Mechanical Properties of the Woven Natural Fiber Reinforced Sheet Stocks Used for the Laminated Object Manufacturing (LOM) Rapid Prototyping Process

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ABSTRACT: This paper investigates the mechanical properties of potential sheet stocks of a Laminated Object Manufacturing (LOM) 3D printer made using woven jute fabrics infused with two types of bioresin. The combinations of bioresins and the reinforcements would make green sheet stocks that are expected to be environmentally friendly comparing to traditional synthetic fibers infused with regular resins. Pure resin samples are also involved for comparison purposes. Both tensile and flexural properties are measured following ASTM D638 and D3039 standards (for tensile tests) as well as ASTM D790 and D7264 standards (for flexural tests). Detailed processes of specimen preparation followed by test procedures are introduced. Tensile strengths and moduli as well as flexural strengths and moduli are obtained for comparison. Based on the study of the mechanical properties of both types of pure resin and woven jute fiber-reinforced composites, the research team concluded a few important findings that could be used as guidelines in the sheet stock selection and preparation for the LOM 3D printer that is currently under the building process.

1. INTRODUCTION

Rapid prototyping (RP) is a family of technologies used to fabricate engineering prototypes of parts in minimum possible lead time based on a computer-aided design (CAD) model of the item. The traditional method of fabricating a prototype part is machining, which can require significant lead times—up to several weeks, sometimes even longer, depending on part complexity, difficulty in ordering materials, and scheduling production equipment. A number of rapid prototyping

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techniques are now available that allow a part to be produced in hours or days rather than weeks, given that a computer model of the part has been generated on a CAD system. All of these technologies work by adding layers of material to an existing part or substrate. Laminated-object manufacturing (LOM) produces a solid physical model by stacking layers of sheet stock that are each cut to an outline corresponding to the cross-sectional shape of a CAD model that has been sliced into layers. The layers are sequentially stacked and bonded on top of previous ones to build the part. After cutting, the excess material in each layer remains in place to support the part during building. Traditional starting materials in LOM include paper, cardboard, and plastic in sheet stock form, with a thickness from 0.05 to 0.50 mm (0.002 -0.020 in) [1]. However, these starting materials come with limited mechanical properties and therefore their engineering applications are limited. Researchers have tried to implement composite materials, especially ceramic-based materials, which include monolithic ceramics, glass and glass ceramics, and ceramic composites [2]. Klosterman et al. [3] developed a curved layer LOM process for monolithic ceramics and ceramic matrix composites. Gomes, et al. [4] explored the detailed fabrication process of using a glass-ceramic substrate, based on the LZSA system, by LOM using water-based cast tapes. The thermal, mechanical, and electrical properties of LZSA glass-ceramic laminates fabricated by LOM make them potential candidates for substrate applications. Weisensel et al. [3] demonstrated the fabrication of dense biomorphous SiSiC laminar composites by LOM. They concluded that the microstructure of the final SiSiC-ceramics depends on the density, porosity, and pore size distribution of the biocarbon preform, which can be varied by changing the parameters of the LOM-processing. Windsheimer et al. [4] reported a novel SiC-filler-loaded cellulosic paper, so-called preceramic paper, that was developed and processed by LOM with the eventual goal of fabricating dense Si-SiC objects with complex shapes. In contrast to common paper, the preceramic paper contains a substantially higher level of the filler phase. The microstructural evolution and dimensional changes of the LOMed bodies were investigated, and the mechanical properties of the composites were determined. Due to their laminar structure, a pronounced anisotropy was found for these objects, which strongly affects their mechanical behavior. Other engineering materials being used include fiber-reinforced composites and graphene foams. Tari et al. [7] reported using vinyl ester resin reinforced by E-glass fibers for making a unidirectional glass fiber mat as the sheet stock for the LOM process. This sheet stock was then used for making the resin transfer molds that are durable enough for producing I-beams. The authors also found this mold fabrication reduces the man-hours and lead time associated with conventional methods and therefore leads to significant savings in the manufacturing process. Luong et al. [8] developed a 3D Laser-induced Graphene (LIG) foam printing process based on LOM, combined with the newly developed subtractive laser-milling process to yield further refinements to the 3D structures. Various 3D graphene objects were printed by combining both techniques. The LIG foams showed good electrical conductivity and mechanical strength, as well as viability in various energy storage and flexible electronic sensor applications.

