is 6% lower than the UD fibre with two layers.

As illustrated in Figure 3.4 b), there is a correlation between the number of layers and the equivalent tensile strength and elongation. As more layers were added, the tensile sample showed a clear increase in the force it could withstand. However, despite the expansion in the cross-sectional area between UD one layer and UD two layers, the corresponding increase in force was not proportionate, leading to a relatively lower stress level for UD two layers, shown in Figure 3.4d). On the other hand, UD with six layers showed twice the force compared to UD with three layers. Also, it is important to note that force measured by UD six layers is higher than a carbon sample with three layers. However, when considering the tensile strength, the cross-sectional area need to be taken into account. The cross-sectional area is much larger in the UD six layers sample, resulting in a lower tensile strength than carbon fibre composite.

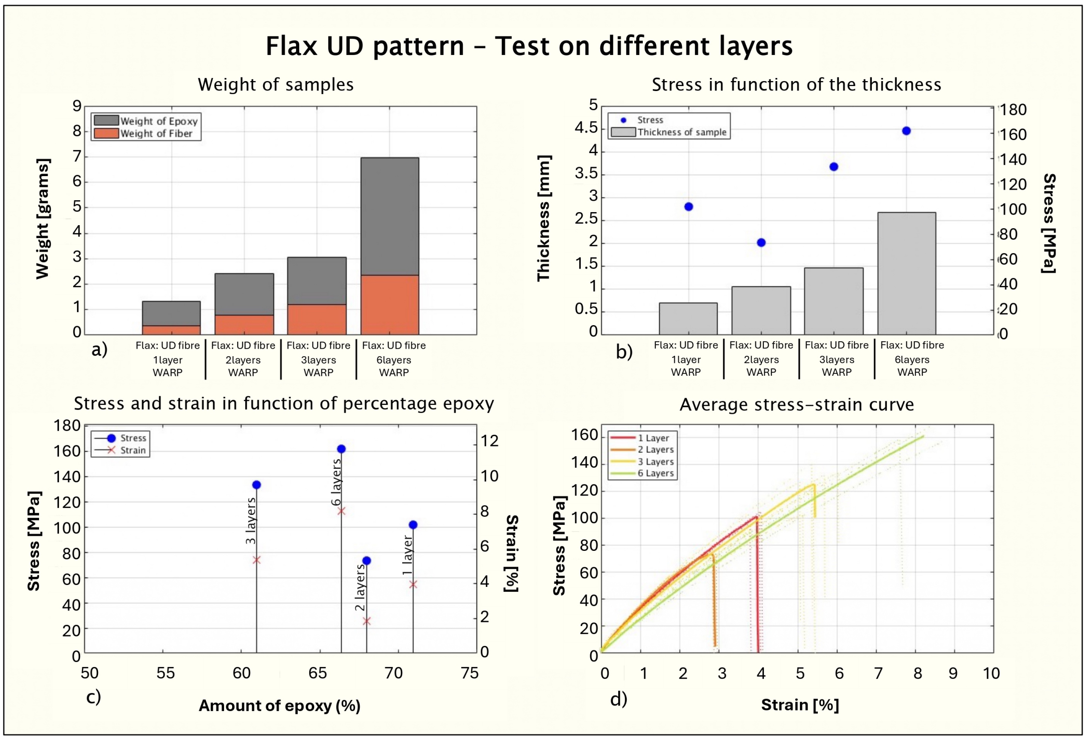



Figure 3.4: Summary of UD flax plate properties, demonstrating increased strength when using more layers of UD flax.

**Different Directions**
Besides testing on the different layers of the UD flax fibre, tests were also carried out on tensile strength in different directions. It is known that in UD fibres, all fibres lay in the longitudinal direction and only a few fibres in transverse directions that serves as support. Results from Figure 3.5 show that UD fibre in weft direction effectively offers no forces. These results indicate once again the importance of using UD fibres in the proper direction, if forces are applied in other directions, they are likely to fail immediately under load.

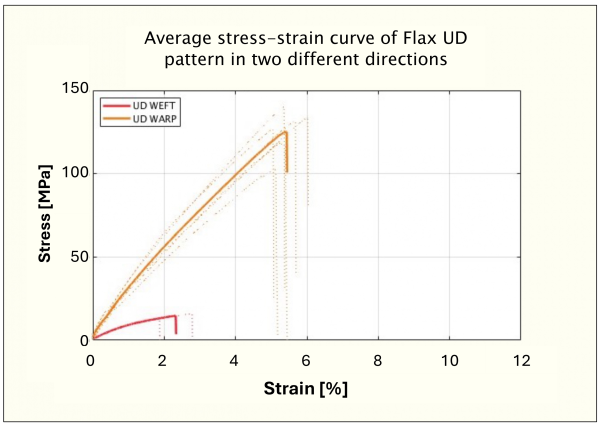



Figure 3.5: Illustrating stress-strain curves of unidirectional (UD) flax fibres in two distinct directions, demonstrating the lack of strength in the weft direction.

### 3.2.2 Twill 2x2 Weave Pattern in Weft Direction

A study was conducted on the twill 2x2 weave pattern, focusing the strength of the fibres in the weft direction. The expectation of this part was as the weight of the fibres increased, the strength of the material would also increase because of the varying weights of the fibres. When comparing the experimental results, Figure 3.6 confirms the expected outcome. Figure 3.6a) shows the amount of epoxy and fibre in the samples. This shows that as the weight class increases, so does the weight of epoxy and fibre. This can be explained because in larger weight classes, thicker fibres are used.

However, by looking to Figure 3.6d) the tensile strength does not increase in the 300g weight class. This can be explained by examining the amount of epoxy compared to the total weight. As shown in Figure 3.6c) a decrease of 3% is noted. This decrease led to a corresponding drop in tensile strength.

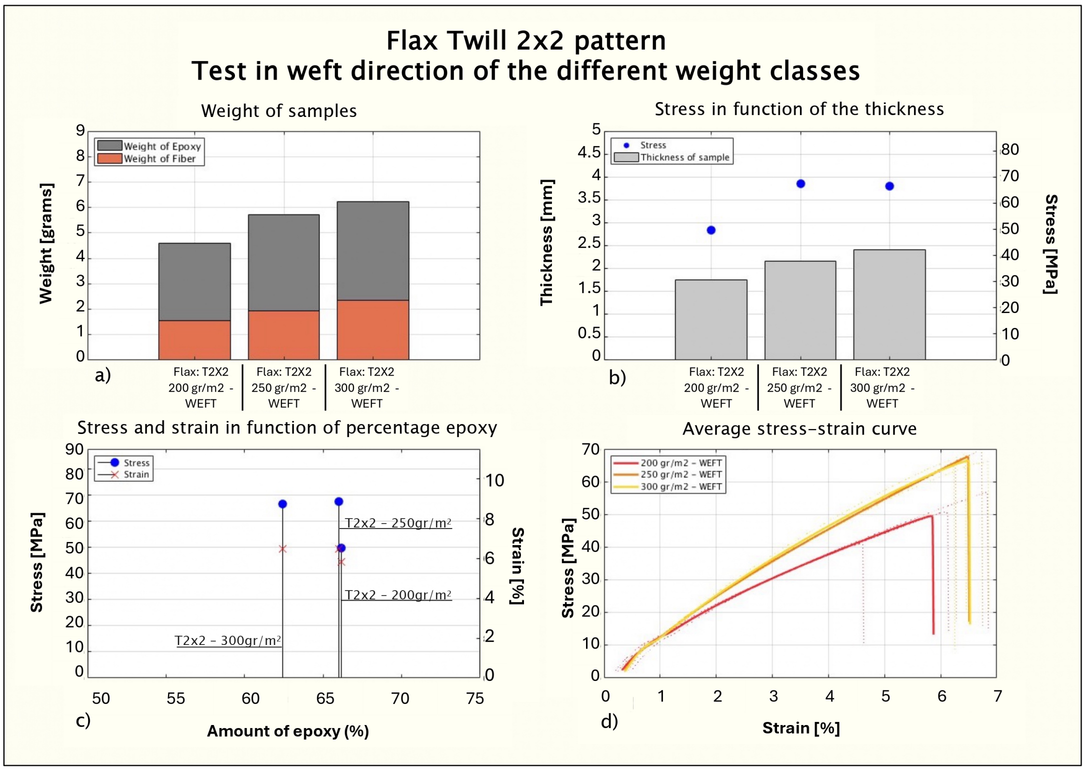



Figure 3.6: Overview of twill 2X2 flax plate properties in the weft direction, highlighting the increase in tensile strength across three distinct weight classes.

### 3.2.3 Twill TEX Weave Pattern in Two Directions

The Tex fibre variation, distinguished by its loosely arranged fibres, demands an increased epoxy content to ensure optimal performance, shown in Figure 3.7a) Furthermore, TEX fibres underwent tensile testing in two different directions across two distinct weight categories, the stress strain curves are shown in Figure 3.7d). Fibres aligned along the woven direction exhibited a bigger stress, which can be related to the relatively higher percentage of epoxy to total weight, as shown Figure 3.7c). This can also be visually observed. In Figure 22 and Figure 24 TEX samples in warp direction are shown. In this figures fibres are seen to be exposed, indicating insufficient epoxy content and thus sub optimal tensile strength. The differences in tensile strength can be attributed to a decrease of 10% in epoxy content. If the same amount of epoxy were used, it would be expected that the tensile strength in both weft and warp would be similar and show minimal differences.

The differences in the amount of epoxy are not visible in Figure 3.7b). The thickness between two plates made of the same fibre, but with different percentages of epoxy, have the same thickness. From this, we can conclude that the fibre determines the thickness, not the amount of epoxy.

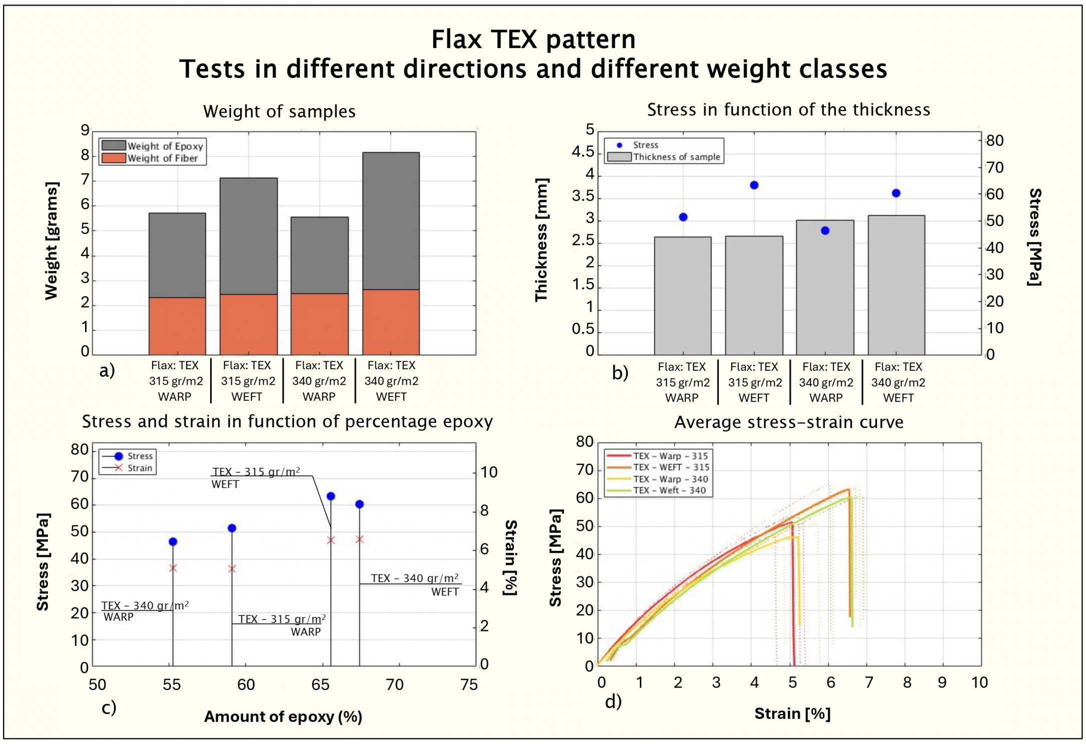



Figure 3.7: Summary of all the properties of TEX fibres, showing the differences in epoxy content leading to different result for tensile strength.

