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Property enhancement of 3D printed timber waste/PLA composite by surface coating

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Abstract Poly Lactic Acid (PLA) is a biodegradable polymer that is both biocompatible and biodegradable. It is one of the bio-driven polymers. Additive manufacturing has opened up a plethora of new product types and application possibilities. In order to print components and parts, the fused deposition modeling technique makes use of polymer filaments. An experimental investigation was carried out to determine the effects of layer thickness and epoxy resin coating on the mechanical and water absorption capabilities of 3D printed timber waste/PLA composites. The results of the investigation are presented in this paper. The specimens were printed using a commercial Fused Deposition Modelling (FDM) method with layer thicknesses of 0.15 mm, 0.20 mm, and 0.25 mm. The specimens were made of wood waste and PLA composite. It was decided to cover the specimens with Araldite LY556 epoxy resin, with Aradur HY 591 serving as a hardener. Standard ASTM testing procedures were used to evaluate the tensile, impact, and water absorption capabilities of the material. Layer thicknesses of 0.15 mm yield the greatest results in terms of tensile strength and impact resistance. The samples with 0.15 mm layer thicknees provided the best tensile strength of 14.647 MPa, impact strength of 4.952 KJ/mm and 1.813 Wt. % of water absoption. The Araldite LY556 epoxy coating improved the tensile and impact strength of 3D printed specimens of different layer thicknesses and also reduced the water absorption to an appreciable amount. The coating improved the average tensile strength by 25.66% and impact strength by 33.16% and also reduced the water absorption by 89.96%..

Keywords: 3D printing, FDM, natural composites, PLA

1. Introduction

Polymers have become inextricably connected with human life. However, they pose a significant harm to the environment, and petroleum supplies are not replenishable. As a result of their inherent nature as non-biodegradable materials, polymer products wind up in landfills or are disposed of in the sea after serving their purpose. This results in environmental difficulties due to the fact that they are not biodegradable. In this regard, biodegradable and biocompatible polymers as well as bio-composites are in high demand nowadays. Governments all over the world are supporting efforts to create biocompatible or biodegradable polymers and natural composites for use in a variety of applications. Poly Lactic Acid (PLA) is a biodegradable polymer that is both biocompatible and biodegradable. It is one of the bio-driven polymers. Natural resources such as corn, starch, and sugar beet are fermented to produce lactic acid, which is then polymerized by ring-opening or slow poly-condensation polymerization to produce PLA.

New possibilities for the fabrication of complicated-shaped goods are made possible by additive manufacturing. 3D printing is an additive manufacturing method in which material is added in layers, allowing users to create a tangible product directly from a 3D computer model, as opposed to subtractive manufacturing methods. It is known as fused deposition modeling (FDM) and is a popular additive manufacturing process because of its high dependability, low cost, and little waste. It is used to print parts through a nozzle using thermoplastic filaments. PLA is a widely used material in FDM because of its good printability and moderate mechanical qualities. It is also inexpensive. Natural composites are made up of natural filler materials such as flax, jute, and sisal, among others. Timber waste is also used as a filler ingredient in order to minimize production costs while also making the product more environmentally friendly and sustainable. Researchers have conducted a number of experiments to better understand the properties of natural composites that have been created using the 3D printing method.

In 3D printing, a variety of natural fibers are combined with PLA to create the final product. Spent coffee grounds, rice bran, flax, bamboo, coconut, hemp, wood flour, and basalt fiber are just a few of the natural reinforcement materials that are widely utilized with PLA in additive manufacturing (Arockiam et al 2021; Deb 2021). Screw extruders are the most common

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type of equipment used to produce composite filaments. Each type of reinforcement has its own set of advantages and disadvantages based on how it affects the quality of the 3D printed component that is produced.