Synthetic fibers provide excellent mechanical properties and allow for versatile design possibilities. Yet environmental and economic concerns are stimulating research in the design and production of innovative materials for the aeronautic, railways, and automotive industries. Particularly attractive are new materials in which a good part is based on natural renewable resources, preventing further stresses on the environment [9]. Among these materials, Natural Fibers-Reinforced Composites (NFRC) are finding much interest as a substitute for glass or carbon-reinforced polymer composites thanks to their numerous advantages such as low cost, biodegradability, eco-friendly nature, relatively good mechanical properties, and a growing emphasis on the environmental and sustainability aspects of engineering materials [10]. Among all-natural fibers, jute fibers are easily available in fabric and fiber forms with good mechanical and thermal properties. The fibers are extracted from the ribbon of the stem, and are the most promising reinforcement material due to their high content of cellulose (61-72%), hemicellulose (14-20.4%), lignin (12-13%), and pectin (0.2%) [11]. In this paper, the sheet stock for the LOM 3D printing process is being made using woven jute fabrics infused and cured with two different bioresins. The two mechanical properties of these pre-made sheet stock, both tensile and flexural, are tested and then analyzed.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

Fiber reinforcements used in this research are woven jute fabrics with a fiber density of 13 threads per inch, and an average area density of 338g/m^2. The average thickness of a single ply of this burlap is 0.071 mm, as shown in Fig. 1. Two types of bioresin were used in this study: the first bioresin is a hard thermoplastic hydrovanilloin -diglycidyl ether phenoxy resin (Glass Transition Temperature T_g = 135°C), which can be cured under room temperature overnight. It was developed by Amarasekara et al. [12] as an effort in the development of novel renewable carbon-based monomers and polymers. Amarasekara and his team explored the potential of vanillin in the synthesis of new polymer materials, which could be prepared by reacting disodium salt of hydrovanilloin : epichlorohydrin with 1 : 2 mol ratio in an aqueous medium at 80°C. This oligomer could be cured with aliphatic diamines: 1,2-diaminoethane, 1,4-diaminobutane, 1,6-diaminohexane, and IPDA to give hard epoxy resins. Another bioresin tested is a commercial resin named Elium, developed by Arkema [13]. The adopted Elium 150 resin is a low viscosity liquid, thermoplastic resin for infusion and RTM processes. Through the use of the same low-pressure processes and equipment to produce thermoset composite parts, these formulations lead to the production of thermoplastic composites reinforced by continuous glass, carbon, or natural fibers. According to Arkema, the resulting thermoplastic composite parts show mechanical properties similar to those of parts made of epoxy resins while presenting the major advantages of being post-thermoformable and recyclable and offering new possibilities for composite/composite or composite/metal assemblies. Fiber-reinforced Elium parts can be thermoformed with heat and pressure. This process requires the heating of the consolidated part at 180-200°C for a few minutes, and the compression at a pressure between 5 and 20 bars depending on the reinforcement type and the thickness of the part [14].

Figure 1. Woven jute textile used as reinforcements in this study.

2.2 Mechanical Test Samples Preparation

All pure resin samples were made by pouring liquid resin into premade molds using molding clay (shown in Fig. 2) and let them cure for two days, while fiber-reinforced samples were prepared using the hand lay-up technique to allow tight dimensional and resin amount control. For making the hydrovanilloin resin-infused woven sheets, aluminum foils were used as a release sheet, woven jute sheet was pre-cut to a sample panel with a geometry of 127 × 254 mm. Once the resin had been prepared, it was applied onto the pre-cut sheets and the fiber was made sure to be fully infused. 2-ply samples were made for tensile tests, so the resin-infused sheets were stacked together and then let cure under room temperature in the lab for 24 hours. For the Elium resin, Dupont Kapton HN Film Tape was used as the release sheet, with the same sample panel geometry being used. 2-ply samples were made for tensile tests, while 3- and 4-ply samples were made for flexural tests. These resin-infused samples were heat pressed in a Carver thermal press at 180°C under 5 bar pressure for 10 min. Some polymer was squeezed out under the pressure, indicating full impregnation of the fiber in the case of excessive resin.