### 3.2.4 Twill 4x4 Weave Pattern in Two Directions

Test were conducted to define the properties of the twill 4x4 weave pattern, the pattern is pulled in different directions. Surprisingly, when pulling in the weft direction, an expected increase in tensile strength is not visible. In fact, the version with 300 g/m$^2$ performed worse than the one with 250 grams per square meter, possibly because it had much less epoxy compared to its total weight than 200 g/m$^2$ and 250 g/m$^2$. In the sixth bar in Figure 3.8a), there is significantly less epoxy used in the twill 4x4 300 g/m$^2$ compared to the same fibre mat in the warp direction. This reduction in epoxy is also observable in Figure 3.8c).

Then, tests were also conducted in the longitudinal direction, also known as the warp direction. It was expected that the results in this direction would align, as the type of fibre being stretched in this direction are all the same. However, when examining the stress strain curves in Figure 3.8d), an outlier can be seen with the twill 4x4 - 200 grams per square meter variant, this plate also contains 3% more epoxy over total weight than the other plates in warp direction as shown in Figure 3.8c). Looking at the twill 4x4 warp direction in the 250 and 300 gram weight classes, the tensile strength and elongation are consistent. A possible explanation for this outlier can be found in Figure 3.8b). The cross-section of the twill 2x2 200 g/m$^2$ is lower due to the use of thinner fibres.

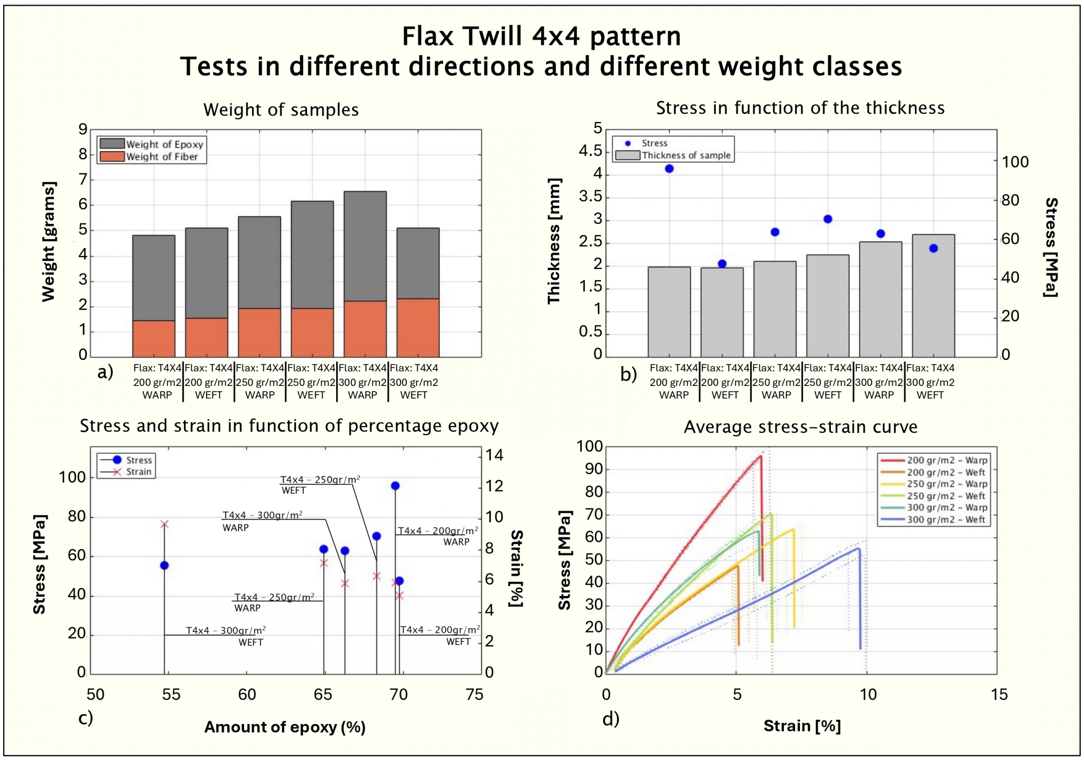



Figure 3.8: Test results for twill 4x4 weave pattern plates show unexpected variations in tensile strength between different weight classes and directions of pull, potentially influenced by epoxy content.

### 3.2.5 Comparison of Carbon, Glass and UD Flax

We performed a comparison between carbon and glass, each in three layers, and unidirectional (UD) flax in three layers and six layers. Figure 3.9a) shows the weight of epoxy and fibre in each sample. Glass requires the least amount of epoxy. The weight difference between three-layer UD flax and three-layer carbon is minimal. In addition, the cross-sectional area of each sample is shown in this graph. Figure 3.9b) shows the tensile strength and the resulting force for each sample. The force is determined by multiplying the tensile strength by the cross-sectional area. The results show that six-layer UD flax exhibits the highest strength. However, due to the larger cross-sectional area, the tensile strength is lower.

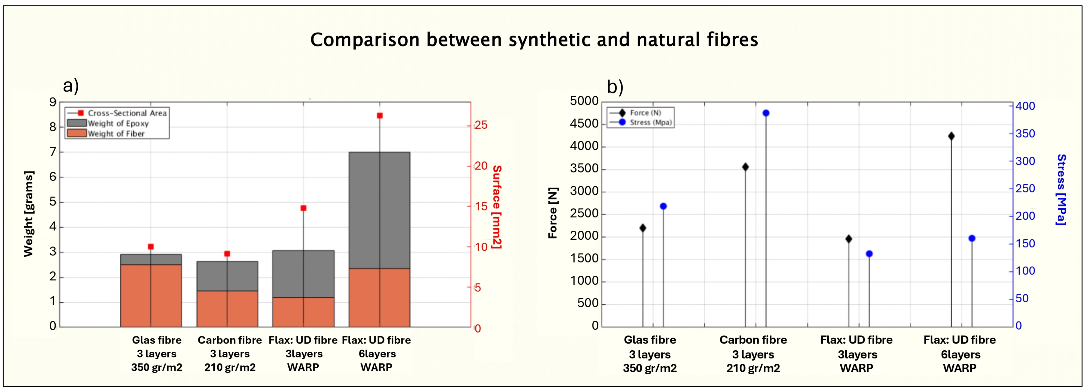



Figure 3.9: Comparison of weight, cross-sectional area, tensile strength, and force for carbon, glass (3 layers each), and UD flax (3 and 6 layers).

### 3.2.6 Comparison of Flax Twill Patterns

A comparison was carried out between twill 2x2 and twill 4x4 pattern, each in three different weight classes. All tests were carried out in the weft direction.

Figure 3.10 a) shows that the amount of fibre and epoxy is consistent between 2x2 and 4x4 patterns. Only 4x4 300gr shows a lower epoxy content, which is also reflected in graph 3.10 c). This reduction in epoxy content leads to a decrease in tensile strength.

Figure 3.10 b) shows a clear increase in sample thickness with an increase in weight class. Moreover, in this figure, twill 4x4 consistently shows a slightly larger thickness than twill 2x2.

Finally, Figure 3.10 d) shows a summary of all samples, from which it can be concluded that there are no significant differences between twill 4x4 and twill 2x2. The choice between the two patterns does not depend on strength, but on the application. Twill 4x4 allows fibres to be more easily folded around surfaces.

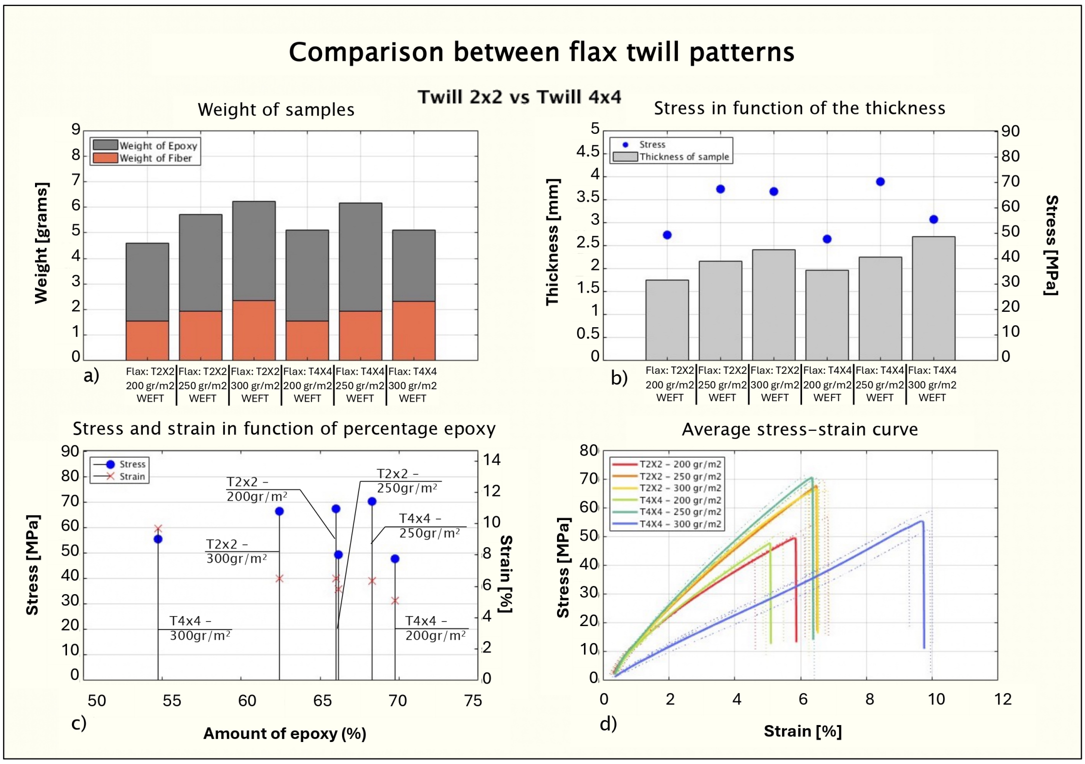



Figure 3.10: Comparison of twill 2x2 and twill 4x4 patterns in different weight classes, showing fibre/epoxy amounts, sample thickness, and tensile strength.

