The effect of natural *Gongura roselle* fiber on the mechanical properties of 3D printed ABS and PLA composites

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Abstract: The influence of the natural *Gongura roselle* fiber on the tensile and flexural properties as well as on Shore D hardness of acrylonitrile-butadiene-styrene (ABS) and poly (lactic acid) (PLA) was investigated. The composites were printed in fused deposition modeling (FDM) 3D technique. The addition of natural fiber improved the mechanical properties of the tested composites, while the flexural strength, modulus and hardness were better in the case of ABS-based composite. Whereas, PLA-based composites showed higher tensile strength. The influence of the nozzle angle on the mechanical properties of the composites was also investigated. The best results have been obtained when using an angle of 0°.

Keywords: natural fiber, *Gongura roselle*, poly(lactic acid), acrylonitrile-butadiene-styrene, 3D printing.

Wpływ naturalnego włókna *Gongura roselle* na właściwości mechaniczne kompozytów ABS i PLA otrzymanych metodą druku 3D

Streszczenie: Zbadano wpływ naturalnego włókna *Gongura roselle* na właściwości mechaniczne przy rozciąganiu i zginaniu oraz twardość Shore'a D akrylonitrylu-butadienu-styrenu (ABS) i poli(kwasu mlekowego) (PLA). Kompozyty otrzymano metodą osadzania topionego materiału (FDM) w technice 3D. Dodatek naturalnego włókna poprawił właściwości mechaniczne badanych kompozytów, przy czym wytrzymałość na zginanie, moduł sprężystości i twardość były lepsze w przypadku kompozytu na osnowie ABS. Natomiast kompozyty na osnowie PLA miały większą wytrzymałość na rozciąganie. Zbadano również wpływ kąta ustawienia dyszy na właściwości mechaniczne kompozytów. Najlepsze wyniki uzyskano stosując kąt 0°.

Słowa kluczowe: włókno naturalne, *Gongura roselle*, poli(kwas mlekowy), akrylonitryl-butadien-styren, druk 3D.

Polymer matrix composites (PMC) reinforced with natural fiber, due to their structure, provide many advantages over traditional synthetic composites in terms of specific stiffness and strength, corrosion resistance, recyclability, large fatigue strength, lower life-cycle costs, higher impact absorption capacity, and lower toxicity [1]. Furthermore, the properties and performance of products made from natural fiber composites are primarily influenced by the contents' individual properties, compatibility, and the polymer/filler interfacial characteristics, which expand the possibilities for creating a variety of exciting new materials with entirely new qualities. On the other hand, increasing the use of cellulosic-fiber composites rather than synthetic-fiber composites would have various advantages in terms of infrastructure management, general sustainability, and an environmentally friendly production trend.

Additive manufacturing is known as three dimensional printing, which forms an object from successive layers of thermoplastics injected from the nozzle to cover widespread applications [2]. It has the potential to simplify the manufacturing process and overcome the challenges of producing complex geometry. Interfacial bonding between the successive layers influences the mechanical durability of fabricated components. Scientists and researchers are trying to overcome this effect by improving the mechanical and thermal properties of the produced components [3]. In additive process, number of techniques is available to develop the functional components. A fused deposition modeling (FDM) technique is suitable for preparing the composite laminates and

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functional parts as well [4]. Functional durability and sustainability of the components are closely related to the injection temperature, nozzle speed, and print orientation, which are some of the input parameters. Mainly, the preparation of the fiber affects the mechanical properties and sustainability of the parts produced using FDM. A wide range of products with a multi-variety of materials can be fabricated using FDM. In the present studies, ABS, PLA, and natural fibers were selected to print the laminates for testing [5].

In 1940, acrylonitrile-butadiene-styrene (ABS) and other relative polymers were used for production of bullet-proof jackets in World War II. It exhibited high impact resistance and low thermoplastic flow [6]. ABS polymers were found to have greater toughness over other styrene and that was a reason of their availability in 1950′ and usage for many applications [7]. They were selected due to their strength and durability, even at low temperatures and also at high temperatures. They are cheap performing and easily available, making them suitable for 3D printing, which is a newer technology developed for production of prototype models of all products [8]. These 3D printing materials are being developed and will play a major role in the upcoming future. In our studies we used a 3D printing material, ABS, to make a fiber reinforcement of polymer matrix [9, 10].