(a) (b)

Figure 2. Pure Elium samples made for (a) Tensile, (b) Flexural tests.

2.3 Test Methods

2.3.1 TENSILE TEST

Tensile tests are generally performed on flat specimens. In this study, tensile tests were conducted based on ASTM D638 - 14 standard for pure resin samples, and ASTM D3039/D3039M - 14 standard for resin infused and cured samples on an INSTRON 5582 Universal Testing Machine (UTM) as shown in Fig. 3, with a constant strain rate of 1.27 mm/min. Pure resin dogbones were made with the dimensions shown in Fig. 4, while 2-ply 127×12.7 mm rectangular resin infused and cured test specimens (shown in Fig. 5) were used. The maximum loads were recorded for calculating the ultimate tensile strength, and tensile moduli were later obtained by calculating the average of force-displacement curve slopes of the five samples tested. Tensile tests of different samples are shown in Fig. 6.

Figure 3. Instron 5582 UTM used for this study.

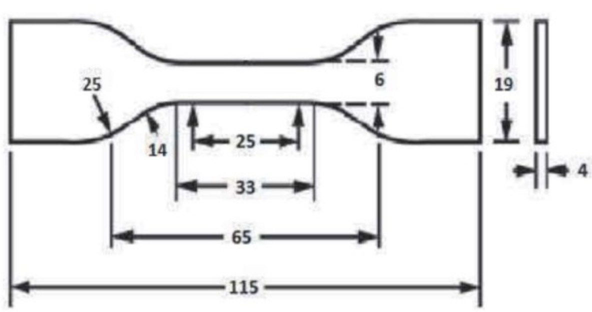
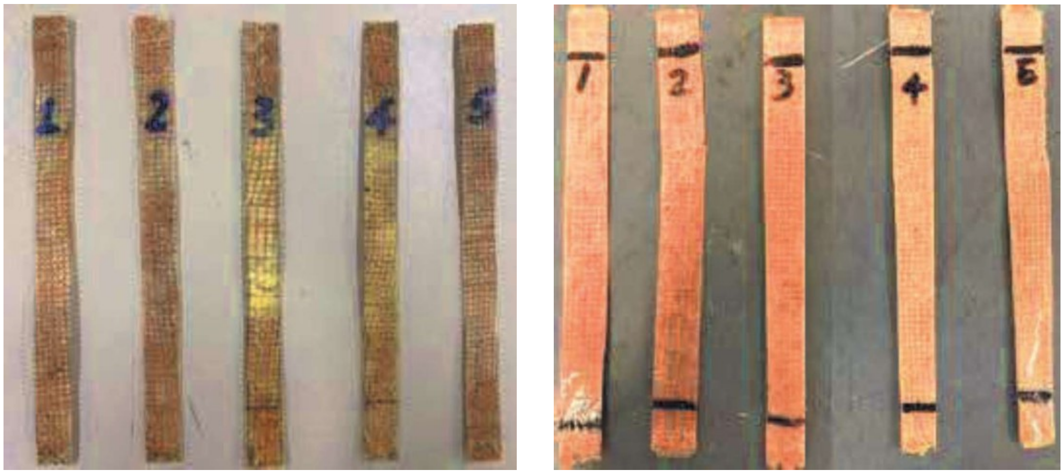
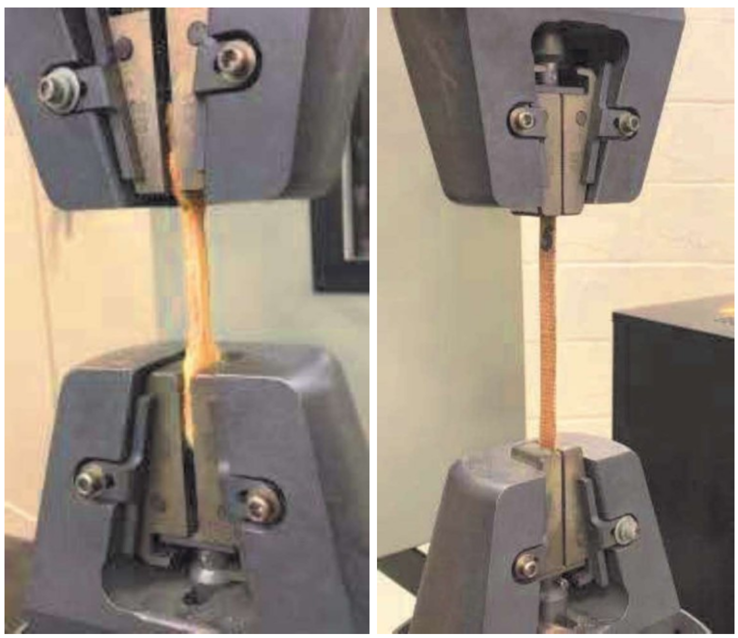