## 3.3 Construction of Composite Samples

### 3.3.1 Epoxy Needed for Laminating process

The following table illustrates the quantity of epoxy used during the lamination process. Excess epoxy is absorbed by the breather material. Upon weighing the samples, the amount of epoxy effectively remaining in the plates is calculated. It is observed that, in most instances, approximately 50% of the epoxy is absorbed by the breather or is lost to the environment before being sealed in the vacuum bag. This Figure enables us to determine the required epoxy quantity for the various types of flax. This table can also serve as a reference for determining the required amount of epoxy during future lamination processes.

Table 3.1: Epoxy measured in plate after lamination and epoxy used during lamination for different materials.

| Material | Epoxy used during lamination (g) | Epoxy measured after lamination (g) |
|---|---|---|
| Carbon | 60.00 | 28.48 |
| Glass | 70.00 | 11.16 |
| TEX | 168.25 | 90.70 |
| Twill 2x2 | 126.00 | 68.86 |
| Twill 4x4 | 142.85 | 68.79 |
| UD | 122.67 | 46.55 |

### 3.3.2 Visual Inspection

This part examines the results from processing composite plates. The fabrication process offers valuable insights into the saturation level and overall quality of the composite plates. Through visual inspection and analysis, we can clarify the degree of saturation attained during the manufacturing process.

In Figure 3.11, a setup for laminating flax fibre sheets is shown. Upon closer inspection of a flax sheet, areas where the fibres become loose and appear white are notable. This suggests that the fibres are being loosened, potentially impacting mechanical properties. During lamination, it is crucial not to stay too long over a particular area when laminating.

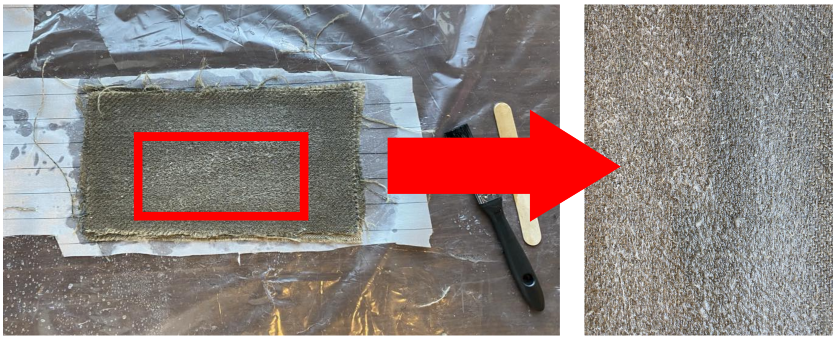
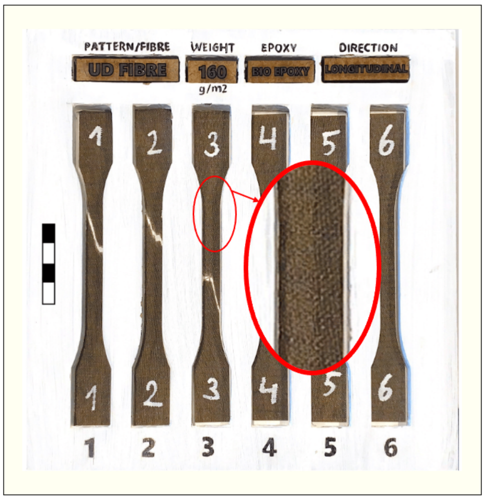
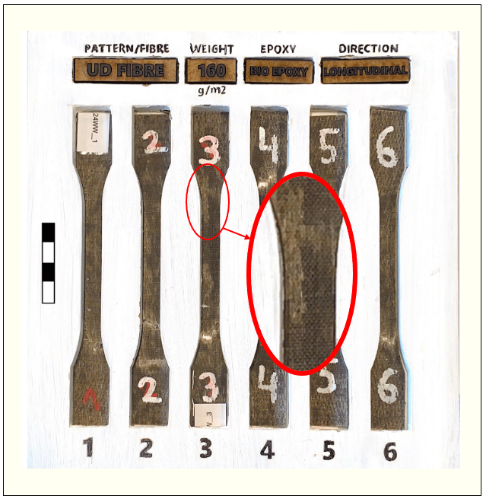


Figure 3.11: The setup of the laminating process, including a close-up of a flax sheet, demonstrating the impact of excessive friction in a localized area.

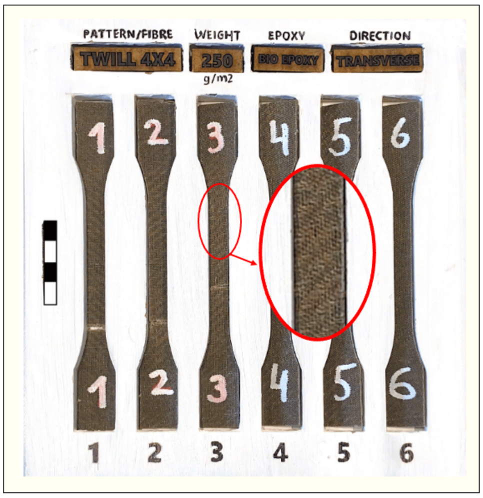
**Saturation** During the fabrication of composite plates, it became evident that complete saturation was not uniformly achieved. Visual examination revealed the presence of both dark and light patches on the surface of the plates, this can be validated in Figure 3.12. The occurrence of these light patches serves as a visual indicator of incomplete saturation. Incomplete saturation is also visible by inspecting the plate's texture. The presence of a visibly rough surface suggests that the fibres beneath are exposed. This rough texture provides a clear indication of incomplete impregnation, highlighting areas where additional epoxy is required to ensure the optimal composite structure.



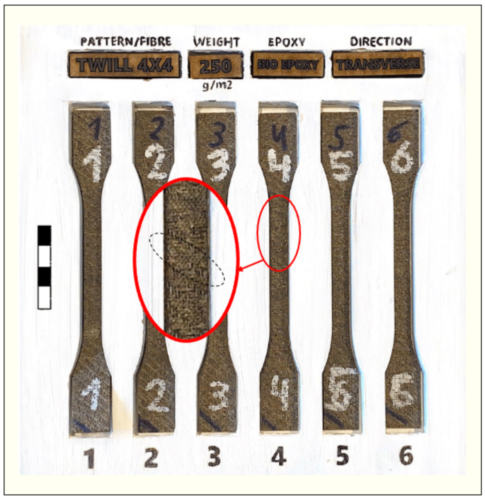

((a)) Image of UD 2-layer weft samples with evenly spread epoxy, resulting in a distinct brown surface.




((b)) Image of samples UD-3 layer weft with clear visible light and dark patches.




((c)) Image of Twill 4x4 250g/m$^2$ samples in weft direction with evenly spread epoxy, resulting in a distinct brown surface.




((d)) Image of Twill 4x4 250g/m$^2$ samples in weft direction, showing a rough surface.

Figure 3.12: Two examples of poor saturation in composite samples, highlighting areas of insufficient epoxy impregnation and exposed fibres.

### 3.3.3 Thickness of the Samples

During hand lay-up, epoxy is manually spread across the surface, often leading to uneven plates. It is advantageous to analyze the thickness of various samples, as it impacts tensile strength. Tensile strength is determined by the cross-sectional area, where greater thickness results in a larger area and consequently lower stress. Figure 3.13 displays the thickness of each sample within a single plate, with each line denoting a distinct plate. Furthermore, Figure 3.13 reveals that carbon and fibreglass exhibit thinner profiles compared to flax. Flax plates naturally have thicker fibres, leading to thicker composite plates. Understanding these variations in thickness provides valuable insights into the structural characteristics of the composite materials.

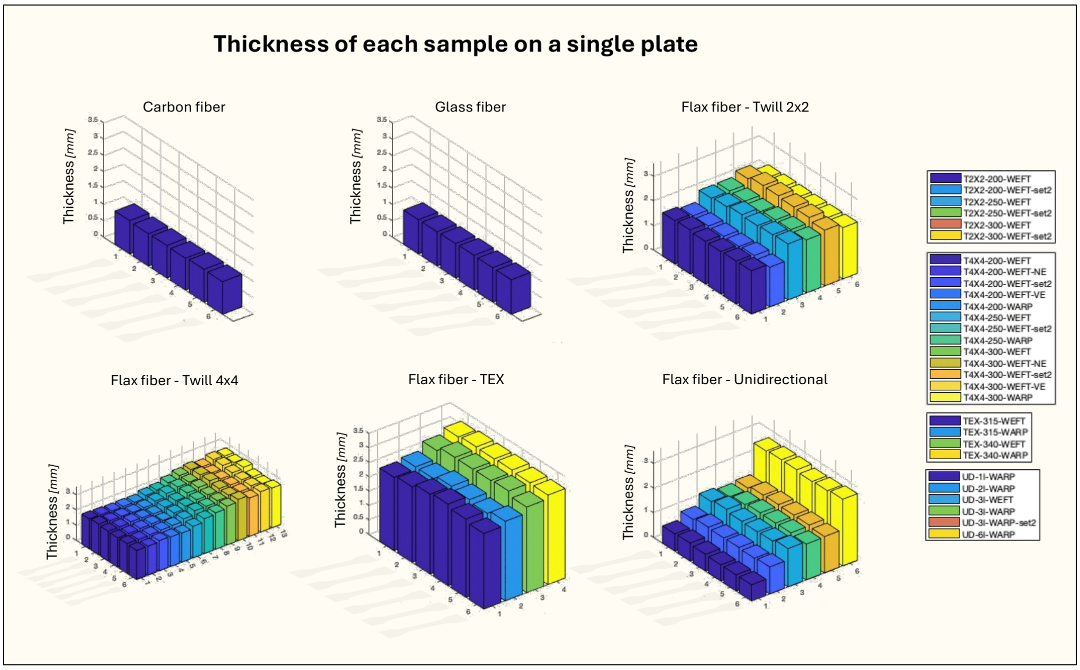



Figure 3.13: The thickness of each sample for all different plates shows that samples three and four often exhibit a larger thickness because of bad epoxy spreading.

### 3.3.4 Production Process

In the graph evaluating the production process, we constructed three sheets of 4x4 twill in three different weight classes in the WEFT direction. At a later time, an attempt was made to reproduce these three plates with exactly the same amount of epoxy during lamination. After curing, it was discovered that significantly less epoxy was recorded in all the samples of the second set, for unknown reasons, as shown in Figure 3.14 a).

Subsequently, when calculating the epoxy ratio, it was found to be significantly lower in set two, resulting in significantly reduced mechanical properties, as shown in Figure 3.14 c). The epoxy was found to be less concentrated inside the fibres and not on the surface, as shown in Figure 3.14 b), showing that the thickness of the samples remained consistent in the same weight class.

This highlights the challenge of controlling the amount of epoxy during the production process and also underlines the importance of the epoxy-to-total weight ratio, as illustrated in Figure 3.14 c). Finally, Figure 3.14 d shows the stress-strain curve for all tested samples. In this graph, we can see that 300g/m$^2$ set one shows the largest elongation, to know the reason for this further research needs to be carried out.

