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CHARACTERIZING THE BASE PROPERTIES OF A UNIDIRECTIONAL FLAX-EPOXY COMPOSITE MADE OF A UD-MAT REINFORCEMENT

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ABSTRACT

This work aims to characterize a unidirectional (UD) flax-epoxy composite for its base stiffness and strength properties in view of future developments of numerical models. Focusing on an innovative UD-mat reinforcement developed using a papermaking process, the tensile, shear, and compressive testing in the fiber longitudinal (0°) and transverse (90°) orientations are performed at a 40% fiber volume fraction. The results highlight the known bilinear behavior for the longitudinal tension while nonlinear responses for the shear and compressive tests are observed. The presence of the mat binder slightly reduces the tensile and compressive moduli in the fiber direction while enhancing them transversely. A modest increase in the shear modulus with a slight reduction in strength were observed. Globally, the results bring the basic ply properties required for future finite element simulations of composite laminates using the flax UD-mat as reinforcement.

1 INTRODUCTION

Natural fiber-reinforced composites (NFRC) are emerging as an interesting alternative to traditional synthetic fiber composites. This shift towards materials with a lower environmental footprint is particularly pronounced in the domain of natural fibers, with flax fibers as interesting prospects due to their advantageous mechanical properties and environmental benefits [1, 2]. Despite the potential of NFRC, their integration into complex composite structures poses significant challenges, primarily due to their variability in mechanical performance and the difficulties in achieving consistent adhesion with polymer matrices [3].

In response to these challenges, this study focuses on an innovative reinforcement for composite laminates combining a unidirectional (UD) flax layer with a low-density mat layer (serving as a binder for the UD layer) to enhance the mechanical properties in the axial and transverse directions of the resulting UD composite [4, 5, 6]. The objective is to characterize the UD flax-epoxy composites to determine the tensile, shear, and compressive properties in longitudinal and transverse orientations. Such detailed characterization is essential for the future development of numerical models of composites using these UD-mat reinforcements. Numerical models for natural fiber composites are under development for structural applications [7]. So, the findings are expected to provide valuable insights that could lead to a more effective use of natural fibers in composites, thereby supporting the advancement of sustainable material solutions for the industry [8].

2 EXPERIMENTAL PROTOCOLS

2.1 Materials

This study utilizes flax fibers and SikaBiresin® epoxy 820 resin as primary materials. The flax fibers, sourced from Safilin Inc. (Szczytno, Poland), are used in two formats: Tex 400 yarns for the unidirectional (UD) layer and Tex 5000 ribbon for the mat layer. The resin was chosen for its low viscosity to facilitate wetting of the reinforcement and evacuation of air during impregnation of the reinforcement. This system includes a base epoxy resin (SikaBiresin® CR72) and a hardener (SikaBiresin® CH72-3), mixed at an 18% mass ratio.

2.2 Fabrication process for the flax UD-Mat reinforcement

The manufacturing process for the flax UD-mat reinforcement involves three main steps, developed in previous works, and refined over time [4, 5, 6]. Figure 2.1 illustrates the complete process. The step 1 consists in the preparation of the UD layer. It begins with the manual winding of flax yarn around an aluminum plate. A meticulous alignment of the UD yarns is performed using a steel plate to finely adjust the orientation and spacing of the individual yarns. For the mat layer (step 2), 12 g of fibers are cut to 6 ± 1 mm from the Tex 5000 ribbon and dropped in 20 liters of water to get a homogeneous solution of short fibers and water by thoroughly agitating the solution.

