Testing and Evaluation of the Mechanical Strength of New Epoxy and Silk Composite Materials

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ABSTRACT

This study describes the testing and assessment of the mechanical strength of a novel epoxy–silk composite material. Owing to their attractive characteristics, including high strength-to-weight ratio, low density, and enhanced mechanical performance, composite materials have received significant interest from various industries. This study aims to investigate the development and categorization of a novel composite material consisting of a Silk-epoxy Reinforced Polymer (SRP). The purpose of this study was to test and analyze the mechanical behavior of six layers of silk and epoxy composites through tensile, impact, hardness, and microscopy tests, followed by a comparison with another composite material consisting of Fiberglass-Reinforced Polymer (FRP). Both specimens were produced using a hand-layup approach, and the specimens were cut following the ASTM specifications for conducting the experiments. The experimental results confirmed that the maximum tensile stress for the novel composite material SRP was 8.56 MPa, with an elastic modulus of 640 MPa and Rockwell hardness value of 5.3 HV. The FRP composite exhibited good results, with a maximum tensile stress of 78.5 MPa, elastic modulus of 1800 MPa, and Rockwell hardness value of 33.3 HV. These results can be used in potential engineering applications, such as water tanks and pipelines.

Keywords-silk-reinforsed polymer; tensile stress; impact strenght; silk; epoxy; fiberglass

I. INTRODUCTION

A composite material is created by combining two or more materials with different characteristics. It contains two types of constituents: one is called reinforcement, and the other is the matrix where the reinforcement is embedded. The fabrication of new composite materials requires at least one part of each type [1]. The primary function of the matrix constituent is to transfer the stress between the reinforcing silk (holding silk together) and protect the silk from mechanical and/or environmental damage, while the reinforcement constituents in the matrix improve the mechanical properties, such as strength and stiffness. The constituents are combined in such a way that they maintain their physical properties, so that the composite takes advantage of their superior properties without compromising their weaknesses. The composite materials are expected to have advantages, such as a superior strength-to-weight ratio, light weight, resistance to corrosion, and sequestration of carbon dioxide (reducing the greenhouse effect) [2, 3]. Therefore, the composite materials have attracted considerable attention in various industries [4] because the growing environmental consciousness has resulted in more stringent sustainability regulations and spurred businesses to develop eco-friendly products [5-7].

II. METHODOLOGY

All specimens and raw materials were conditioned at 23 ± 2 °C and 50 ± 5% relative humidity for 48 h before the tests, following the ASTM D618 standards. SRP can form composites with excellent mechanical performance. This section discusses the fabrication process of SRP and FRP composites, as illustrated in Figure 1.

Fig. 1. The procedure for creating new materials.

A. *Materials and Experimental*

Raw material selection: The silk and epoxy used in the current study were high-quality raw materials that are readily available.

Matrix selection: Epoxy is a high-strength adhesive, dimensionally stable, and chemically resistant, making it best suited as a matrix [8, 9]. Preparation of the composite: Six layers of silk were combined with epoxy [6] and stacked at various angles: 0°, 45°, 90°, and -45°, as shown in Figure 2.

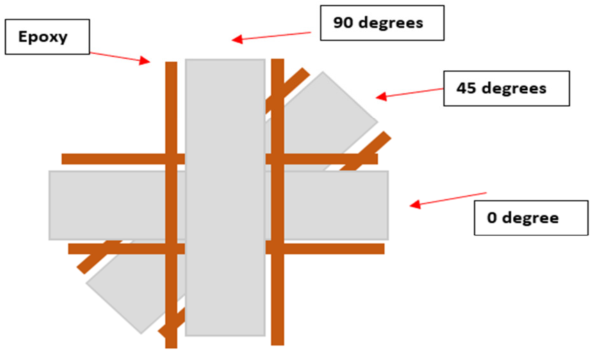

Fig. 2. SRP and FRP layering orientation.

Preparation of test samples: Rectangular specimens (2 mm) were manufactured and tested following the ASTM D3039 (tensile), ASTM D256 (impact), and ASTM E384 (hardness) standards. Five identical specimens were tested for each method to ensure statistical reliability (n = 5). Additionally, the specimens were characterized by Scanning Electron Microscopy (SEM) [10].