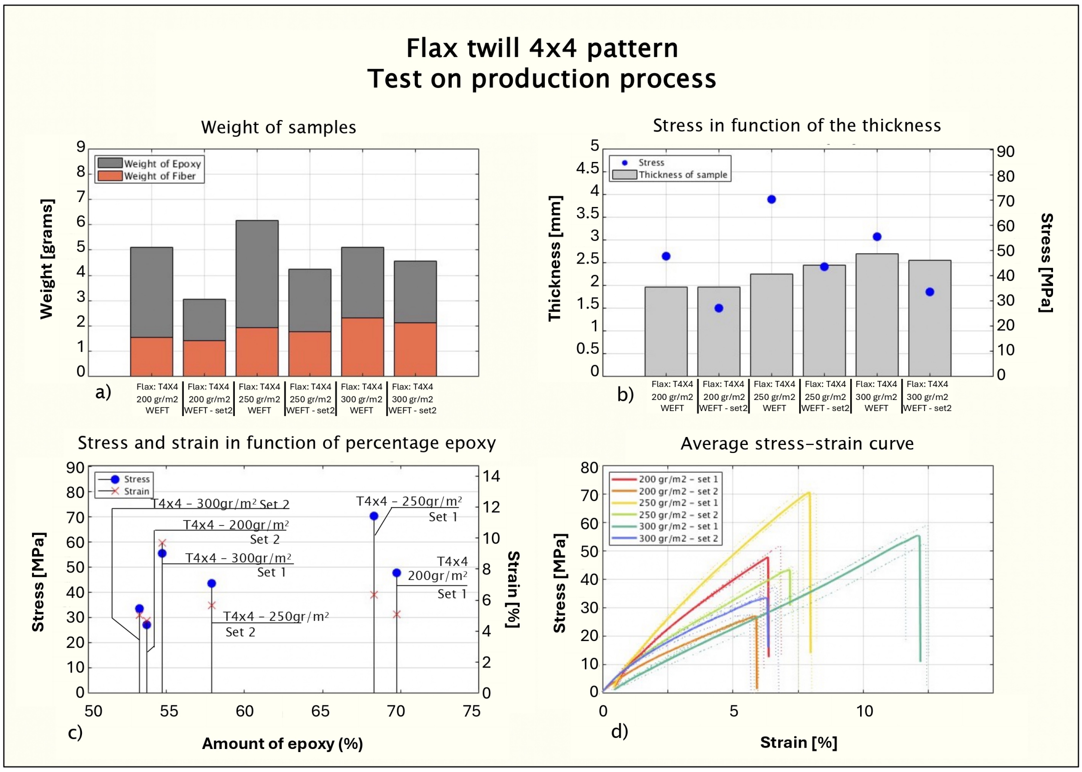



Figure 3.14: Evaluation of the production process, comparing epoxy distribution and mechanical properties in twill 4x4 composite plates of varying weight classes in the weft direction.

## 3.4 Water Absorption

### 3.4.1 Moisture Content

Figure 3.15 shows the increasing moisture percentage over time of four different flax fibre types. For four days, the moisture content was measured in the different test samples: Unidirectional fibre, Twill 2x2 200g/m$^2$, Twill 2x2 250g/m$^2$ and Twill 2x2 300g/m$^2$. A maximum moisture percentage of 22% is reached in the UD fibre. This means that 22% of the total weight of the test sample is moisture. This is remarkable and was not predicted. In a situation with vacuum infusion, it would be expected that a test sample will not absorb any moisture. In this situation, the moisture content of 22% can be attributed to the space between the cellulose chains, not being entirely filled with epoxy, as explained in section 1.3.2.2. This shows that the hand lamination process is not consistent and that there is a risk of water absorption. This must be taken into account when using flax in combination with hand lamination process.

### 3.4.2 Mechanical Properties of the wet and dry samples

Both the dry and wet test bars were pulled to failure to determine the tensile strength and elongation. Both elongation and tensile strength show higher values when containing moisture, as illustrated in Figure 3.16. This means that the wet samples can withstand a greater force. This can be explained by the moisture between the cellulose chains. The moisture helps to keep the chains for longer elongation, resulting in a greater force being achieved, and consequently, a higher stress. The graph below shows the increase in strength and elongation for the four different plates.

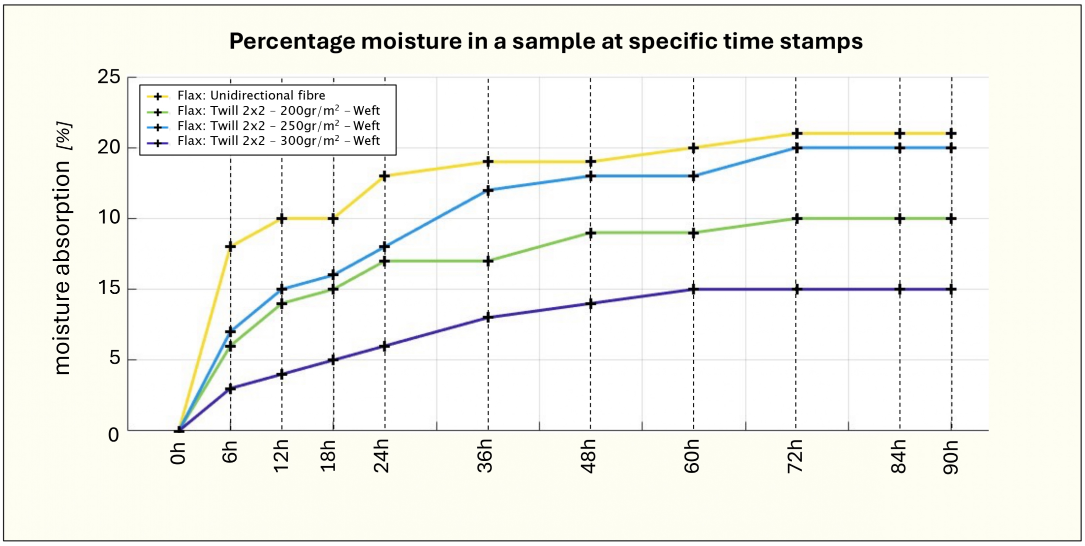



Figure 3.15: Graph illustrating the increase in moisture percentage over time, showing that UD fibres reach a maximum moisture absorption of 22%.

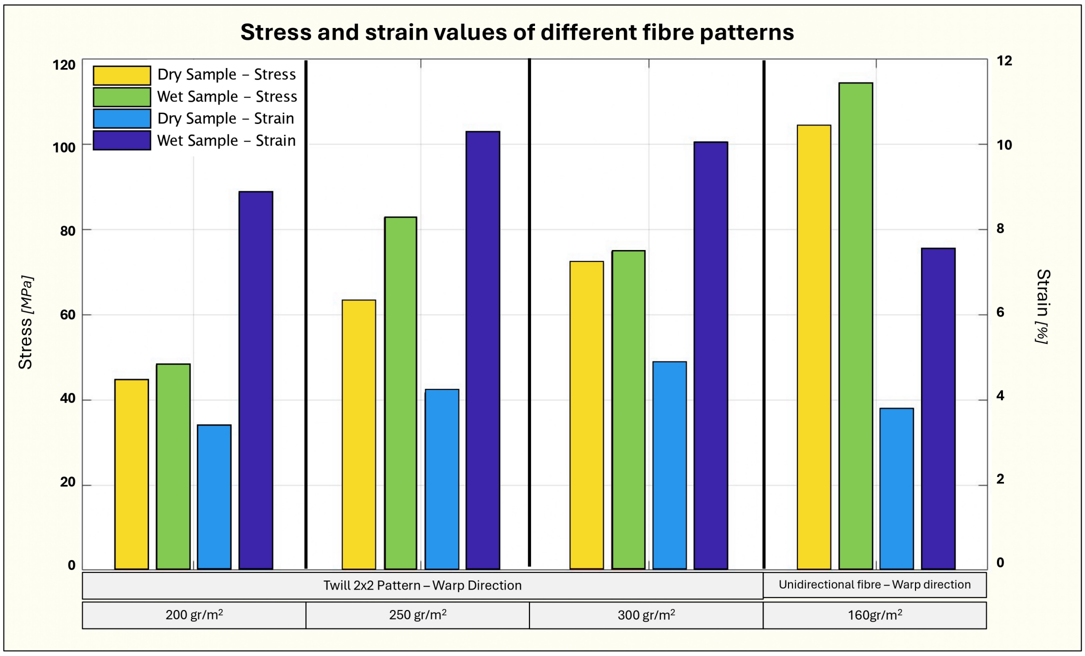



Figure 3.16: Graph displaying stress and strain values for all water absorption-tested samples. Wet samples shows higher values in both stress and strain.

# 4 Discussion

## 4.1 Mechanical Properties

The results of the research of the mechanical properties of different fibre cloths provide valuable insights into the performance of various flax fibre patterns. In this chapter, the best options and why some fibre types perform better than others are discussed.

The ratio of fibres to epoxy in the samples indicates that synthetic fibres require less epoxy than natural fibres such as flax. Natural fibres with Twill weaving patterns exhibit a relatively consistent epoxy usage, attributed to the uniform fibre distribution. However, Twill TEX fibres require more epoxy due to their looser fibre structure. These fibres are less tightly twisted, leading to higher epoxy consumption.

When comparing different types of epoxy, it appears that the use of bio-epoxy has no significant impact on the mechanical properties of twill 2x2 fabrics in the 300 $g/m^2$ weight class. This suggests that bio-epoxy is a viable option for sustainable composites without sacrificing strength or elongation.

When testing unidirectional (UD) fibre-reinforced polymers, it was found that the tensile strength and elongation increase with a higher number of layers. Although the UD six layer configuration exhibits equivalent forces to carbon fibre, the greater thickness of the UD sample leads to a lower tensile strength compared to carbon fibre.

**Twill Weave pattern**
The study of the twill 2x2 weave pattern in the warp direction revealed that with increasing fibre weight, the material strength should increase. However, upon examining the amount of epoxy relative to the total weight, a decrease in epoxy percentage at 300 $g/m^2$ resulted in a decrease in tensile strength. This underlines the importance of an optimal epoxy ratio for maintaining mechanical properties.

During testing of the twill 4x4 weave pattern, the expected increase in strength when pulling in the warp direction was not observed. The version with 300 $g/m^2$ performed worse than the one with 250 $g/m^2$, likely due to the lower epoxy percentage. In the length or warp direction, it was found that the twill 4x4 variant of 200 $g/m^2$, which contained 3% more epoxy, exhibited a significantly higher tensile strength.

Comparing these two types of twill weaving patterns, we can conclude that are no big differences in tensile strength. Notably, the strength increased with higher weight class, which is due thicker fibre are used.

TEX fibres, known for their looser fibre structure, require an increased epoxy content for optimal performance. Tested in two directions and weight categories, the fibres exhibited similar tensile strengths in both horizontal and vertical directions. This is because the difference in fibre weight in the warp and weft directions is minimal. The higher epoxy ratio in the warp direction contributes to the increased tension.