Poly(lactic acid) (PLA) is a biodegradable and bioactive thermoplastic material derived from renewable resources such as corn starch, cassava roots, chips, or sugarcane. It exhibits wide range of structural and mechanical properties, which lie in between polystyrene and polyethylene [11]. Environment friendliness, biocompatibility, and biodegradability characteristics promote PLA to employ for medical and structural applications [12].

MATERIALS AND METHODS

Materials

Acrylonitrile-butadiene-styrene (ABS) and poly(lactic acid) (PLA), polymer filament materials, were purchased from WOL 3D, India. Their properties are given in Table 1.

Methods

Flexural tests were performed according to ASTM D790 standard using Deepak Poly Plast Universal Tester (50 kN). Test specimens with dimensions of 3.2 × 12.7 × 127 mm were used. Shore D hardness tests were performed using durometer hardness testers in accordance with the ASTM D2240 standard. Tensile properties were tested in accordance with the ASTM standard D 638 & 3039 using universal tensile tester (UNITEK-9450, Fuel Instruments and Engineers Pvt. Ltd.) with a capacity of 50 kN. Dimensions of test specimen according to the ASTM standard D638 for polymer materials are depicted. SEM images were obtained using Field Emission Scanning Electron Microscopy (FE-SEM) (SIGMA HV – Carl Zeiss With Bruker Quantax 200 – Z10 EDS Detector).

Chemical treatment of natural fibers

Gongura roselle is a plant commonly available in tropical regions with a very low cost. Its fibers, extracted from the plant, which are shown in Fig. 1, reveal high strength. Raw fiber is coated with wax, and this affects the structural properties of the fiber. In our studies fibers were chemically treated to remove this wax. Twenty samples of fiber stack were treated with different chemicals in different time intervals. Fibers were soaked in 2%, 4%, and 6% KOH and acetic acid for 45, 90, and 135 minutes, respectively [13, 14]. The tensile strength and impact strength of chemically treated fibers were tested using

Fig. 1. *Gongura roselle* fibers

T a b l e 1. Properties of ABS and PLA

Property	Material	
	ABS	PLA
Technical name	Acrylonitrile-butadiene-styrene (ABS)	Poly(lactic acid) (PLA)
Chemical formula	$(C_8H_8)_x{\cdot}(C_4H_6)_y{\cdot}(C_3H_3N)_z$	$(C_3H_4O_2)_n$
Melt temperature (°C)	190–200	170–180
Density (g/cm³)	1.04	1.24
Heat deflection temperature (HDT) at 0.46 MPa (66 PSI)	100–125°C	49–52°C
Specific gravity (g/cm³)	1.04	1.24
Shrink rate (%)	0.4–0.9	0.37–0.41

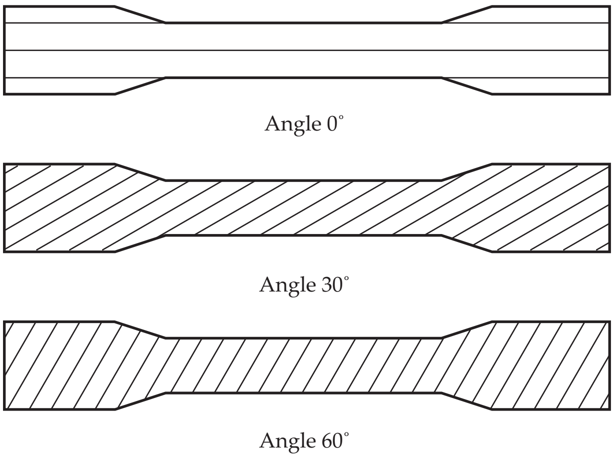

Fig. 2. Fiber orientation in test samples

a stelometer and a torsion instrument. Fiber stack treated with 2% concentration of KOH in 45 min was chosen because of its promising results compared to the others and subjected to several other tests like tensile, flexural, and hardness tests [15].