III. EXPERIMENTAL RESULTS

A. *Tensile Measurements*

For the tensile characterization, a Universal Testing Machine (UTM) was used with a certified (calibrated to the ISO 7500-1:2018) model XYZ-100. Table I lists the results of the tensile measurements and standard deviations to indicate variability and ensure consistent and replicable results. The values are the means of five independent test measurements, similar to the ones shown in Figures 3-6. Figures 3 and 4 show the force and strain curves of the SRP sample, respectively. The corresponding curves for the FRP samples are displayed in Figures 5 and 6.

TABLE I. TENSILE TEST RESULTS

Sample	SRP	FRP
Area (mm^2)	78.5	78.5
Modulus of elasticity (MPa)	640	1800
Maximum force (N)	586	5931
Maximum stress (MPa)	8.56	78.5
Yield stress (MPa)	7.74	74.25
Fracture stress (MPa)	2.15	12.55
Strain at fracture (%)	13.6	18.2
Std. deviation (±MPa)	0.52	1.24

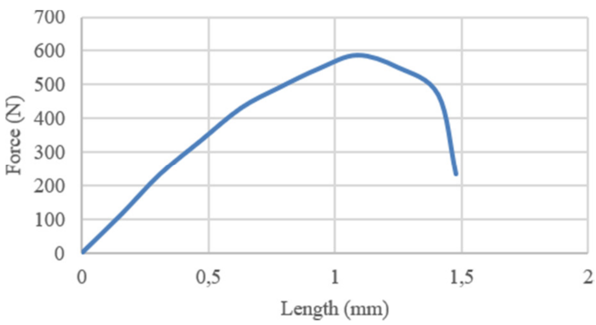

Fig. 3. The force exerted on the 2 mm SRP specimen.

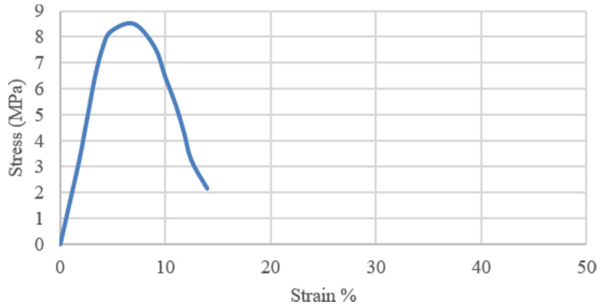

Fig. 4. The stress-strain curve of the 2 mm SRP specimen.

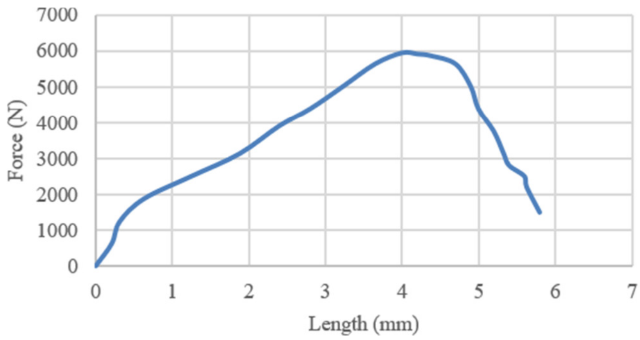

Fig. 5. The force exerted on the 2 mm FRP specimen.

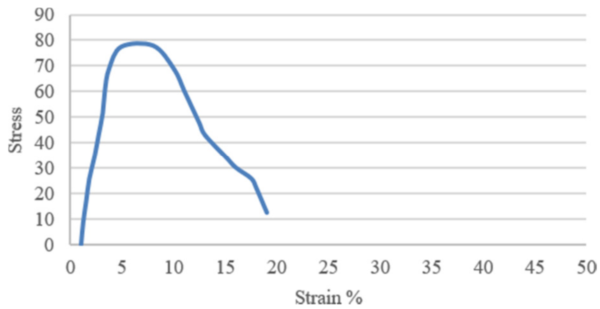

Fig. 6. The stress-strain curve of the 2 mm FRP specimen.