## 4.2 Limitations

Performing experiments to determine the mechanical properties of different fibre cloths has given valuable insights, but the research also has some limitations and imperfections. It is important to identify these limitations so that they can be taken into account for future research.

**Variability of Natural Material** A significant limitation of using flax is the inherent variability of natural material. The fibre cloths used in this thesis are not entirely uniform. Since flax is a natural material, it shows variations between individual plants and harvest years. This means that the results we obtained may not be fully repeatable for future tests. The flax produced next year may show significant differences from the flax used in this study. This lack of consistency makes it difficult to draw general conclusions about the performance of flax compared to synthetic fibres such as carbon.

**Limitations in Method and Equipment** During the research, it also became clear that the methodology and equipment were not perfect. Although the tests were conducted with the best available equipment, there are always small variations and measurement uncertainties that can affect the results. The accuracy of our measuring instruments and the precision of the test setup were not always optimal and could influence the final results. We tried to minimize this issue by performing multiple measurements and always taking an average of multiple measurements.

**Limitations in Hypotheses** This study used several assumptions and hypotheses that could not always be fully validated. It was assumed that the fibre mats were produced and tested under identical conditions, which is difficult to guarantee in practice. The set-up in the solar boat laboratory was not always consistent, temperature and humidity varied depending on the time of year. Moreover, we assumed that the measured mechanical properties are representative for larger structures and applications, scale and edge effects are not taken into account.

**Drawbacks of Flax compared to Carbon** One of the objectives of this thesis was to determine the properties of flax, considering its potential use as a substitute for carbon fibre. Although we achieved comparable forces in some cases, flax fibres were found to be significantly heavier and thicker to attain the same strength as carbon. This makes flax less suitable as a direct replacement for carbon in many applications, especially in weight-critical parts remain carbon still the optimal choice. Often, carbon is selected for its strength without thorough analysis. However, by precisely calculating the maximum strength requirements of specific components, we can conclude that carbon can be replaced with flax fibre.

## 4.3 Recommendations and Opportunities for Future Research

Considering the limitations and imperfections of our current research, there are several areas that need further research.

**The Influence of Processing and Production Methods** Further research can be conducted into the influence of various processing and production methods on the mechanical properties of flax fibre. It is important to investigate how variations, for example, the vacuum process or the cutting of test specimens, affect the ultimate strength, stiffness, and durability of the material. Experiments using different vacuum levels may assist in determining the optimal production processes for flax fibre composites. Additionally, exploring new processing techniques such as resin infusion methods or alternative curing processes could offer valuable insights into enhancing the mechanical performance and consistency of flax-based materials.

**Epoxy Ratio** As demonstrated in section 3.2.3, minor variations in epoxy compared to total weight significantly influence the mechanical properties. It is crucial to investigate the relationship between the amount of epoxy and the fibre. We anticipate that this relationship is not linear, but rather characterized by a unique curve for each fibre type. In this thesis, the amount of epoxy in the test specimen was not predetermined, as estimating the outcome post-processing is challenging. Figure 4.1 illustrates a potential curve for the TEX fibre, with several points already plotted. The green points represent a hypothetical strength in relation to the percentage of epoxy. Further research could involve systematically varying the epoxy ratio and analyzing its impact on mechanical performance to clarify the optimal epoxy-fibre balance for the best material properties.

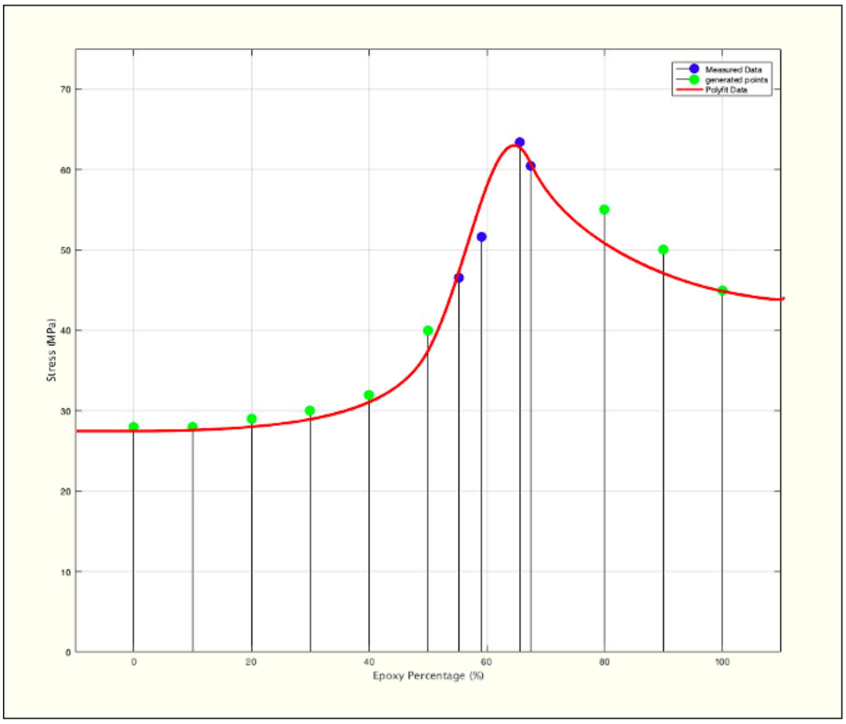



Figure 4.1: Graph illustrating the potential relationship between stress and the percentage of epoxy in relation to total weight.

**Water Absorption** Another crucial aspect requiring further investigation is the water absorption of flax fibre composites. Currently, it has been found that hand-laminated plates absorb an average of 20% moisture. This high moisture absorption rate can affect the mechanical properties of the material. Future research should focus on various aspects of this issue. Firstly, it is important to examine how the moisture absorption of hand-laminated plates compares to those manufactured with vacuum infusion. Vacuum infusion should theoretically create a denser fibre-matrix connection, reducing moisture absorption to nearly zero percent. In addition, the effect should be investigated if we would wet fibres first and then dry them again. Investigating the mechanical properties of fibre composites that have been wet and then dried can help determine the best moisture content for utilizing flax fibre composites. Lastly, composite edge treatment needs to be examined. To mitigate moisture absorption, it may be beneficial to treat the edges of the composites. Research into various edge treatment methods, such as applying waterproof coatings or using specialized sealants, can help reduce moisture absorption. Experimental studies can determine which methods are most effective and how they influence material performance.

# 5 Conclusion

The research into the mechanical properties of various fibre cloths has shown that flax is a promising ecological fibre for composite production. However, achieving the same strength as carbon requires three times the weight and thickness, making it less suitable for weight-sensitive applications. The importance of the correct fibre-epoxy ratio is emphasized by our findings. Results indicate that the twill 4x4 pattern with a constant epoxy ratio achieves a quarter of the tension of carbon. Conversely, UD flax fibres exhibit the highest tension value of all the flax fibre cloths due to their alignment in the same direction. The research on different patterns demonstrates that even minor variations in epoxy content can significantly impact mechanical properties, underlining the necessity of precise control over the production process.

Bio-epoxy proves to be an excellent substitute for traditional epoxies, offering similar strength and elongation without negative effects on the composite. The bio-epoxy used in this thesis contains up to 34% biodegradable material. Overall, flax holds considerable potential as a sustainable alternative to carbon, provided that appropriate production methods and fibres are employed. The differences in strength among different weight classes within the same pattern are minimal, indicating that the choice of fibre cloth has little impact.

# Bibliography

[1] J. Arne and van Rhienen Thibault, "Gewichtsreductie en materiaaloptimalisatie van de zonneboot," 2023. 1, 6

[2] A. Jacob, "The popularity of carbon fibre," *Reinforced Plastics*, vol. 50, pp. 22–24, 03 2006. 1

[3] M. Beecham, "Racing to find a sustainable alternative to carbon fibre," 2021, accessed: 2024-05-26. [Online]. Available: https://www.just-auto.com/interview/racing-to-find-a-sustainable-alternative-to-carbon-fibre/ 1

[4] "Are natural fiber composites environmentally superior to glass fiber reinforced composites?" vol. 35, 4 2004, pp. 371–376. 1, 6

[5] R. D. Leener, "Duo uit kortrijk vaart leie af met zelfgemaakte kano uit vlas: goed voor tocht van 131 kilometer," 6 2023. 1

[6] K. Andrews, "Be.e electric scooter by waarmakers," 7 2013. 1

[7] S. K. Ramamoorthy, M. Skrifvars, and A. Persson, "A review of natural fibers used in biocomposites: Plant, animal and regenerated cellulose fibers," pp. 107–162, 1 2015. 2, 37

[8] Alliance for European Flax-Linen and Hemp, "Everything you need to know about european flax," 2023, accessed: 2024-05-26. [Online]. Available: https://allianceflaxlinenhemp.eu/en/all-about-european-linen 2

[9] A. Amiri and C. Ulven, "Hybridized carbon and flax fiber composites for tailored performance in automotive components," *Materials & Design*, vol. 89, pp. 9–20, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0264127516304579 2

[10] T. E. of Encyclopædia Britannica, "Flax," url: https://www.britannica.com/plant/flax, 10 2023. 2

[11] T. B. Times, "Hidden belgium: The crop that made flanders rich," 2022, accessed: 2024-05-21. [Online]. Available: https://www.brusselstimes.com/210450/hidden-belgium-the-crop-that-made-flanders-rich 2, 37

[12] C. Flipts, private communication, 2024. 2, 3, 4

[13] P. Osterkamp. (2022) Warp and weft: Another spelling situation. Accessed: 2024-05-26. [Online]. Available: https://peggyosterkamp.com/2022/12/warp-and-weft-another-spelling-situation/ 3

[14] F. House. (2022) Woven fabrics. Accessed: 2024-05-26. [Online]. Available: https://www.fabrichouse.com/int/information/woven-fabrics/ 3

[15] Shapers, "Flax fibre cloth 3.5oz," 2024, accessed: 2024-05-21. [Online]. Available: https://shapers.com.au/flax-fibre-cloth-3-5oz-25/ 3, 37

[16] A. Lefeuvre, A. Duigou, A. Bourmaud, A. Kervoelen, C. Morvan, and C. Baley, “Analysis of the role of the main constitutive polysaccharides in the flax fibre mechanical behaviour,” *Industrial Crops and Products*, vol. 76, pp. 1039–1048, 12 2015. 3

[17] A. Melelli, A. Bourmaud *et al.*, “Microfibril angle of elementary flax fibres investigated with polarised second harmonic generation microscopy,” *Industrial Crops and Products*, vol. 156, p. 112847, 2020. 3, 4, 37

[18] D. Živanić and N. Ilanković, “Fundamentals of conveyor belts ”savremeni trendovi i inovacije u tekstilnoj industriji” savez inženjera i tehničara tekstilaca srbije fundamentals of conveyor belts osnove transportnih traka,” 2022. [Online]. Available: https://www.researchgate.net/publication/363690291 5, 37

[19] J. C. Materials, “Types of weave patterns,” https://jpscm.com/blog/types-of-weave-patterns/, 2024, accessed: 2024-05-25. 5

[20] CottonWorks, “Twill weaves,” https://cottonworks.com/en/topics/sourcing-manufacturing/weaving/twill-weaves/, 2024, accessed: 2024-05-25. 5