For 3D printing, Tao et al (2017) designed and researched a wood flour loaded PLA composite filament, which they called "wood flour filament." In order to determine the mechanical and thermo-mechanical properties of the newly designed composite filament, which contains 5% wood flour, was tested. PLA gained mechanical strength as a result of the addition of wood flour filler. The created filament's compatibility with 3D printing was also effectively proved in this study. Ayrilmis et al (2019) investigated the effect of layer thickness on the tensile, bending, and moisture absorption capabilities of 3D printed timber waste/PLA composites in their research. The results revealed that the thickness of the layer has an effect on the tensile, bending, and moisture absorption capabilities of the material. The mechanical and moisture absorption properties of the layer were improved when the layer thickness was reduced. Butylina et al (2010) conducted research to assess the water absorption and mechanical qualities of two different types of composites: timber waste/PLA and timber waste/polypropylene. Soft wood sawdust was used as reinforcement in both the PLA and polypropylene composites, and the results were promising. To evaluate the mechanical and moisture absorption characteristics of the material, water immersion tests, mechanical tests, and a cycle test were carried out. By examining SME pictures, it was possible to determine the fracture surfaces. When comparing the mechanical and water absorption capabilities of the timber waste/PLA composite with those of the timber waste/polypropylene composite, the researchers discovered that the latter had significantly worse mechanical and water absorption properties. Ayrilmis et al (2019) investigated the surface characteristics of timber waste/PLA composites, including surface roughness and wettability, when varied amounts of wood flour were used. Results revealed that the addition of wood flour increases the surface roughness while simultaneously reducing the wettability of the surface.

Guo et al (2018) investigated the influence of several toughening agents on the impact strength of a 3D printed timber waste/PLA composite, which was manufactured in three dimensions. The use of toughening chemicals resulted in significant improvements in the mechanical properties of the composite. Antonio Travieso-Rodriguez et al (2020) conducted an investigation. The fatigue behavior of a PLA-timber waste composite produced through fused filament manufacturing is investigated. Experiments were conducted to determine the influence of layer height, nozzle diameter, infill density, and extrusion velocity on the fatigue properties of non-reinforced PLA specimens and PLA-Timber waste composite specimens made of non-reinforced PLA and PLA-Timber waste composites. When using a honeycomb pattern, the fatigue properties are improved, and the print velocity has no effect on the properties. Because it reduces adhesion and inter-laminar bonding, the timber-fill has a negative impact on the mechanical characteristics of the PLA matrix.

Haidiezul et al (2018) investigated the possibility of increasing the surface texture of 3D printed parts by using additive manufacturing techniques. The XTC-3D coating, which was applied to the 3D printed pieces, significantly decreased the stair casing effect while also improving the surface finish. When it comes to 3D printing PLA, Spoerk et al (2017) evaluated the effects of various process settings on inter and intra-layer bonding strengths. The best quality was obtained with a layer thickness of 0.2 mm and a printing temperature of 250 degrees Celsius. In their research, Vicente et al (2019) looked into the possibility of increasing the mechanical and water absorption capabilities of 3D printed PLA by covering it with acrylic and polyurethane (PU) coatings. The mechanical and water absorption properties of the material improved significantly as a result of the research. Awal et al (2015) investigated the properties of cellulose fiber-reinforced polylactic acid (PLA) bio-composites that were produced by the extrusion and injection molding processes. This investigation of the thermal characteristics of the bio-composites was carried out using Thermo-Gravimetric analysis (TGA). A bio-additive, bio-adimide, was used to evaluate the effect of the addition of cellulose fibres to reinforced polylactic acid (PLA) bio-composites on their tensile and impact strengths. Based on the findings, Awal et al (2015) concluded that bio-additive bio-adimides increased the thermal distortion temperature while also marginally improving the mechanical properties. In their study, Bhagia et al (2020) evaluated the effects of several wood flour processing procedures on the tensile characteristics of poplar timber waste–polylactic acid composites. The tensile characteristics of the ball milled poplar flour were superior to those of the fibrillated poplar flour. According to the data, it was discovered that the addition of wood flour to PLA diminishes the strength of the matrix.