FDM printing

Acrylonitrile-butadiene-styrene (ABS) and poly(lactic acid) (PLA) were selected as matrix materials for experiments performed on the effect of FDM nozzle orientation on structural properties.

Fiber stack which was treated with 2% KOH for 45 min was used in 3D printing. The filament materials in FDM were ABS and PLA [16]. Chemically treated fiber was embedded in ABS and PLA with a 25% volume fraction in successive layers. When fiber spread randomly over the first layer, the second layer of structural material was injected [17].

To improve the tensile strength of the printed material, the FDM machine nozzle was oriented at 0°, 30°, and 60° (Fig. 2). Three specimens were printed with fibers and one specimen without fibers. For each material, four samples were printed as shown in Fig. 3. Fibers were glued over the surface to avoid wiping of fiber through the nozzle [18]. Thin layer of adhesive liquid, commercially named as Fevicol, spread over the printing face. Due to producer's data, adhesive property of this glue disappears at 170°C. It had a negligible effect on material properties as well. The specimen without fibers was used for comparison during the testing. All printed samples were taken into the tests.

RESULTS AND DISCUSSION

Flexural properties

The three point bending tests were performed to characterize the flexural behavior of multilayered samples. The outer layer of test specimens was subjected to maximum compressive and tensile stresses at the neutral axis of zero [19]. The force was applied at the centre of the specimen. The corresponding deflection was at the bottom layer [20].

Fig. 3. ABS printed samples

The test results are shown in Figs. 4 and 5. It was revealed that the increase of applied load affected the bonding strength of successive layers, and excessive load resulted in delamination of layers [21]. A further increase of load led to the failure of laminates at ultimate strength. The fiber started to fail before yielding, then a minor crack initiated the breakage of the molecular chain. On the base of Fig. 4 data it may be concluded that the ABS material with a 30° fiber orientation showed the most promising results compared to the rest of samples.

Fig. 4 presents the flexural strength of structural material with and without fibers. The thickness of all layers of FDM specimens was kept constant [22]. Transverse rupture strength of the ABS with 0° fiber orientation revealed better results than the others. The flexural strength of ABS-based composite just before yield point was 132 MPa.

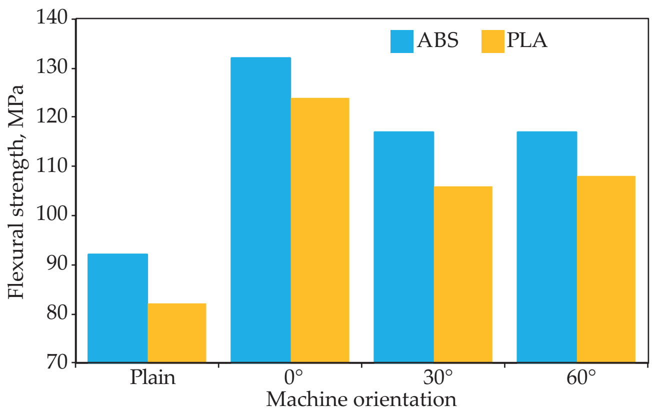

Fig. 4. Flexural strength of PMC with and without fibers

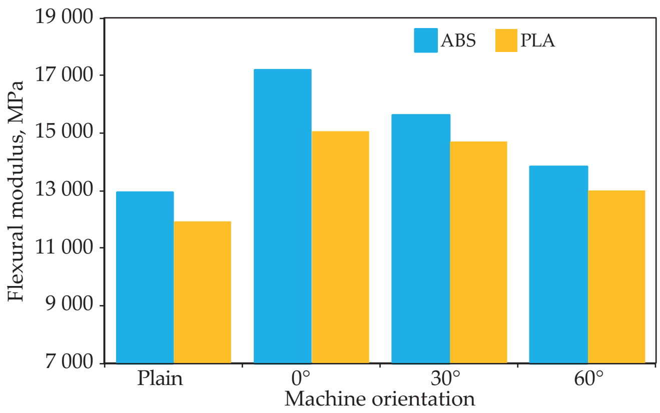

Fig. 5. Flexural modulus of PMC with and without fiber

Bending modulus, also known as flexural modulus (Fig. 5), is a material property which is measured as stress-strain ratio during bending deformation [23]. The test revealed the tendency to resist the bending load acting the specimen. Higher modulus showed maximum resistance to bending. The same trend was observed in flexural modulus.