[21] Q. Dai, J. Kelly, J. Sullivan, and A. Elgowainy, “Life-cycle analysis update of glass and glass fiber for the greet tm model,” 2015. 6

[22] H. Khayyam, M. Naebe, A. S. Milani, S. M. Fakhrhoseini, A. Date, B. Shabani, S. Atkiss, S. Ramakrishna, B. Fox, and R. N. Jazar, “Improving energy efficiency of carbon fiber manufacturing through waste heat recovery: A circular economy approach with machine learning,” *Energy*, vol. 225, p. 120113, 6 2021. 6

[23] T. Ghosh, H. Kim, D. Kleine, T. J. Wallington, and B. Bakshi, “Life cycle energy and greenhouse gas emissions implications of using carbon fiber reinforced polymers in automotive components: front subframe case study,” *Sustainable Materials and Technologies*, vol. 28, July 2021. 6

[24] A. Lotfi, H. Li, D. V. Dao, and G. Prusty, “Natural fiber–reinforced composites: A review on material, manufacturing, and machinability,” pp. 238–284, 2 2019. 6, 36

[25] T. S. Lemmi, M. Barburski, and B. T. Samuel, “Analysis of mechanical properties of unidirectional flax roving and sateen weave woven fabric-reinforced composites,” *Autex Research Journal*, vol. 21, 6 2021. 6

[26] J. Andersons and R. Joffe, “Estimation of the tensile strength of an oriented flax fiber-reinforced polymer composite,” *Composites Part A: Applied Science and Manufacturing*, vol. 42, pp. 1229–1235, 9 2011. 6

[27] “Enhancement of mechanical properties of flax-epoxy composite with carbon fibre hybridisation for lightweight applications,” *Materials*, vol. 13, 1 2020. 6

[28] S. IVKOV, “A study on accelerated ageing of flax fiber reinforced composites with hygrothermal cycling sava ivkov,” 2022. 7

[29] E. Muñoz and J. A. García-Manrique, “Water absorption behaviour and its effect on the mechanical properties of flax fibre reinforced bioepoxy composites,” *International Journal of Polymer Science*, vol. 2015, 2015. 7

[30] A. Moudood, A. Rahman, H. M. Khanlou, W. Hall, A. Ochsner, and G. Francucci, “Environmental effects on the durability and the mechanical performance of flax fiber/bio-epoxy composites,” *Composites Part B*, vol. 171, pp. 284–293, 2019. [Online]. Available: https://doi.org/10.1016/j.compositesb.2019.05.032 7

[31] A. Oun, A. Manalo, O. Alajarmeh, R. Abousnina, and A. Gerdes, “Long-term water absorption of hybrid flax fibre-reinforced epoxy composites with graphene and its influence on mechanical properties,” *Polymers*, vol. 14, 9 2022. 7

[32] X. Liu, X. Yi, and J. Zhu, “Bio-based epoxies and composites as environmentally friendly alternative materials,” *Thermosets: Structure, Properties, and Applications: Second Edition*, pp. 621–637, 2018. 7

[33] P. Ortiz, M. Wiekamp, R. Vendamme, and W. Eevers, “Bio-based epoxy resins from biorefinery by-products.” 7

[34] P. Agbo, A. Mali, D. Deng, and L. Zhang, “Bio-oil-based epoxy resins from thermochemical processing of sustainable resources: A short review,” 9 2023. 7

[35] X. Yi and S. Chen, “Research progress on natural fiber-reinforced composites,” *Materials Today: Proceedings*, vol. 5, pp. 23 329–23 334, Jun. 2018. [Online]. Available: https://ui.adsabs.harvard.edu/abs/2018MsT..........6Y/abstract 7

[36] H. Sreehari, A. S. Sethulekshmi, and A. Saritha, “Bio epoxy coatings: An emergent green anticorrosive coating for the future,” *Macromolecular Materials and Engineering*, vol. 307, p. 2200004, 8 2022. [Online]. Available: https://onlinelibrary.wiley.com/doi/full/10.1002/mame.202200004https://onlinelibrary.wiley.com/doi/abs/10.1002/mame.202200004https://onlinelibrary.wiley.com/doi/10.1002/mame.202200004 7

[37] L. Yue, A. Maiorana, A. Patel, R. Gross, and I. Manas-Zloczower, “A sustainable alternative to current epoxy resin matrices for vacuum infusion molding,” 2017. [Online]. Available: http://dx.doi.org/10.1016/j.compositesa.2017.05.024 7

[38] R. RIM, “What are composites?” 2023. 8, 37

[39] T. Olsen, “Model 300st electromechanical universal tester,” https://www.tiniusolsen.com/product/model-300st/, accessed: 2024-05-25. 10

[40] T. Ltd, “Lloyd lrx plus tensile test machine,” https://www.tts-ltd.co.uk/lloyd-lrx-plus-tensile-test-mach, accessed: 2024-05-25. 10

[41] WAZER, “The first desktop waterjet cutter,” https://wazer.com/, accessed: 2024-05-25. 10

[42] B. Lasers, “Lasermachines voor graveren & snijden,” https://www.brmlasers.be/, accessed: 2024-05-25. 10

[43] International Organization for Standardization, “ISO 527-4:2021 - plastics — determination of tensile properties — part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites,” https://www.iso.org/standard/80369.html, 2021, accessed: 2024-05-21. 10, 37

[44] Sysadm, “Is epoxy resin plastic?” 9 2020. 10

[45] N. Saba, M. Jawaid, and M. T. Sultan, *An overview of mechanical and physical testing of composite materials*. Elsevier, 1 2018, pp. 1–12. 10

[46] “Vacuum infusion - an overview | sciencedirect topics.” [Online]. Available: https://www.sciencedirect.com/topics/materials-science/vacuum-infusion 10

# List of Tables

# List of Figures

# Overview of the specification of each plate

Table 1: Table with all the properties of different plates, values are the average of 3 samples

| Nr. | Plate | Mean weight of fibre [g] | Mean weight of epoxy [g] | Mean Weight [g] | Mean Width [mm] | Mean Thickness [mm] | Stress [Mpa] | Strain [%] |
|---|---|---|---|---|---|---|---|---|
| 1 | CAR-210 | 1,44 | 1,19 | 2,63 | 9,11 | 1,00 | 387,65 | 6,41 |
| 2 | GLAS-350 | 2,50 | 0,42 | 2,92 | 9,53 | 1,05 | 219,15 | 6,95 |
| 3 | T2X2-200-WEFT | 1,56 | 3,05 | 4,61 | 10,59 | 1,76 | 49,61 | 5,82 |
| 4 | T2X2-200-WEFT-set2 | 1,46 | 2,37 | 3,83 | 9,82 | 1,66 | 48,05 | 8,84 |
| 5 | T2X2-250-WEFT | 1,94 | 3,77 | 5,71 | 10,53 | 2,16 | 67,67 | 6,48 |
| 6 | T2X2-250-WEFT-set2 | 1,84 | 2,74 | 4,58 | 9,90 | 2,10 | 82,72 | 10,27 |
| 7 | T2X2-300-WEFT | 2,34 | 3,90 | 6,24 | 10,59 | 2,40 | 66,58 | 6,50 |
| 8 | T2X2-300-WEFT-set2 | 2,23 | 3,06 | 5,28 | 9,98 | 2,08 | 74,69 | 10,04 |
| 9 | T4X4-200-WARP | 1,47 | 3,34 | 4,81 | 9,87 | 1,99 | 96,00 | 5,94 |
| 10 | T4X4-200-WEFT | 1,55 | 3,57 | 5,12 | 10,49 | 1,96 | 47,80 | 5,08 |
| 11 | T4X4-200-WEFT-set2 | 1,41 | 1,65 | 3,06 | 9,39 | 1,97 | 27,15 | 4,70 |
| 12 | T4X4-200-WEFT-S.Epoxy | 1,47 | 3,57 | 5,04 | 9,89 | 1,96 | 60,47 | 4,15 |
| 13 | T4X4-200-WEFT-V.Epoxy | 1,47 | 2,98 | 4,46 | 9,91 | 1,95 | 36,95 | 3,50 |
| 14 | T4X4-250-WARP | 1,94 | 3,60 | 5,54 | 10,55 | 2,10 | 63,80 | 7,20 |
| 15 | T4X4-250-WEFT | 1,95 | 4,21 | 6,16 | 10,58 | 2,25 | 70,55 | 6,35 |
| 16 | T4X4-250-WEFT-set2 | 1,77 | 2,46 | 4,23 | 9,45 | 2,44 | 43,59 | 5,69 |
| 17 | T4X4-300-WARP | 2,21 | 4,34 | 6,56 | 9,91 | 2,54 | 63,03 | 5,87 |
| 18 | T4X4-300-WEFT | 2,31 | 2,79 | 5,10 | 10,41 | 2,69 | 55,52 | 9,69 |
| 19 | T4X4-300-WEFT-set2 | 2,13 | 2,44 | 4,57 | 9,47 | 2,56 | 33,74 | 5,02 |
| 20 | T4X4-300-WEFT-S.Epoxy | 2,30 | 3,08 | 5,38 | 10,39 | 2,73 | 52,17 | 6,93 |
| 21 | T4X4-300-WEFT-V.Epoxy | 2,31 | 2,47 | 4,78 | 10,43 | 2,71 | 54,91 | 10,66 |
| 22 | TEX-315-WARP | 2,33 | 3,38 | 5,71 | 9,94 | 2,64 | 51,61 | 5,07 |
| 23 | TEX-315-WEFT | 2,46 | 4,68 | 7,13 | 10,59 | 2,67 | 63,40 | 6,55 |
| 24 | TEX-340-WARP | 2,48 | 3,06 | 5,54 | 9,78 | 3,01 | 46,50 | 5,08 |
| 25 | TEX-340-WEFT | 2,65 | 5,49 | 8,14 | 10,57 | 3,13 | 60,51 | 6,60 |
| 26 | UD-1l-WARP | 0,38 | 0,93 | 1,32 | 9,59 | 0,70 | 101,79 | 3,96 |
| 27 | UD-2l-WARP | 0,77 | 1,64 | 2,41 | 9,67 | 1,05 | 73,55 | 1,86 |
| 28 | UD-3l-WARP | 1,19 | 1,88 | 3,07 | 10,05 | 1,47 | 132,96 | 5,36 |
| 29 | UD-3l-WARP-set2 | 1,16 | 1,57 | 2,73 | 9,71 | 1,43 | 114,16 | 7,56 |
| 30 | UD-3l-WEFT | 1,17 | 1,69 | 2,86 | 9,78 | 1,51 | 13,98 | 2,07 |
| 31 | UD-6l-WARP | 2,35 | 4,63 | 6,98 | 9,84 | 2,67 | 161,30 | 8,21 |