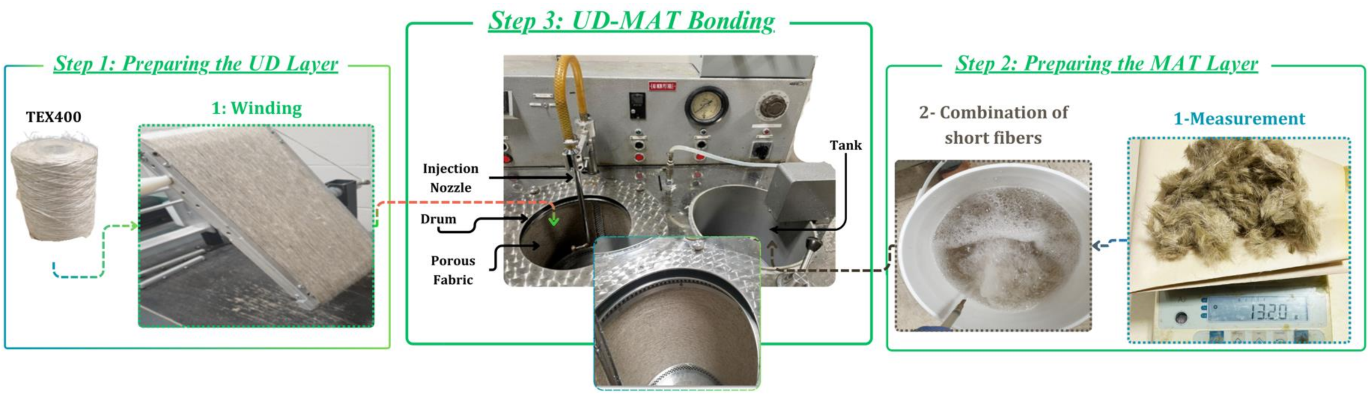


Figure 2.1 : Overview of the UD-Mat flax fiber reinforcement manufacturing process.

Step 3 concerns the formation of the UD-Mat reinforcement layer. It consists in the use of a dynamic former designed to project the fiber-water mixture onto a moving fabric (containing the pre-placed UD layer) installed inside a rotating spinning drum. The wet reinforcement is finally dried (over a drying roll) and characterized for its grammage (weight per unit area), fiber distribution, and the absence of visual defects.

2.3 Composite plate molding process

Composite plates were produced using the Resin Transfer Molding (RTM) process, where the mold was preheated to 90°C to ease resin flow and impregnation of the fibers. The mold cavity thickness was controlled with aluminum spacers located at the mold corners. After filling, the plates are cured for 4 hours in the oven and post-cured at 90°C for 2 hours. Table 2.1 presents the ply stacking sequence for each manufactured plate and the fiber volume percentage (V_f), which was set at around 40%. A porosity level below 2% was ensured through visual inspection with light to detect major defects and a recalculation of V_f after molding, confirming minimal voids in the material.

Tableau 2.1 : Ply stacking sequence for each plate, the respective number of layers, and their fiber volume percentage V_f (%)

Plate designation	UDM-01	UDM-02	UDM-03	UDM-04	UDM-05
Ply stacking sequence	$[0]_8$	$[90]_8$	$[0]_8$	$[90]_8$	$[+45/-45]_4$
V_f (%)	40,71 ± 0,47	40,02 ± 0,11	40,22 ± 0,26	41,07 ± 0,13	40,71 ± 0,51

2.4 Mechanical characterization tests

Characterization tests were conducted using an Instron-UL50 LM tension-compression testing machine equipped with a 50 kN load cell. For the tensile tests, an Instron 2620 extensometer with a 50 mm gauge length was used to measure the axial deformation. Tensile testing was conducted according to ASTM D3039 to measure the tensile modulus and strength in the axial ($[0_8]$) and transverse ($[90_8]$) directions. Strain gauges (CEA-13-240UZA-120) from Intertechnology Inc. (Toronto, Canada), were used to measure strain in both longitudinal and transverse directions, allowing the determination of the modulus and Poisson's ratios (ν_{12} and ν_{21}). Compression testing was conducted following ASTM D6641, using uniaxial and biaxial strain gauges (C2A-13-125LW-120 and CEA-06-125UT-120 respectively). They were positioned on opposite sides of the sample to ensure that the relative difference between the strain measurements of the two gauges remains below the 10% threshold recommended to avoid excessive bending or buckling deformation. Finally, shear testing was performed under ASTM D3518, involving the $[\pm 45]_4$ layup specimens, with strain gauges placed at 0° and 90° from the load axis, thus enabling the calculation of shear modulus and maximum shear strength. For most of the tests, at least 5 coupons were tested except for tests in the compressive transverse direction, where 4 coupons were tested.

3 RESULTS

3.1 Tensile tests

3.1.1 Longitudinal tensile test

The longitudinal tensile test showed a bilinear stress-strain behavior, depicted in Figure 3.1a, with a distinct transition point around 0.1 to 0.15% strain, which is typical for unidirectional flax fiber composites [7]. The primary modulus of elasticity (E_{11p}) averaged 26.83 ± 0.51 GPa, while the secondary modulus (E_{11s}) was 16.29 ± 0.21 GPa with a Poisson's ratio ν_{12} of 0.45 ± 0.02. The average tensile strength (F_{1t}) is 248.66 ± 1.10 MPa. Figure 3.1b shows a failed specimen. Figure 3.1c shows further details of the microstructural failure mechanisms, such as fiber-matrix decohesion and fiber pull-out. Although the failure modes do not directly show the effect of the mat, comparing the modulus and strength results with Saadati [7] and Habibi [8] works, as well as other literature, demonstrates the mat's influence on the composite's mechanical integrity.