B. *Impact Measurements*

The Charpy test is a method used to measure a material's ability to absorb energy when a blow is delivered to it. The specimens were notched and placed horizontally on two supports, as shown in Figure 7, and a pendulum was dropped to strike the specimen. The energy absorbed by the specimen was then measured [11, 12]. Table II presents the results.

Fig. 7. Notched specimens for the impact test.

TABLE II. CHARPY IMPACT TEST RESULTS

Specimen	Impact angle	Absorbed energy (J)
SRP	262.4	4.036
FRP	255.0	11.256

C. Hardness Measurements

Hardness tests were conducted to measure the material's resistance to indentation or deformation. The specimens were placed between the two plates, and then the load was applied to the upper plate. The indentation depth created by the load was then measured and the results are portrayed in Table III.

TABLE III. HARDNESS TEST RESULTS

Sample	Vickers Hardness HV	Brinell Hardness HB	Rockwell Hardness HRC
SRP	328	311	33.3
FRP	178	170	5.3

D. Morphology Characterization

SEM images were acquired to examine the surface morphology of the SRP composite. The microstructure of the composite is shown in Figures 8-10, and is captured at a magnification of 500x. A resolution indicator in the form of a 50 µm scale bar was added to the SEM image for the dimensional context. The SEM images reveal the distribution of the silk fibers within the epoxy matrix. Clear evidence of fiber-matrix debonding, resin-rich zones, and voids is observed in multiple regions. These defects indicate a loss of interfacial adhesion, which may have contributed to the lower tensile strength and energy absorption recorded for the SRP compared to the FRP. Additionally, the apparent fiber pull-out features and matrix cracks support the idea that the physical interactions between the silk fibers and the epoxy resin were not sufficient in this case. On the contrary, the FRP showed tighter fiber packing, better wetting of the fibers, and very few voids (not shown here), which is evident from its superior mechanical performance, as observed in the experiments. These microscopy results support the initial hypothesis that the fiber-matrix interactions play a significant role in determining the strength of the composites.

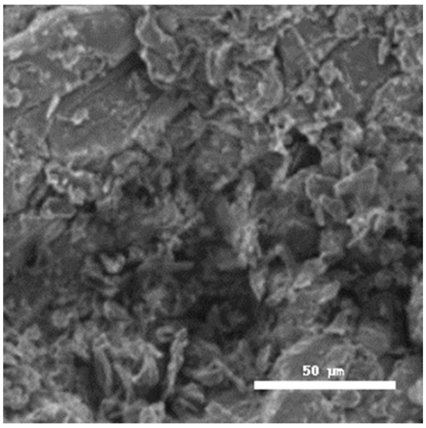

Fig. 8. SEM image (500×) of a 2 mm SRP specimen showing fiber distribution, interfacial debonding, and voids.

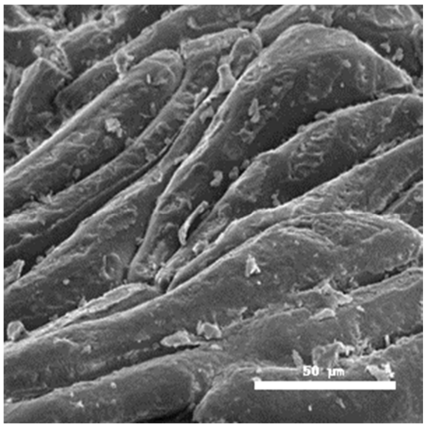

Fig. 9. SEM image (500×) of a 2 mm neat epoxy fracture surface showing fiber distribution, interfacial debonding, and voids.

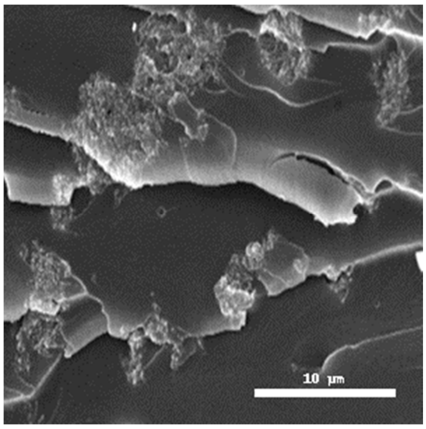

Fig. 10. High-resolution SEM image of the epoxy fracture surface.