Diverse controllable elements, such as layer thickness, orientation, nozzle size, bed temperature, and nozzle temperature, all have an impact on the strength and surface finish of 3D printed components. The parameters of the FDM process are considered to be interrelated and significant for the quality of the parts. The efficiency of the FDM process as well as the quality of printed objects can both be enhanced by optimising a specific set of process parameters (Dey et al 2019). Figure 1 depicts the many process parameters that have a direct impact on the quality of the printed item and how they are affected.

Based on the findings of the literature research, it was concluded that the layer thickness has the greatest influence on the mechanical properties of 3D printed polymers. It was also shown that several types of surface coatings on 3D printed polymers increased the water absorption properties while also somewhat increasing the mechanical properties. 3D printed timber waste/PLA composites have been tested for their tensile, impact, and water absorption capabilities. The current work analyses the effect of printing layer thickness and epoxy coating on these parameters. The tests were carried out in accordance with ASTDM guidelines, and the findings were analysed.

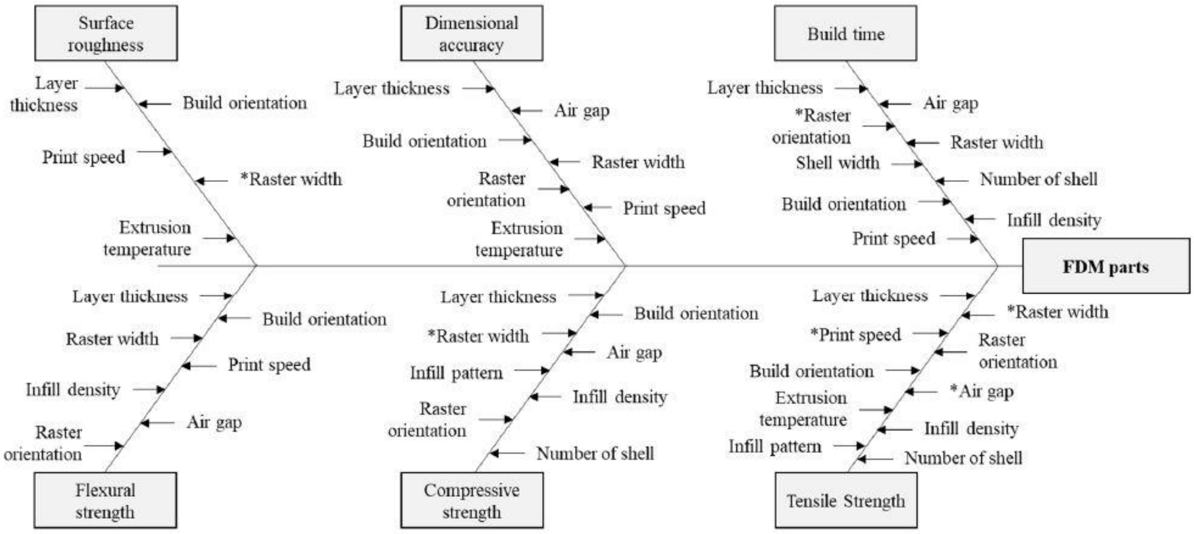

Figure 1 A fishbone diagram to illustrate the impacts of process parameters on part characteristics.

2. Materials and Methods

The wood-PLA filaments were extruded on a desktop filment extruder. The wood flour was treated with NaOH and dried. The processed wood flour was mixed with virgin PLA with required weight percentage. The filament is composed of 80 percent PLA and 20 percent wood waste (flour). The PLA-Wood mix was supplied to the extruder and extruded into filaments with 1.75 mm diameter. The extruded filaments were then cured in an oven. Figure 2 depicts a scanning electron microscope image of the extruded filament. The extrusion marks and the wood particles in the PLA matrix are visible in the SEM image.