3.1.2 Transverse tensile test

The transverse tensile test exhibited a non-linear stress-strain behavior as shown in Figure 3.2a. The average transverse modulus of elasticity (E_{22}) and tensile strength (F_{2t}) were respectively 6.48 ± 0.25 GPa and 36.59 ± 1.20 MPa. These results represent substantial improvements over those in the literature for similar UD composites molded without the presence of the mat binder [7]. The obtained transverse Poisson's ratio ν_{21} was 0.091 ± 0.006. Figure 3.2b shows a typical coupon after failure, highlighting the composite’s response to transverse stresses.

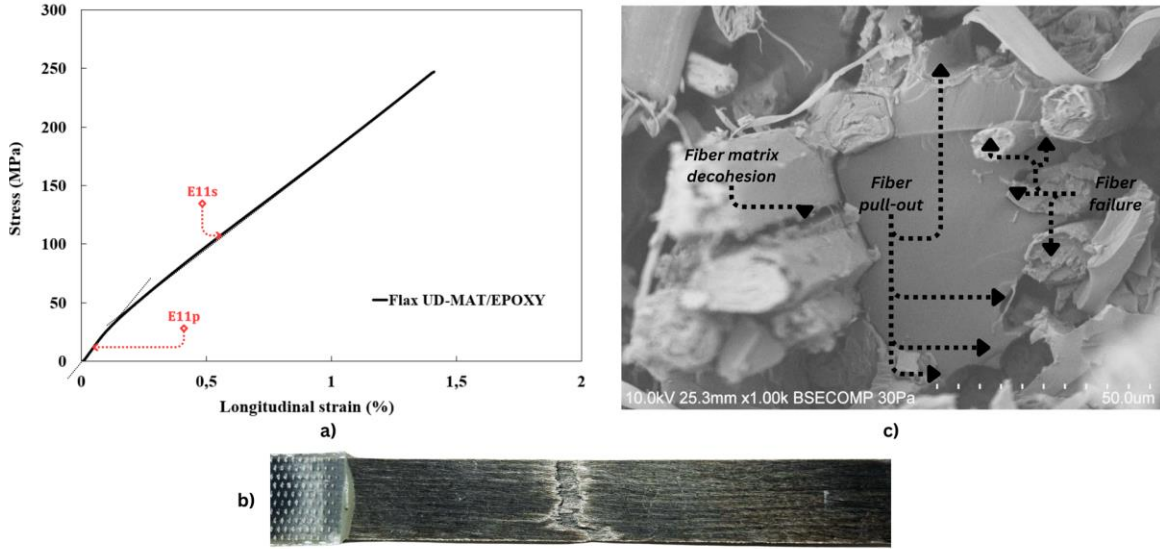


Figure 3.1 : Longitudinal tensile test results for the [0_8] configuration: (a) Stress-strain curve; (b) Typical failure modes; (c) SEM image.