Hardness

The material hardness can be measured using various methods, *e.g.* soft materials such as rubber and plastics can be tested using durometer hardness testers. During the hardness test resistance of the material against indentation is measured. The hardness of the material influences the mechanical properties, such as wear resistance, strength, and ductility [24]. Our experiments confirmed the suitability of material for high payload applications.

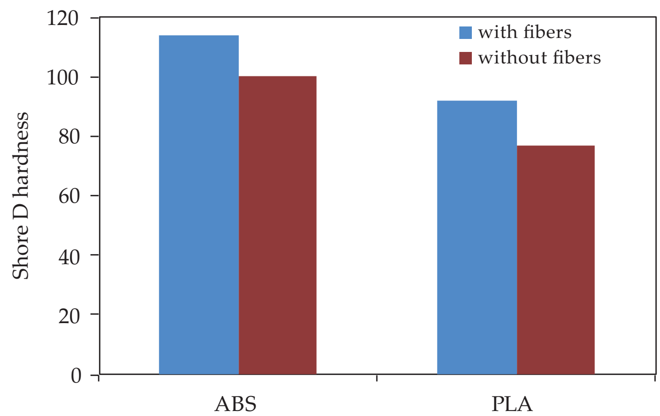

Fig. 6. Effect of natural fiber on hardness of the composites

The results of the experiments, as an average of 10 tests, are shown in Fig. 6. Penetration of specific indenter attached to the tester allowed for penetrating the material under specified conditions of time and force. The natural fibers reinforcement of the matrix increased its hardness by nearly 81%, thanks to the distribution of the test load on natural fibers, which reduced the penetration of the test indenter to the surface of the fabricated composite material and raised the composite material's hardness. This finding was very similar to the tensile testing results, which showed that addition of natural fibers resulted in a significant improvement in tensile strength of both ABS and PLA materials.

Tensile properties

The most common purpose of the tensile tests is to verify tensile strength, yield strength, and ductility of the specimen. Tensile strength is the material's ability to withstand a pulling force defined as the unit of force per cross sectional area. During the tests, the amount of applied force required to break a specimen is measured as well as elongation or stretching to the breaking point [25].

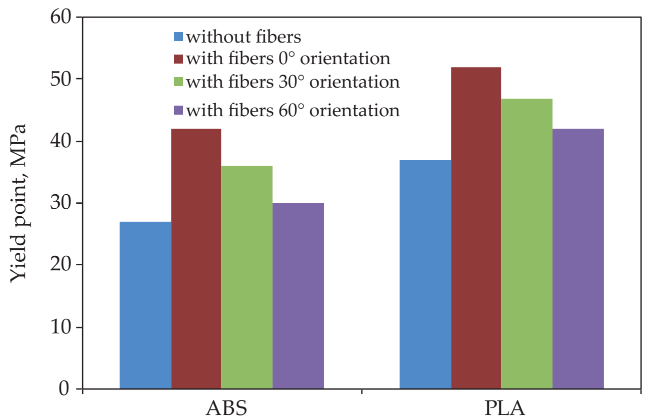

Fig. 7. Yield point of the specimens

Tensile properties of the polymer composites are anisotropic and depend on the 3D printer nozzle orientation, reinforcement material property, and interfacial bonding strength between the layers [26]. Fiber orientation parallel to the injector nozzle direction improved the tensile strength as compared with other samples. Polymer composites with 0° orientation showed high internal resistance against tensile failure. The same trend was observed for both materials (Fig. 7). On the other hand, tensile strength decreased with the increase of fiber orientation angle.

PMC microstructure

Interfacial adhesion occurs during joining, blending, or mixing of two distinct materials. It may result in greater material dispersion in the matrices. Typically, to improve interfacial adhesion, mixtures of materials with similar properties, such as hydrophilic fillers and hydrophilic matrices or hydrophobic fillers and hydrophobic matrices, are used, resulting in a strong bonding between them. Interfacial bonding between the *Gongura roselle* fiber and structural material was extremely compact permitting reinforcement fibers to be anchored with matrix material [27].