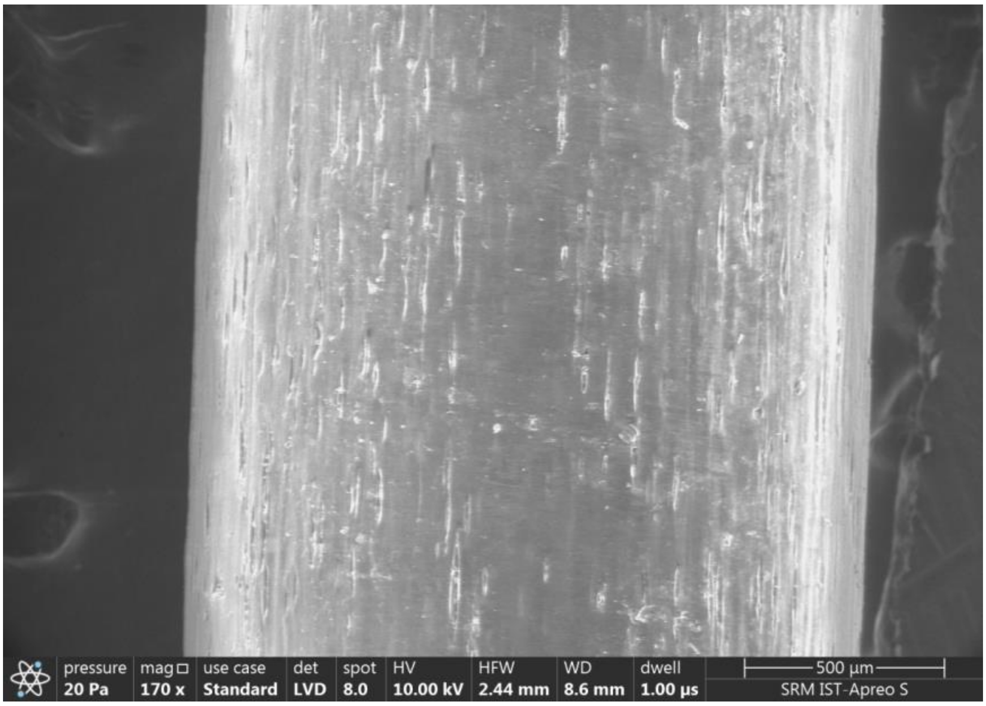

Figure 2 SEM image of extruded Timber waste-PLA filament.

The specimens were printed on a commercial FDM 3D printing machine using FDM technology. The print parameters are listed in Table 1. When performing the tensile, Izod, and water absorption tests, the ASTM D 638, D 256, and ASTM D 570 standards, shown in Figures 3 and 4, were adhered to in the appropriate cases. The CAD models for the ASTM standards were created in commercial solid modelling software according to the specifications of the standards, including their size and geometry. With the help of the cura software, the G-codes for 3D printing were created. For each printing parameter, a total of two specimens are printed. One specimen set is examined as it was made, while the other is tested after being coated with epoxy resin. Figure 3 depicts the microstructure and layer structure of the 3D printed specimen.

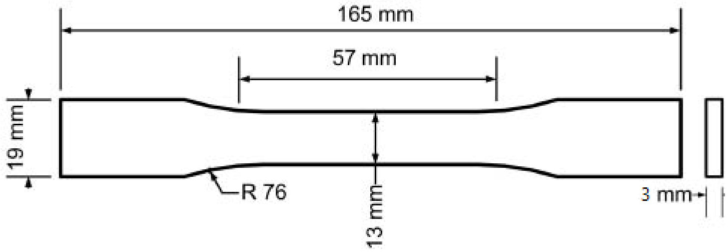

Figure 3 Test specimen dimensions as defined by ASTM D 638.

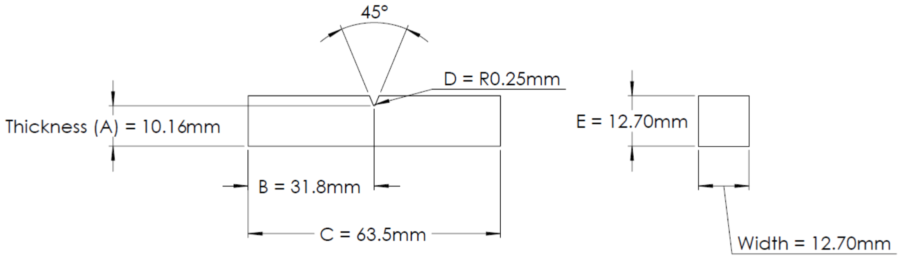

Figure 4 Test specimen dimensions as defined by ASTM D256-10.