Figure 4. Dimension of pure resin dogbone specimens for tensile tests.

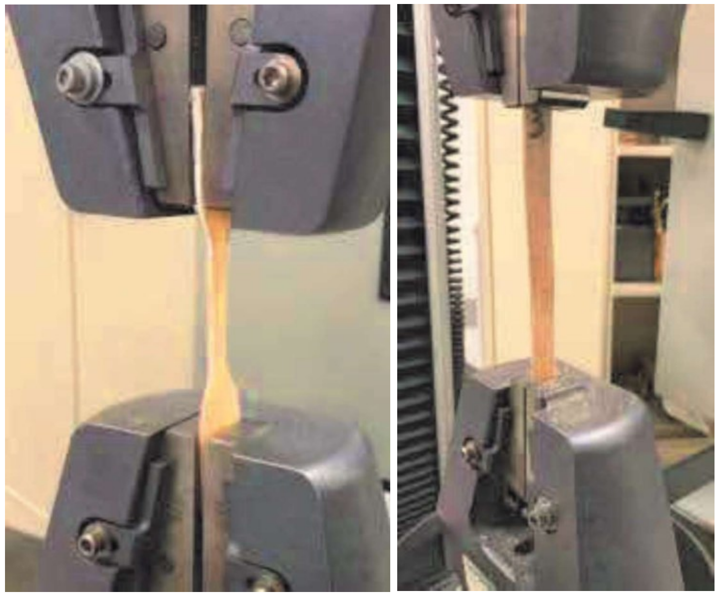


(a) (b)

Figure 5. 2-ply rectangular tensile test specimens with a dimension of 127 × 12.7 mm: (a) Hydrovanilloin resin, and (b) Elium resin.



(a) (b)



(c) (d)

Figure 6. Tensile test on an Instron UTM of: (a) Pure hydrovanilloin resin sample, (b) Hydrovanilloin resin infused and cured sample, (c) Pure Elium resin sample, and (d) Elium resin infused and cured sample.

2.3.2 FLEXURAL TEST

Flexural tests of pure resin samples were performed using three-point bending tests based on ASTM D790 - 10 standard procedure. These samples were made with 73.2 mm length, 12.7 mm width, and a 3.175 mm target thickness. ASTM D7264/D7264M - 07 standard procedure was used for fiber-reinforced samples. Since the fiber-reinforced hydrovanilloin resin samples were not stiff enough for this test, only Elium resin samples were tested. 3-ply and 4-ply specimens of 73.2 mm length (20% longer than the 61.0 mm support span) and 12.7 mm width (shown in Fig. 7) were cut and loaded by three points bending as shown in Fig. 8. The average thickness for 3-ply samples was 1.3 mm, and 1.7 mm for 4-ply samples. These specimens were tested at a crosshead speed of 1.27 mm/min. The test was conducted on the same Instron UTM used for tensile testing. The samples' flexural strength σ can be found using Eqn. (1):