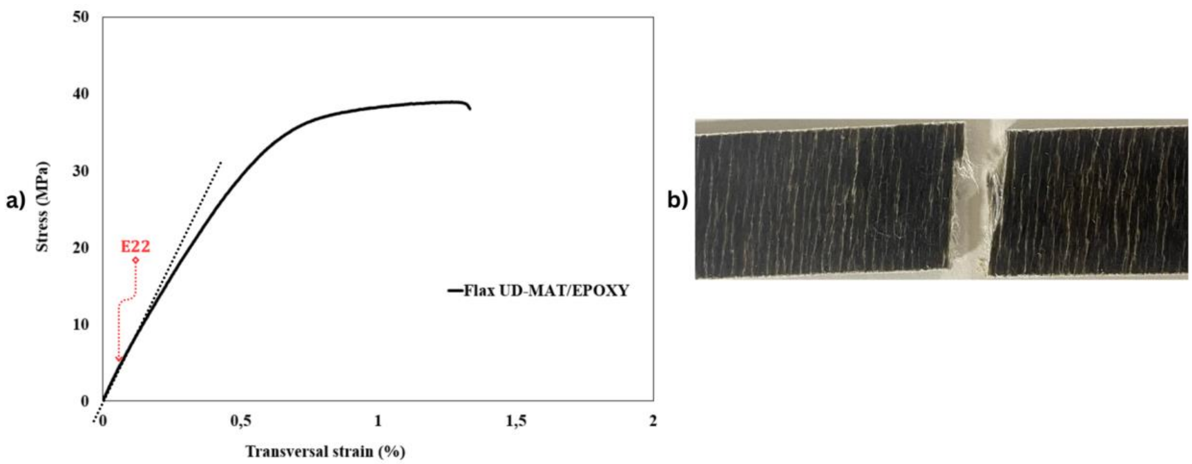
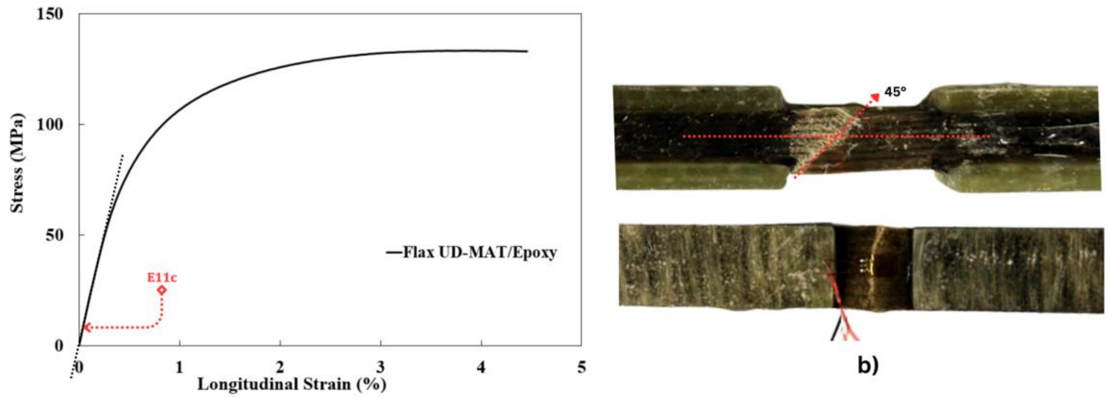


Figure 3.2 : Transverse tensile test results for the [90_8] configuration: (a) Stress-strain curve; (b) Typical failure modes.

3.2 Compression tests

3.2.1 Longitudinal compression test

The longitudinal compression tests showed a non-linear stress-strain response, transitioning from linear to a non-linear behavior at a strain around 0.3% to 0.4%, as illustrated in Figure 3.3a. This behavior aligns with findings from previous studies [7, 9], which document similar mechanical responses in unidirectional flax fiber composites under compression. The average longitudinal modulus of elasticity (E_{11}) was 23.05 ± 0.24 GPa, and the compressive strength (F_{1c}) was 128.33 ± 4.45 MPa. The Poisson's ratio v_{12} obtained was 0.46 ± 0.06. The specimen failure, shown in Figure 3.3b, conforms to ASTM D6641 standards and reveals a fracture at an angle of about 45 degrees from the loading axis. This failure mode is characteristic of the non-linear behavior of these composites, indicating some fiber local misalignment, micro-buckling, and subsequent matrix plastic deformation leading up to the final fracture pattern [7].

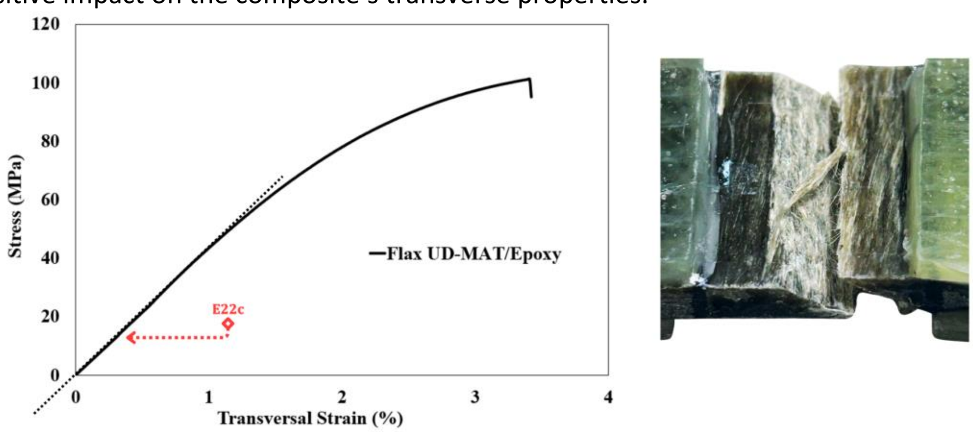


a)

Figure 3.3 : Longitudinal compression test results for unidirectional flax fiber composites: (a) Stress-strain curve; (b) Typical failure modes.