Table 1 3D printer and Printing parameters.

Printing parameters	Values
Technology	Fused Deposition Modelling
Build Volume	300*300*300 mm
Accuracy	0.1 mm
Layer height	0.15, 0.20, 0.25 (in mm)
Infill pattern	Hexagon
Infill density	90%
Bed temperature	60 °C
Extruder temperature	220 °C
Extruder feed rate	80 mm/s

Araldite LY 556 is a medium-viscosity, unmodified epoxy resin based on bisphenol-A. Possesses excellent mechanical properties and resistance to chemicals. Hence it is selected as a coating to improve 3D printed PLA composite. The epoxy resin Araldite LY556 was used in conjunction with the hardener Aradur HY 591. Araldite LY 556 is a medium-viscosity epoxy resin based on bisphenol-A which has not been changed. With outstanding mechanical qualities and chemical resistance, it may be further customised within a wide range of boundaries by incorporating various hardeners as well as fillers into the mix. Araldite LY 556 has a low tendency to crystallise, making it an excellent choice for jewellery. It is necessary to combine the epoxy resin and hardener in a 10:1 ratio before applying it to the 3D printed specimens. Following application to the 3D printed parts, the coating mixture is allowed to cure for 24 hours before being tested. The curing process takes place at room temperature. The coating was applied manually by using a paint brush and the thickness varies from 0.4 mm to 1.5 mm.

The tensile test and the impact test were carried out on both coated and uncoated specimens shown in Figure 5. A total of 24 hours was required for the specimens to be submerged in water for the water absorption test. After the soaking period, the specimens were removed, and the amount of water absorbed was determined by comparing the weights of the specimens before and after soaking.

Figure 5 (a) Uncoated and (b) Coated tensile specimens.

3. Results and Discussions

3.1 Tensile strength

Figure 6 depicts the relationship between layer thickness and the tensile strength of an epoxy coating. The results of the tensile and impact tests revealed that the thickness of the layers has a significant impact on the mechanical properties of the 3D printed timber waste/PLA composite, which was manufactured with PLA. The tensile strength of the three specimens with layer thickness of 0.15 mm, 0.20 mm and 0.25 mm are 14.647 MPa, 1.659 MPa and 12.681 MPa respectively (Table 2). The porosity of the specimen has increased as a result of the increase in layer thickness, resulting in a reduction in tensile strength. The density of the printed specimen decreases in direct proportion to the increase in layer thickness. The mass of specimens printed with a 0.25 mm layer thickness was 7% less than the mass of specimens printed with a 0.15 mm layer thickness, indicating a layer thickness reduction of 7%. Additionally, the rise in layer thickness led to a decrease in the integrity between the layers.