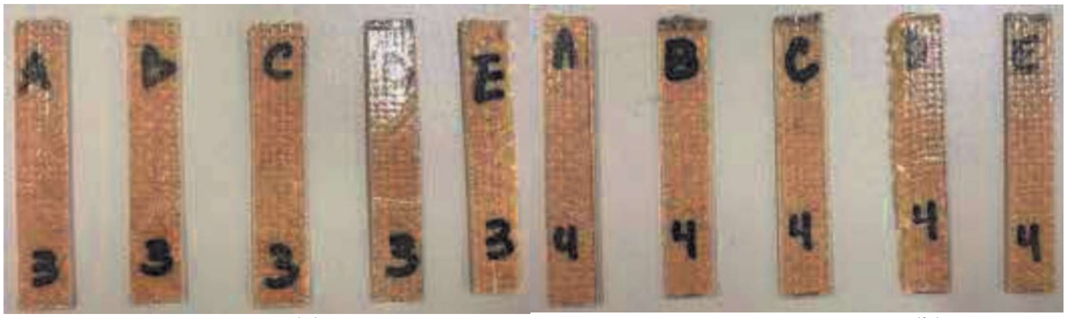
$$\sigma = \frac{3FL}{2bt^2} \tag{1}$$

where F is the maximum load in the test; L is the distance between the two supports; b is the width of the specimen, and t is the sample thickness. The flexural train can be found using Eqn. (2):

$$\varepsilon = \frac{6Dt}{L^2} \tag{2}$$

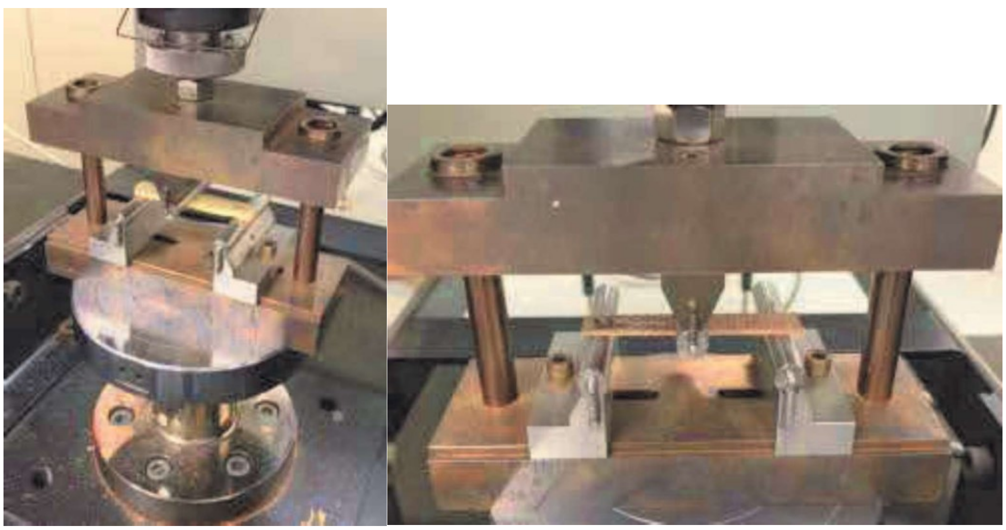
where D is the maximum deflection at the center of the sample beam. The flexural modulus can therefore be obtained by calculating the flexural stress divided by the strain, as shown in Eqn. (3):

$$E = \frac{\sigma}{\varepsilon} = \frac{FL^3}{4Dbt^3} \tag{3}$$



(a) (b)

Figure 7. (a) 3-ply, and (b) 4-ply Elium resin infused and thermo pressed woven jute specimens.



(a) (b)

Figure 8. Flexural test on the Instron UTM of: (a) Pure hydrovanilloin resin sample, and (b) Elium resin infused and cured fiber-reinforced sample.

3. Results and Discussions

The results of all mechanical testing performed in this study are listed in Table I.

TABLE I. MECHANICAL PROPERTIES OF PURE RESIN AND WOVEN JUTE FIBER REINFORCED SAMPLES.