# Pictures of all test samples

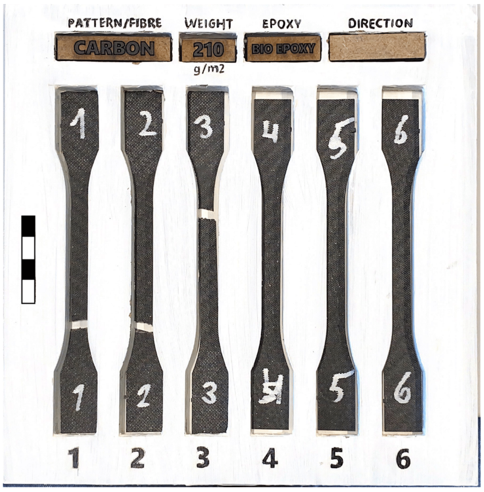



Figure 1: CAR-210

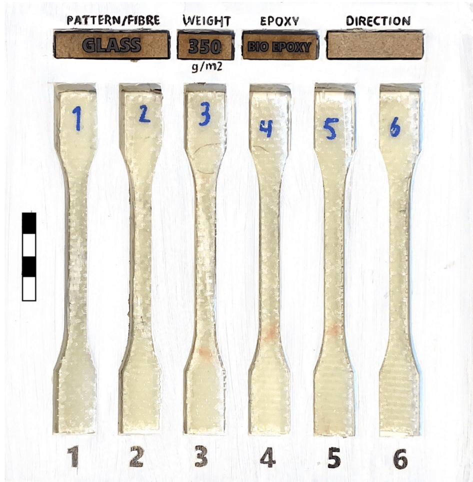



Figure 2: GLAS-350

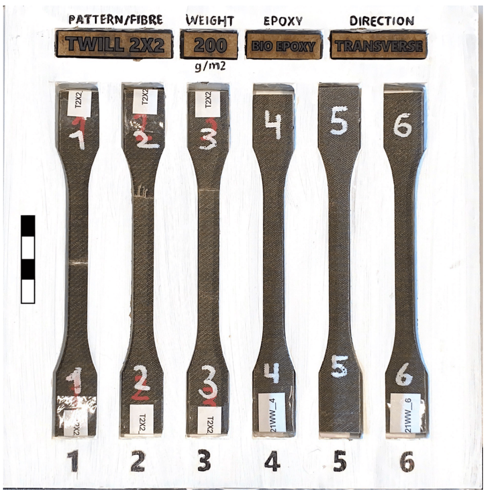



Figure 3: T2X2-200-WEFT

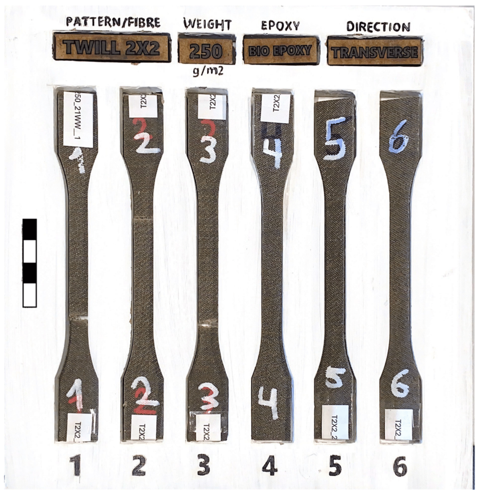



Figure 4: T2X2-250-WEFT

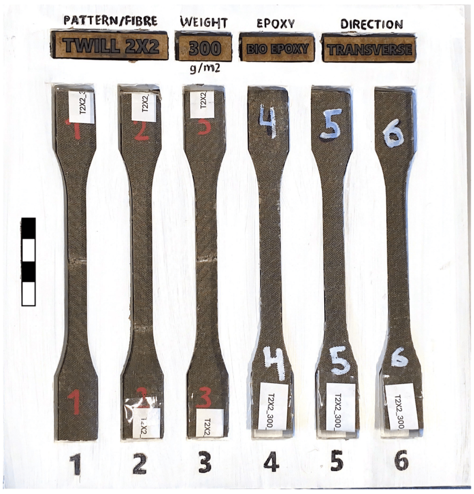



Figure 5: T2X2-300-WEFT


Figure 6: T2X2-200-WEFT-set2

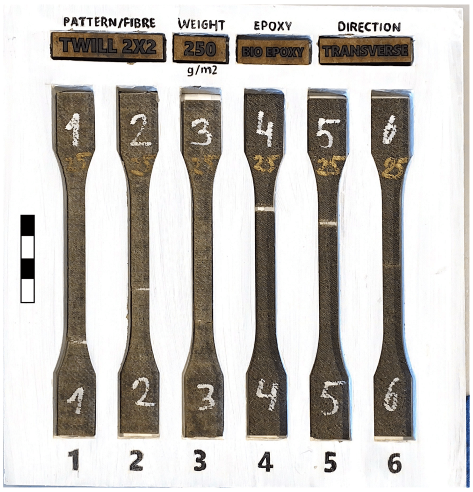



Figure 7: T2X2-250-WEFT-set2

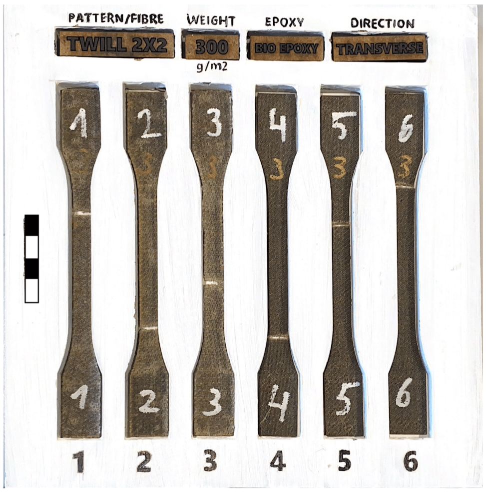



Figure 8: T2X2-300-WEFT-set2

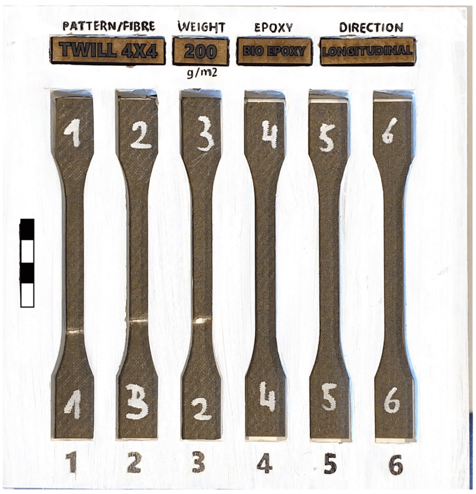



Figure 9: T4X4-200-WARP

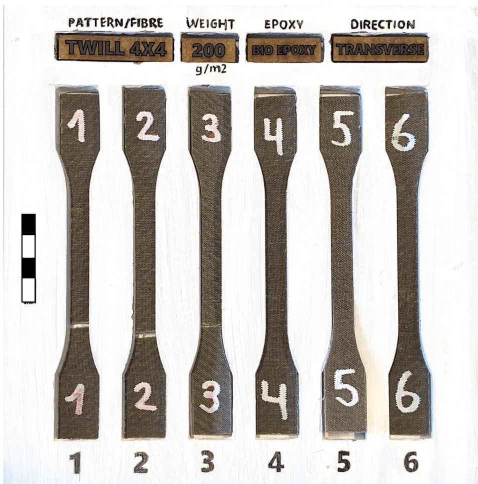



Figure 10: T4X4-200-WEFT

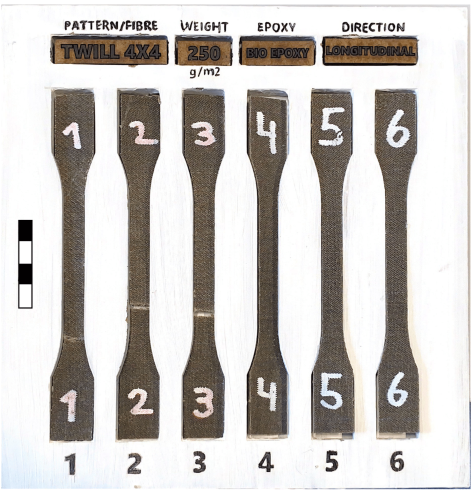



Figure 11: T4X4-250-WARP

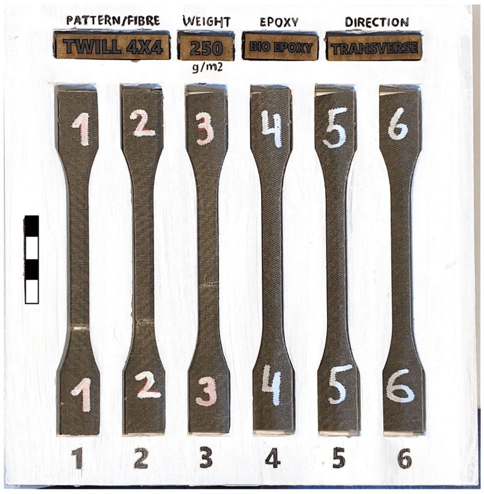



Figure 12: T4X4-250-WEFT

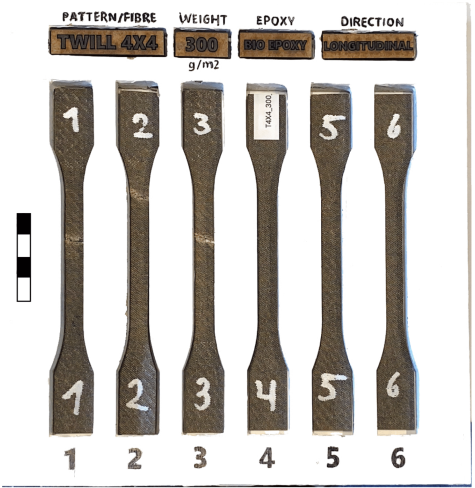



Figure 13: T4X4-300-WARP

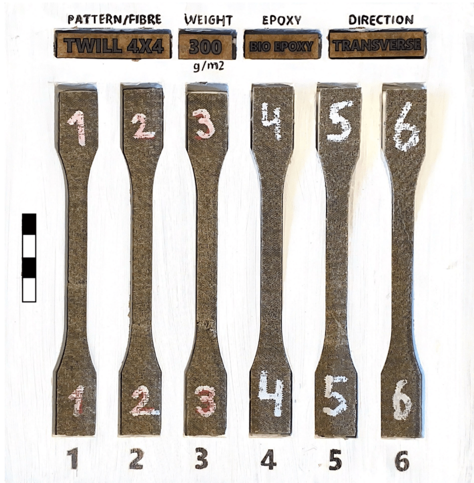



Figure 14: T4X4-300-WEFT

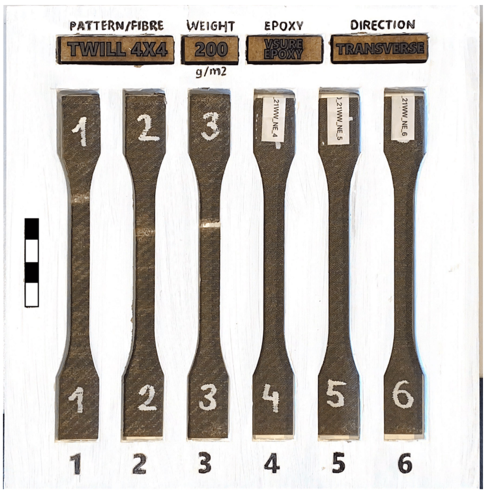



Figure 15: T4X4-200-WEFT-VsureEpoxy