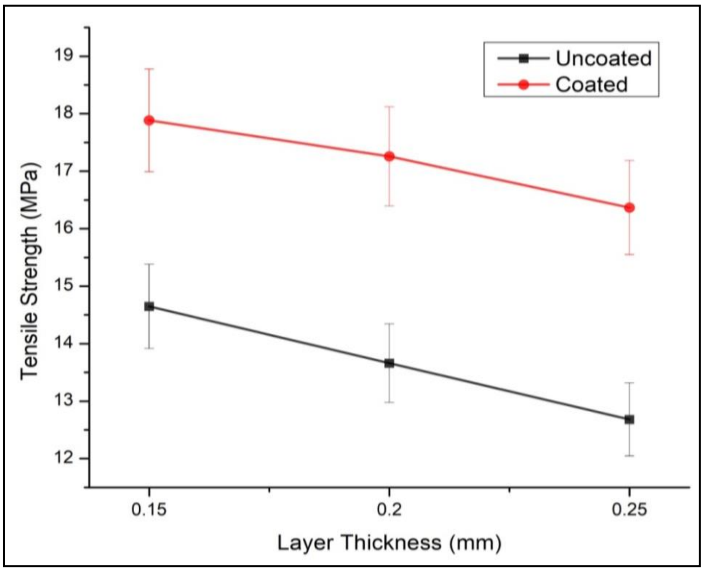

Figure 6 Effect of layer thickness and epoxy coating on tensile strength

In the experiments depicted in figure 6, the epoxy coating enhanced the tensile strength of the specimens. Filling up the gaps between layers and increasing tensile strength are two benefits of epoxy coating. The epoxy coating also serves as a second support, and an increase in tensile strength has been noted as a result. Because of the coating, crack formation and propagation are prevented, and the stress is distributed. The tensile strength of the 3D printed specimens has been significantly increased thanks to the application of an epoxy resin coating. A specimen with a layer height of 0.25 mm outperforms an uncoated specimen by nearly 29 percent. Statistical analysis is carried out to determine thesignificance of the parameters on tensile strength of the 3D printed specimen. The analysis of variance (ANOVA) was used with a significance level of 0.05 and is depicted in Table 3. It is evident from the Table 3 that both layer thickness and coating are significant parameters affecting the tensile strength. Based on F Value, the coating is the most significant factor in deciding the tensile strength of the 3D printed specimens.

Table 2 Experimental results.

Layer Thickness (mm)	Uncoated			Coated		
	Tensile strength (MPa)	Impact strength (kJ/mm²)	Water absorption (Wt %)	Tensile strength (MPa)	Impact strength (kJ/mm²)	Water absorption (Wt %)
0.15	14.647	4.952	1.813	17.883	6.874	0.272
0.2	13.659	3.937	2.355	17.256	4.921	0.255
0.25	12.681	2.937	3.897	16.365	3.952	0.283

Table 3 ANOVA for Tensile strength.

	DF	Sum of Squares	Mean Square	F Value	P Value
Layer Thickness	2	3.03994	1.51997	53.86877	0.01823
Coating	1	18.43455	18.43455	653.33284	0.00153
Model	3	21.47449	7.15816	253.69012	0.00393
Error	2	0.05643	0.02822	--	--
Corrected Total	5	21.53092	--	--	--

3.2. Impact strength

Figure 7 depicts the relationship between layer thickness and surface coating on impact strength. The ability of a 3D printed specimen to absorb impact energy is dependent on the density of the infill material. When it comes to impact strength, it is entirely dependent on the type of the meso-structure, which is responsible for maintaining a delicate balance between the factor of stress intensity and the phenomenon of crack propagation.

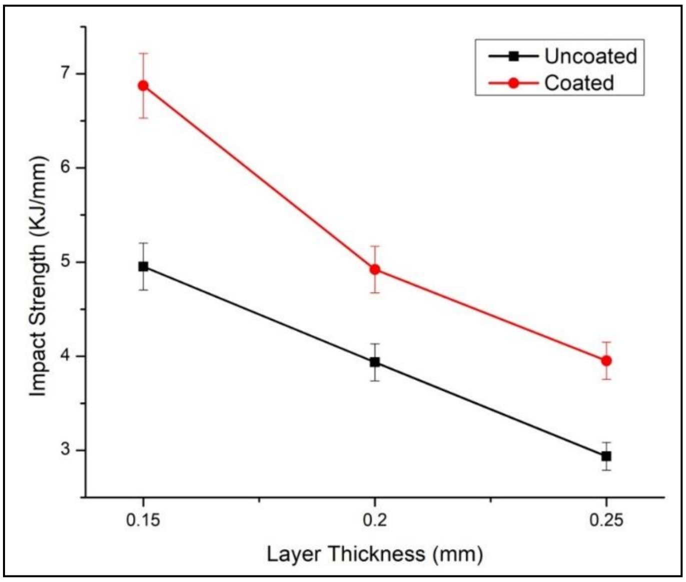

Figure 7 Effect of layer thickness and epoxy coating on impact strength.