Material	Tensile Strength *TS* (MPa)	Tensile Modulus *E* (GPa)	Flexural Strength σ (MPa)	Flexural Modulus *E* (GPa)
Hydrovanilloin resin	2.44	0.80	12.04	1.04
Woven jute fiber reinforced hydrovanilloin resin samples	22.16	1.88	N/A	N/A
Elium resin	1.09	0.04	18.28	0.35
Woven jute fiber reinforced Elium resin samples	28.32	2.68	39.66 (3 plies) 27.17 (4 plies)	2.72 (3 plies) 1.42 (4 plies)

3.1 Tensile Test

The values of tensile strengths and moduli of both pure resin samples and woven jute fiber reinforced ones are presented in Table I. A comparison of tensile strengths and moduli of two types of pure resins and their woven fiber reinforced counterparts are shown in Figs. 9 and 10. It can be found that the hydrovanilloin resin has higher tensile strength and modulus compared to those of Elium resin. While performing tensile tests, however, the research team found that cured hydrovanilloin resin is very brittle and it is very difficult for it to be used directly in any actual applications. Both types of pure resin are significantly strengthened by the woven jute textile, however, both the tensile strength and modulus of the fiber-reinforced hydrovanilloin resin are weaker than those samples infused and cured by the Elium resin. This may be due to the hydrovanilloin resin's poor bonding abilities with natural fibers or the significant strengthening effects of the thermal pressing process for Elium resin. The maximum tensile strength was found to be 28.32 MPa for woven jute fiber reinforced Elium resin, with its maximum tensile modulus being 2.68 GPa.

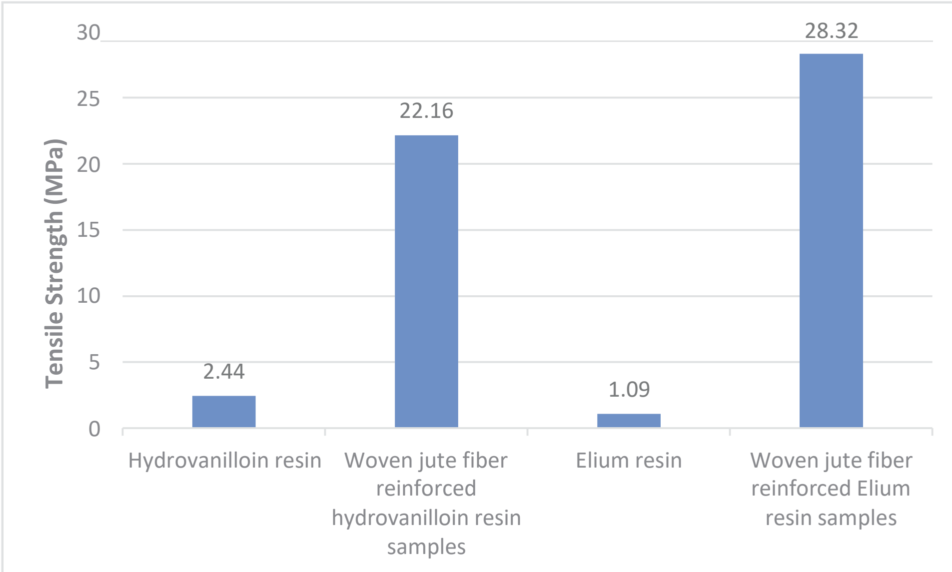


Figure 9. Tensile strength comparison between pure resins and fiber-reinforced samples.