3.2.2 Transverse compression test

The transverse compression tests showed two phases in the stress-strain curve, with an initial linear response transitioning to a non-linear one at around 1% strain, as shown in Figure 3.4a, with the failure mode in Figure 3.4b. The initial elastic behavior was followed by the onset of failure mechanisms, such as microcracking, in the non-linear portion. Compared to the results of Saadati et al. [7] for UD flax laminate, enhanced Young's modulus, averaging to (E_{22}) 5.28 ± 0.28 GPa, and a significant increase in compression strength (F_{2c}) at 102.75 ± 1.26 MPa underscore the mat binder's positive impact on the composite's transverse properties.



a) b)

Figure 3.4 : Transversal compression test results for the $[90_8]$ configuration: (a) Stress-strain curve; (b) Typical failure modes.

3.3 Shear tests

The shear test revealed a non-linear stress-strain behavior (Figure 3.5a), indicating a transition from elastic to inelastic deformation. The average shear modulus (G_{12}) was 2.10 ± 0.07 GPa, and the shear strength (F_6) was 39.88 ± 0.18 MPa. Figure 3.5b shows a typical failure mode, including intralaminar shear matrix fracture, delamination, and fiber-matrix decohesion at the UD-mat interface. These results align with values reported by Saadati et al. [7] and Liang et al. [9]. Compared to unidirectional flax composites with a 40% fiber volume fraction [9], there was a 9.38% increase in G_{12} but a 10.72% decrease in F_6, possibly due to differences in testing methods and the presence of the mat, which is less resistant to shear.

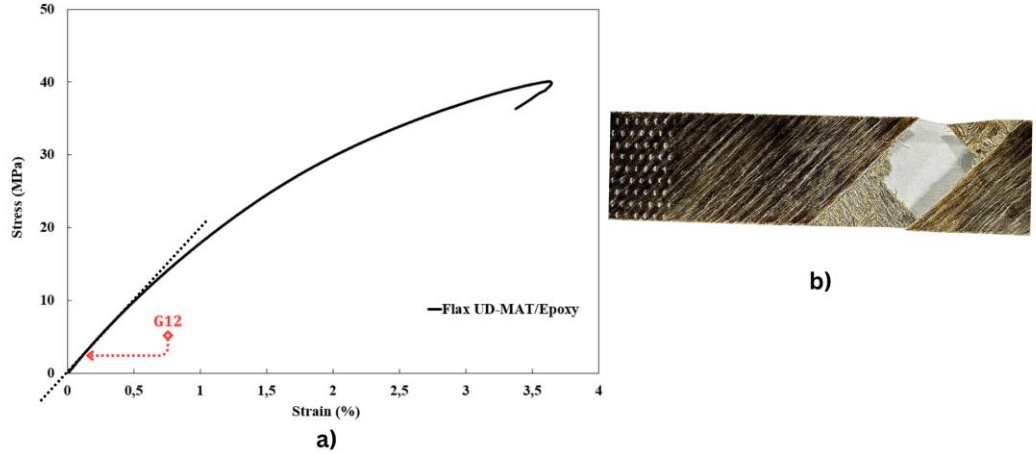


Figure 3.5 : Shear Test Results for Unidirectional Flax Fiber Composites: (a) Stress-strain curve; (b) Typical failure modes.

4 CONCLUSION

This study successfully characterized the mechanical properties of a unidirectional flax-epoxy composite reinforced with a UD-mat reinforcement. The presence of the mat binder slightly reduced the tensile and compressive moduli in the fiber direction while enhancing them transversely. Additionally, shear tests showed a modest increase in the shear modulus with a slight reduction in strength. These findings are crucial for the future developments of numerical models for NFRC. Overall, this research advances the understanding of flax fiber composites.

5 REFERENCES

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