It has been claimed that the impact strength of printed components is lower than that of injection moulded components, owing to the fact that the voids inside the parts act as stress concentration locations. The air gap between FDM pieces is a significant aspect in determining the impact strength of the parts. Layer thickness increases the number of voids and air gaps in an FDM part, while inter-laminar bonding is affected by the amount of time it takes for each layer to dry. Because the layers took longer to print, they had more time to cool before the next layer was printed over them, reducing the bonding between consecutive layers as a result. As a result, the impact strength of the printed item is reduced as the layer thickness is increased. Having a layer thickness of 0.15 mm, the parts are very dense and have very few air gaps. They also have good impact strength.

In Figure 7, it can be seen that the Araldite LY556 epoxy resin coating increased the impact strength of 3D printed specimens. The epoxy resin filled up the surface voids and increased the overall surface properties and the surface finish. In addition, the epoxy inhibited the initiation and propagation of cracks in the surfaces while increasing the absorption of kinetic energy. The impact energy of the coated specimen with a 0.15 mm layer height has been found to be much higher than that of the uncoated specimen, with a value 2.5 times greater than the untreated specimen. It was discovered that this specimen has impact energy of 7.874 KJ/mm.Statistical analysis is carried out to determine thesignificance of the parameters on tensile strength of the 3D printed specimen. Statistical analysis is carried out to determine thesignificance of the parameters on impact strength of the 3D printed specimen.The analysis of variance(ANOVA) was used with a significance level of 0.05 and is depicted in Table 4. It is evident from the Table 4 that both layer thickness and coating are not significant parameters affecting the impact strength of the 3D printed specimens.

Table 4 ANOVA for Impact strength.

	DF	Sum of Squares	Mean Square	F Value	P Value
Layer Thickness	2	4.20799	2.104	4.62802	0.17768
Coating	1	1.42204	1.42204	3.12797	0.21899
Model	3	5.63003	1.87668	4.128	0.20114
Error	2	0.90924	0.45462	--	--
Corrected Total	5	6.53927	--	--	--

3.3. Water absorption

Uncoated specimen after the water absorption test is shown in the Figure 8. The water absorption by the wood fillers is clearly evident from the figure. The Figure 9 depicts the influence of layer thickness and epoxy coating on the water absorption of 3D printed timber waste-PLA specimens, which were manufactured using a 3D printer. The water absorption property of 3D printed uncoated specimens is influenced by the thickness of the layers used. According to ASTM D 570, specimens with a layer thickness of 0.25 mm absorb 3.897 percent of the water they are immersed in for one hour during a water immersion test.

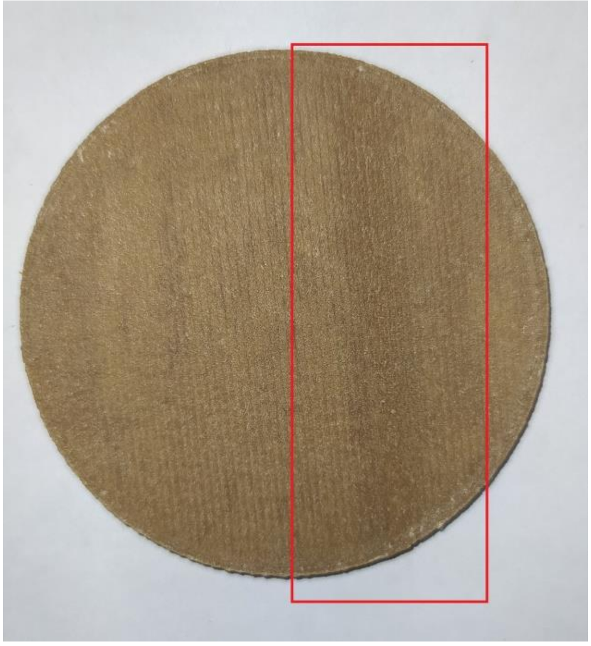

Figure 8 water absorption in uncoated specimen.