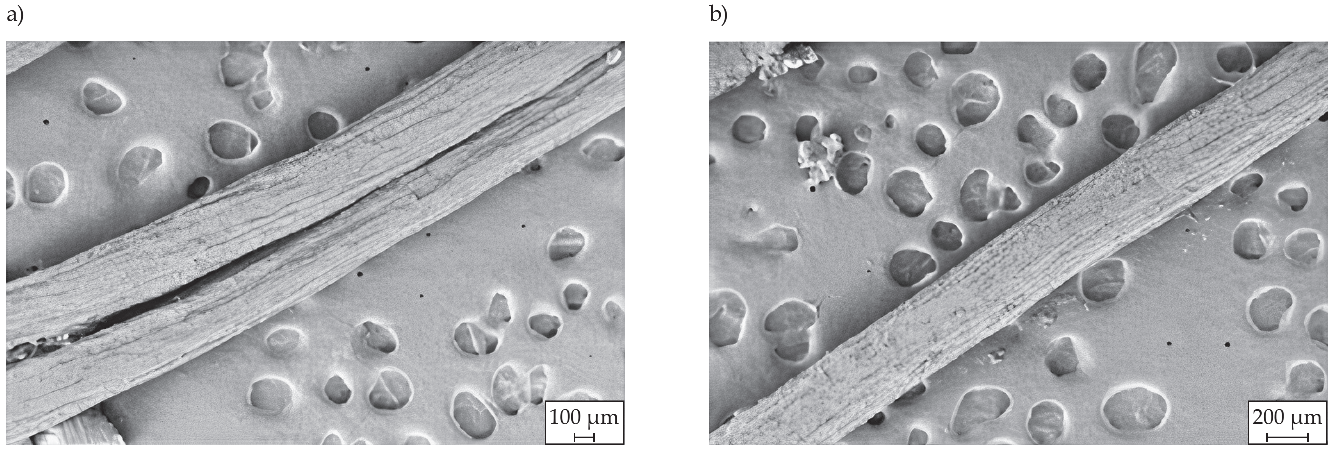

Fig. 8. SEM micrographs of (a) ABS-based and (b) PLA-based PMC

Scanning Electron Microscopy (SEM) images of ABS- and PLA-based composites are shown in Fig. 8. It can be observed that the orientation of fibers in both samples was similar. The *Gongura roselle* fibers improved the crosslinking between polymer chains, as a result, interfacial bonding; agglomeration of polymer structural material was observed as well. Agglomeration area on the fiber surface initiated the stress concentration zone, minimizing the interfacial bonding with fibers. Effect of van der Waals attractive force led to agglomeration the *Gongura roselle* fiber, which reduced the interfacial bonding strength by the stress concentration effect. Agglomerates of reinforced fibers were difficult to detach and break with matrix.

CONCLUSION

Wax content of the *Gongura roselle* reinforcing fibers was removed on the way of alkaline treatment process using KOH to reduce the hydrophilic tendency and improve compatibility with the matrix. ABS- and PLA-based test samples were 3D printed. During printing, *Gongura roselle* fibers were successfully embedded into matrix material. Structural properties like flexural strength, hardness, and tensile strength of the developed composites were tested and the results were compared. In case of 0° orientated fibers in ABS and PLA flexural strength was respectively 43.47% and 51.21% higher than that of specimen without fibers and 12.82% and 16.98% higher than that of other reinforced specimens. Flexural modulus of 0° orientated sample ABS and PLA reinforced with natural fibers was respectively 32.73% and 25.95% higher than that of specimen without fibers and 10.03% and 2.4% higher than that of the other reinforced specimens. Uniform dispersion of *Gongura roselle* fibers into the matrix material was visually confirmed through SEM micrographs. It restricted the plastic deformation of matrix at indentation, resulting in 14% and 19.48% increase of hardness of reinforced polymer. 0° orientated ABS and PLA exhibited 55.6% and 40.5% higher than plan specimen, 16.7% and 10.6% higher than other reinforced specimens.

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