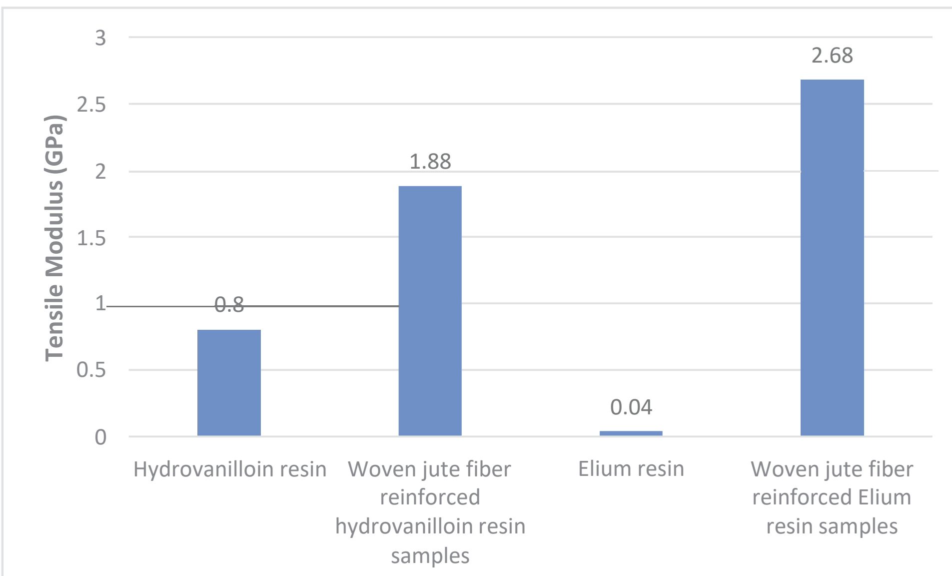


Figure 10. Tensile modulus comparison between pure resins and fiber-reinforced samples.

3.2 Flexural Test

The values of flexural strengths and moduli of both types of pure resin samples and woven jute fiber reinforced ones are presented in Table I. A comparison of flexural strengths and moduli of both types of pure resins and the woven fiber (3-ply and 4-ply) reinforced counterparts of Elium resin are shown in Figs. 11 and 12. It can be indicated by these two figures that the Elium resin has a higher flexural strength than the hydrovanilloin one, but lower flexural modulus. Jute woven fibers improved the flexural properties of both types of resin, however, all samples failed with debonding between layers due to interlaminar shear (shown in Fig. 13), which may be caused by the poor bonding properties at the fiber-resin boundaries and among adjacent fiber plies of Elium resin. Also, it was niticed that 3-ply samples showed better flexural properties comparing to 4-ply ones, this may due to the higher debonding possibilities of adjacent layers in 4-ply samples than 3-ply ones. The research team was unable to perform flexural tests for woven fiber reinforced hydrovanilloin resin samples due to the lack of stiffness of the samples made. The maximum flexural strength was found to be 39.66 MPa, with its maximum flexural modulus being 2.72 GPa.

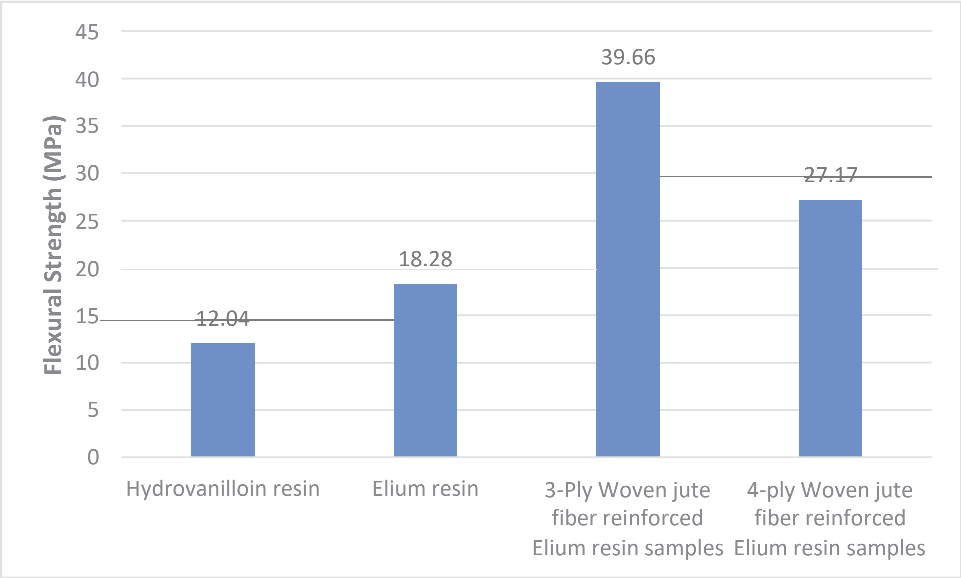


Figure 11. Flexural strength comparison between pure resins and fiber-reinforced samples.