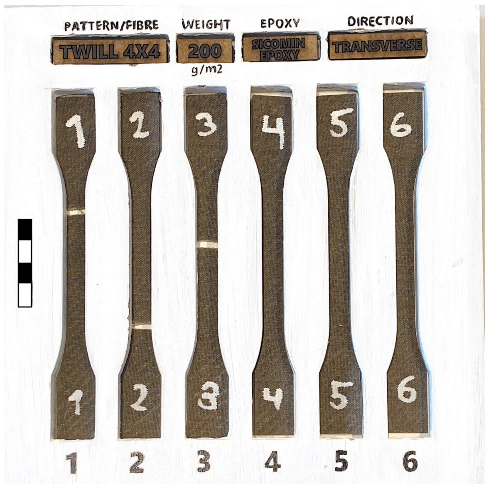



Figure 16: T4X4-200-WEFT-SicominEpoxy

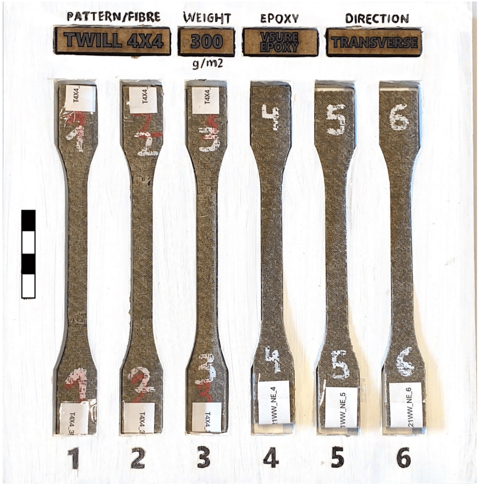



Figure 17: T4X4-300-WEFT-VsureEpoxy

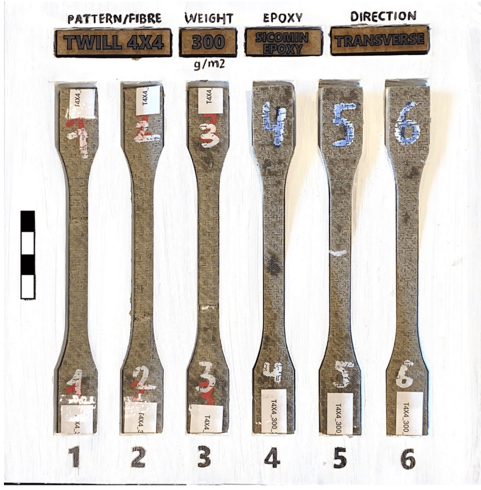



Figure 18: T4X4-300-WEFT-SicominEpoxy

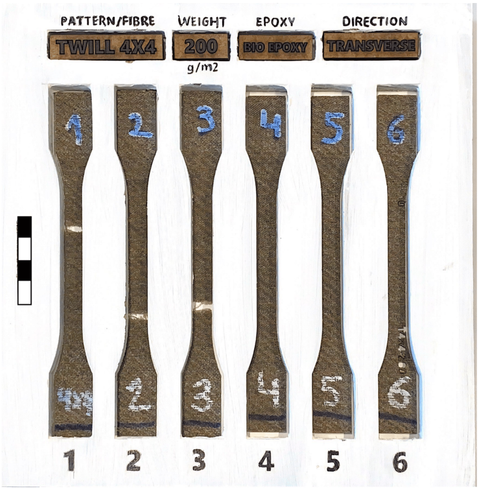



Figure 19: T4X4-200-WEFT-set2


Figure 20: T4X4-250-WEFT-set2


Figure 21: T4X4-300-WEFT-set2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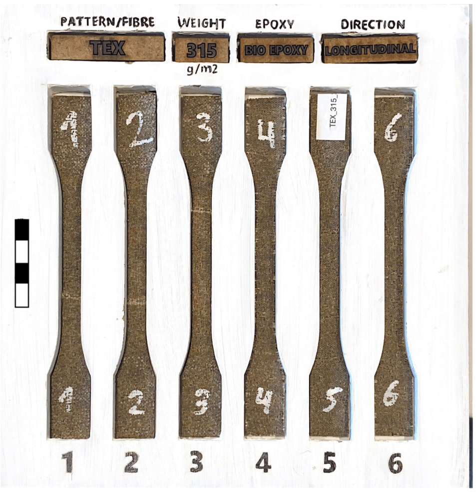


Figure 22: TEX-315-WARP


Figure 23: TEX-315-WEFT

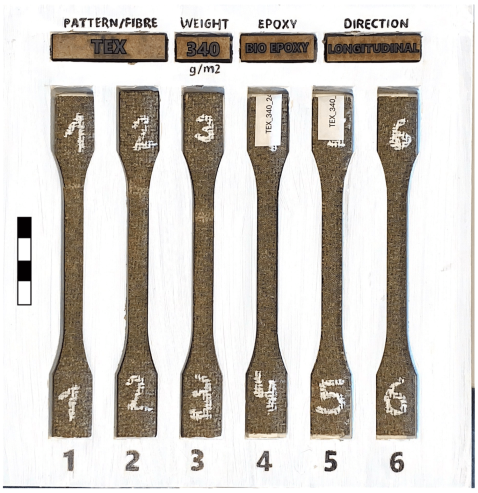


Figure 24: TEX-340-WARP

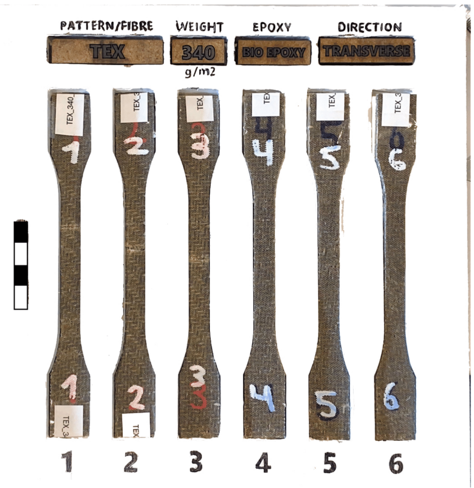


Figure 25: TEX-340-WEFT

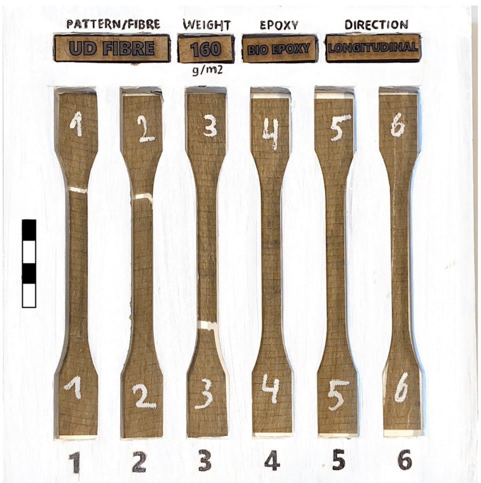


Figure 26: UD-1l-WARP

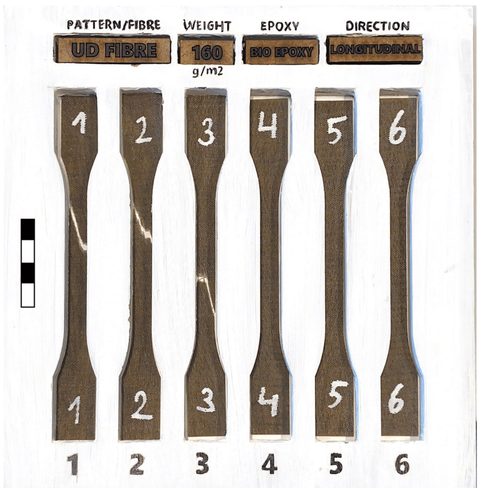


Figure 27: UD-2l-WARP

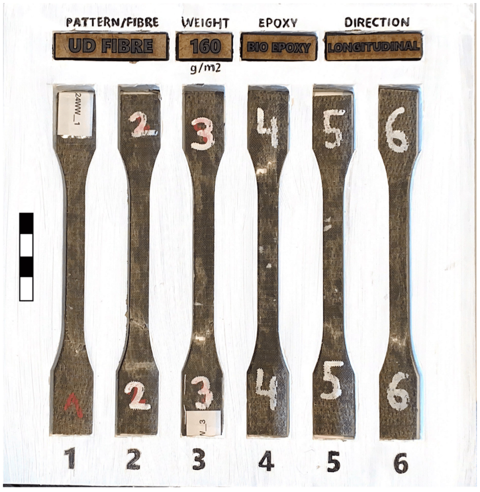


Figure 28: UD-3l-WARP

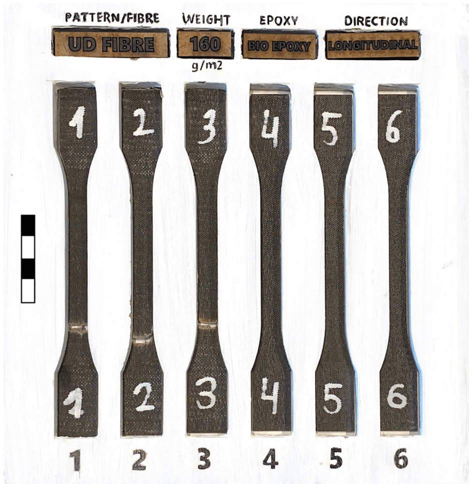


Figure 29: UD-6l-WARP

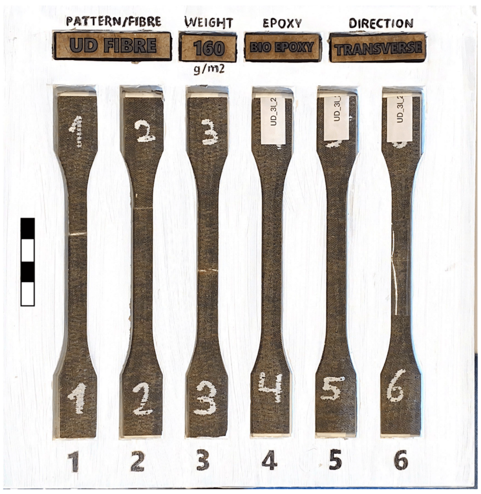


Figure 30: UD-3l-WEFT

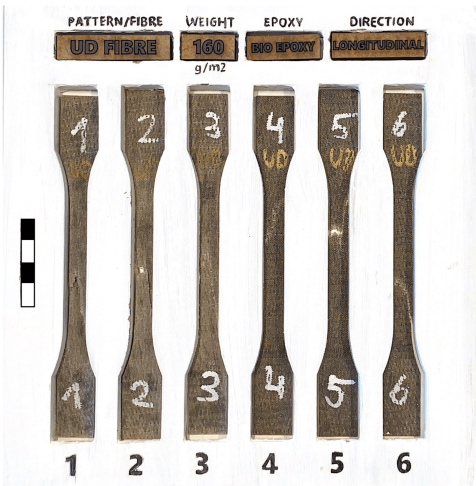


Figure 31: UD-3l-WARP-set2