IV. DISCUSSION

The results of the mechanical tests show that the mechanical properties of SRP differ significantly from those of FRP, as summarized in Tables I–III and shown visually in Figures 3–9. According to the tensile tests (Table I), the SRP specimen exhibited a maximum tensile stress of 8.56 MPa and an elastic modulus of 640 MPa (Figure 4). However, the tensile stress of the FRP specimen was significantly greater at 78.5 MPa and the elastic modulus was 1800 MPa (Figure 6). These differences are also demonstrated in the stress-strain plots in Figures 4 and 6, which indicate that the FRP exhibits superior stiffness and ductility compared to the SRP. The impact test results (Table II and Figure 7) revealed that the energy absorption capacity of the FRP was nearly three times greater (11.256 J) than that of the SRP (4.036 J). This suggests that the fiberglass reinforcement has a superior shock resistance owing to better fiber-matrix interactions. The hardness test results listed in Table III also follow this trend. The Rockwell hardness of the SRP was 33.3 HRC, whereas that of the FRP was only 5.3 HRC, implying that the silk-reinforced composite is less prone to localized plastic deformation. The differences were similar for the Vickers and Brinell hardness values. The microstructure revealed from the SEM images shows the stains (resin) and fibers of the composites. Additionally, the microstructure appears to have voids and an inconsistent arrangement across the fiber bundle, which may explain the less favorable mechanical performance exhibited by the SRP. Figure 11 presents a side-by-side visual summary of the mechanical properties and shows that the FRP is mechanically superior to the SRP for all the measured properties. All results discussed here are consistent with the microstructural observations and the previously described mechanical behavior of the materials. Ultimately, these comparisons show that the FRP appeared to be qualitatively superior in terms of mechanical performance, while SRP offered moderate mechanical performance, which may have some applications, where cost or biodegradability is of concern.

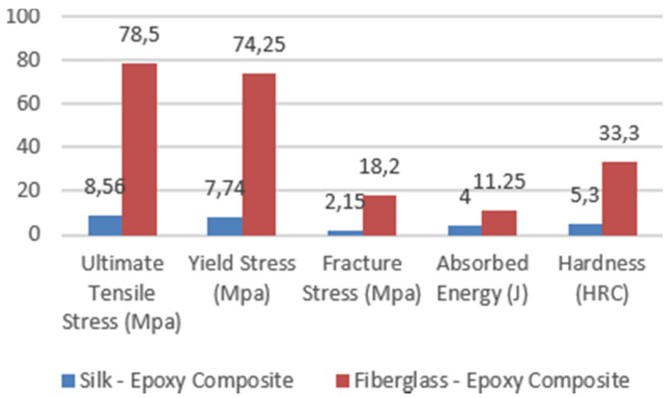

Fig. 11. Mechanical property comparison between SRP and FRP.

V. CONCLUSIONS

In this study, three mechanical tests: tensile, impact, and hardness tests and morphological characterization, were performed to determine the mechanical properties of a new composite material made of Silk-epoxy Reinforced Polymer (SRP) and compared with a Fiberglass-Reinforced Polymer (FRP) composite. The results indicated that the FRP composite was three times better than the silk–epoxy composite in almost all mechanical properties, owing to the enhanced bonding of the fibers and voids existing in silk. Although the fibers are a better reinforcing material than silk, they are very expensive and cannot be recycled, whereas silk is cheaper, recyclable and biodegradable. The results from the Universal Test Machine (UTM) experiments were as follows: from the tensile test, the maximum stress of SRP was found to be 8.54 MPa with a 7.74 MPa yield stress and 640 MPa elastic modulus. According to the impact test results, the SRP can absorb up to 4.0 J of energy and has a hardness value of 5.3 HRC based on the Rockwell testing machine. However, FRP has a maximum stress of 78.5 MPa with 74.25 MPa yield stress and 1800 MPa elastic modulus. FRP can absorb up to 11.2 J of energy, according to impact test results and has a hardness value equal to 33.3 HRC. The distinctive feature of this study is the utilization of untreated natural silk reinforcement aligned in a quasi-isotropic configuration, aiming to explore cost-effective and partially biodegradable composite alternatives.

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