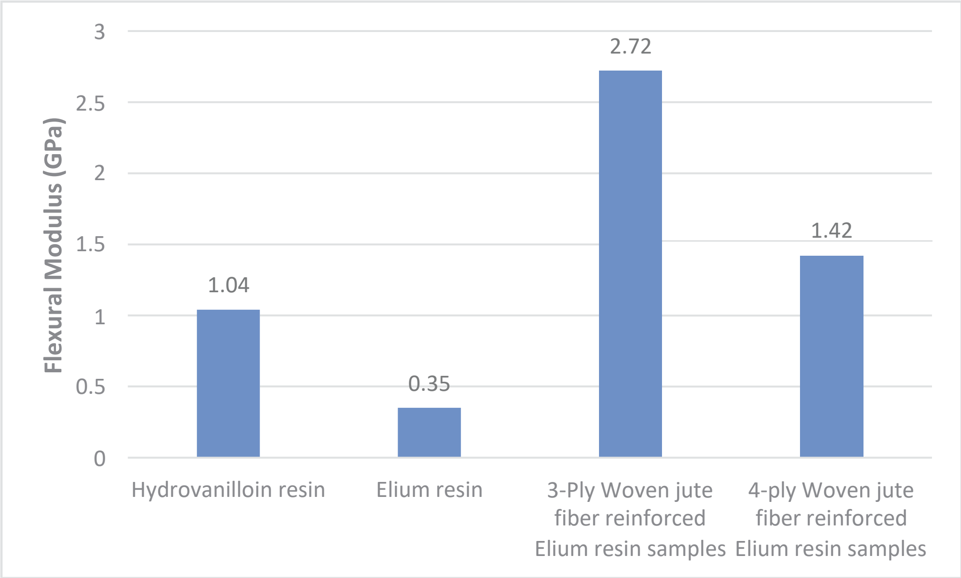


Figure 12. Flexural modulus comparison between pure resins and fiber-reinforced samples.

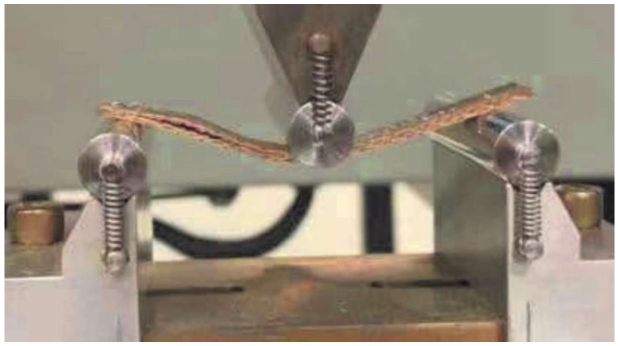


Figure 13. Multi-ply woven fiber-reinforced Elium resin samples failed due to debonding between plies.

4. CONCLUSIONS

Based on the study of the mechanical properties of both types of pure resin and woven jute fiber-reinforced composites, the following conclusions can be made:

1. Samples made from two types of pure resin are both relatively weak, while the ones made from pure hydrovanilloin resin being very brittle.
2. By incorporating woven jute fibers into resins, both resins' tensile and flexural properties can be significantly improved.
3. The maximum tensile strength was found to be 28.32 MPa for woven jute fiber-reinforced Elium resin, with its maximum tensile modulus being 2.68 GPa.
4. The maximum flexural strength was found to be 39.66 MPa for 3-ply woven jute fiber reinforced Elium resin, with its maximum flexural modulus being 2.72 GPa.

Findings from this preliminary study have shown important mechanical properties of the woven jute fabric reinforced biocomposites, which will serve as an important guide for picking and preparing sheet stocks for the LOM 3D printer that is under construction. The research team will move on with both materials with the 3D printer to test the qualities of printed biocomposite parts in the remainder of this research.

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