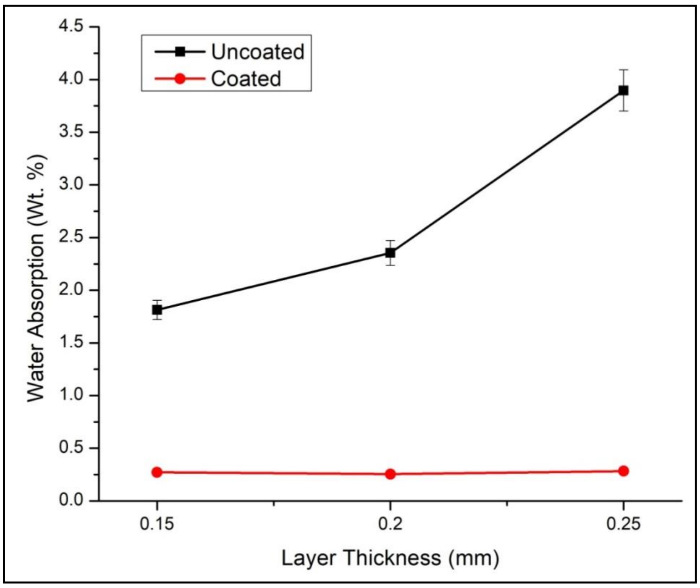

Figure 9: Effect of layer thickness and epoxy coating on water absorption.

The specimen with a layer thickness of 0.15 mm absorbs 1.813 percent of its weight in water, while the specimen with a layer thickness of 0.20 mm absorbs 2.355 percent of its weight in water. The increase in water absorption increases in direct proportion to the increase in the thickness of the layer. This is due to the increased porosity that occurs when the specimens are printed at a greater layer thickness. The increase in layer thickness also results in an increase in the amount of exposed timber waste flour on the surface. Water is absorbed by the hydroxyl polymer found in wood flour, and the increase in exposed surface area increases the amount of water absorbed.

The Araldite epoxy coating applied to the 3D printed specimens significantly limits the amount of water that may be absorbed. As shown in Figure 8, different layer thicknesses of epoxy-coated specimens have different water absorption characteristics. After coating, the water absorption properties of all of the specimens with coating were reduced to 0.2 percent or less. The exposed surface of the wood waste flour has been reduced by the epoxy coating.Statistical analysis is carried out to determine thesignificance of the parameters on water absorption of the 3D printed specimens.The analysis of variance(ANOVA) was used with a significance level of 0.05 and is depicted in Table 5. It is evident from the Table 5 that the coating is the most significant parameter affecting the water absorption of the 3D printed wood-PLA specimens.

Table 5 ANOVA for water absorption.

	DF	Sum of Squares	Mean Square	F Value	P Value
Layer Thickness	2	1.18826	0.59413	1.03297	0.49189
Coating	1	8.7725	8.7725	15.25209	0.05975
Model	3	9.96076	3.32025	5.77268	0.1512
Error	2	1.15033	0.57517	--	--
Corrected Total	5	11.1111	--	--	--

4. Conclusions

The following conclusions can be made from the results of tensile, impact and water absorption tests conducted on coated and uncoated 3D printed specimens.

1. The reduction in layer thickness improved the mechanical and water absorption properties of the 3D printed Wood-PLA composite.
2. The samples with 0.15 mm layer thicknees provided the best tensile strength of 14.647 MPa, impact strength of 4.952 KJ/mm and 1.813 Wt. % of water absoption.
3. The coating improved the average tensile strength by 25.66% and impact strength by 33.16% and also reduced the water absorption by 89.96%.

The Wood/PLA composites with Araldide coating can be used as Domestic and industrial furniture with wood like look and feel with improved life and functionality.

Ethical considerations

Not applicable.

Conflict of Interest

The authors declare that they have no conflict of interest.

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