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Enhancing Mechanical Properties of Poly Lactic Acid (PLA) Composites through Wood Reinforcement: A Comprehensive Investigation

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Abstract: *Finite Element Analysis (FEA) is employed to assess the mechanical properties of wood-reinforced poly-lactic acid (PLA) composites. This study aims to understand the behavior of these composites under various loading conditions. By simulating tensile, flexural, and impact tests, the FEA model evaluates stress distribution, deformation patterns, and potential failure modes. Insights gained from this analysis contribute to optimizing the design and formulation of wood-PLA composites for enhanced strength, stiffness, and durability. The study underscores the importance of computational modeling in advancing the development of sustainable materials for diverse engineering applications. This study outlines the various mechanical tests conducted on laminated composites and presents their corresponding results in the form of data. These composite materials offer a high strength-to-weight ratio, stiffness, and lightweight characteristics, potentially enhancing system efficiency.*

Keywords: Finite Element Analysis (FEA), Wood-reinforced, Poly-lactic acid (PLA), Composites, Mechanical properties

INTRODUCTION:

In recent decades industries and researchers including academic communities are more interested on Additive manufacturing (AM). Components with high printing qualities have been developed using AM process. In AM, polymers with wide range of properties are used as feedstock. Based on the consumer requirement, design of product development and manufacturing would vary frequently. Ease of work for engineers is achieved through employing AM technique. This process of manufacturing reduces time efficiently from weeks to a few hours. In manufacturing sector, AM could minimize production costs and improve the overall efficiency of the manufacturing process. Using AM product with complex design are fabricated with the negligible tolerance. Various industries consider AM for several applications, specifically, aerospace industry, automotive industry, hydropower station (Turbine, Special machinery), medical implants (Dental, orthopedic), and other. To manufacture polymeric components, industries prefer fused deposition modeling (FDM) among other AM technique for its ability to fabricate components with low dimensional tolerance (0.1-0.01 mm). The production rate of industry is increased, due to time efficiency for fabricating a product using FDM technique. Mass productive industries choose FDM technique to fabricate a product. FDM uses polymeric materials for fabrication process, polylactic acid (PLA) are commonly utilized material in manufacturing a prototype model. This PLA is obtained naturally from wheat, straw and corn etc... Through extracting lactic acid from the listed materials. PLA is a hydrophobic polymer, as it is obtained from renewable resource it could also be used as a biocompatible material in medical field (tissue engineering, drug delivery system, temporary and long-term implantable devices). This polymer is used in automobile and automotive industries to manufacture various components (air filter box, car body). Due to its mechanical property and flexibility PLA is reinforced with other material, which draw additional properties like PLA reinforced carbon (CCF reinforced PLA composite) showed maximum tensile strength, respectively. A new class of polymer called PLA reinforced with Wood Fibers (WF) was established. They are generated through mixing WF and thermoplastic resins together to give composite. The reinforced composite is called as WFPC. Specifically, when it comes to product liability and design layout with long-term behavior of the composite, in addition to their processing physical features plays a critical role in AM.

The rapid growth of WF reinforced plastic composite applications has also enhanced the demand for more accurate and uniform product property evaluation across the industry. WF improves the brittleness of PLA. Although WF make composite materials that are lightweight, recyclable, and frequently have good strength-to-weight ratios when mixed with PLA, this combination also presents a number of challenges. WFPC has certain unique advantages such as biodegradability, reinforcing ability, having several uses or simply being used in part, and having recycling possibilities makes WFPC to play a vital role in manufacturing sectors. The capacity to use waste materials and recycle them beyond their use lives are important benefits of utilizing wood with biodegradable or recycled polymers. Here wood reinforced PLA composite (WPCs) is used, through fusing wood dust and other powdered wood derivatives with PLA material this composite is made. Around 30% of wood particles are used to form WPC, in some cases this may vary depending on the brand. Wood is a biotic material which fused with PLA results in a composite filament that is largely biodegradable. When wood particles are combined with PLA the properties of both materials are blended together to form a distinctive property which would be suitable for numerous applications. The test is carried out on different infill pattern for which the failure occur on that material would vary from test to test based on the plane where load is applied. In metallurgy some composition of different materials is termed as Functionally Graded Materials (FGM). Though fusing different materials together, structural matrices would change based on the chemical and mechanical properties of that materials. FGM are used frequently than conventional materials due to its good comprehension of the various composite's fabrication process. FGMs represent a class of novel materials in which microstructures, compositions and constituents would gradually changes along single or multiple spatial directions, resulting in a gradual change in functions and properties which can be tailored for enhanced performance. Models are designed using 3D-Computer aided designing software and modification in parameters, specifications are performed by CURA a slicing software. Once the modifications are adjusted the commands are converted into Geometric codes (G-code), then it is fed to printer to provide the prototype. In space application this FGM is used to achieve the maximum heat resistance and mechanical properties ideal for spacecraft where one side may be exposed to extremely high temperature and other side may be exposed to extremely low temperature. Some automobile industries, were proposed and manufactures crash box using FGM with stepwise strength gradient in longitudinal directions. The proposed property of FGM crash boxes were analyzed using Finite Element Methods (FEM). Crash behavior of the crash box under axial quasi-static and dynamic impact loads were studied. The obtained load-displacement curves and the crash failure patterns then were evaluated to assess the effect of the stepwise strength gradient of crash box [1]. Yubo tao et al. [2] proposed that, through improving the material compatibility will increase interface force between WF and PLA. Which is beneficial for improving the mechanical properties of WF/PLA composite. Teng-Chun Yang et al [3] studied the morphology and mechanical properties of parts printed out of wood reinforced PLA at 30, 50 and 70 mm/s. They concluded that density and darkness of the material is decreased with increase in speed. Also, the compressive and modulus decreased printing at greater speed. From Scanning Electron Microscope (SEM) illustration, it is found that high speed printing produced an uneven surface of the part. J. Mocso et al [4] The endeavor to enhance the interaction at the interface through coupling has been fruitful. However, the enhancement attained was modest, as it only averted the detachment of a handful of sizable wood particles, leaving others prone to fracture. Considering that the failure of the composites primarily stems from fiber fractures, and their intrinsic strength appears to be the main constraint in bolstering composite strength, a fresh approach was imperative to enhance composite properties. Srikanth Pilla et al [5] A Cincinnati Milacron 33-ton injection molding machine was employed to mold the tensile test samples. Before processing, both PLA and PWF were dried in an oven at 55°C and 105°C, respectively, to eliminate any moisture absorbed during storage. Vigneshwaran et al [6] Carbon fibers and ABS resin were utilized as materials, with mixtures containing 10%, 20%, 30%, and 40% by weight of carbon fibers. The findings demonstrate a 115% increase in tensile strength and a 700% increase in modulus for the 3D-printed samples.

MECHANICAL PROPERTIES

Previous works described those mechanical properties of FDM-printed polymer components depended on the printing variables, in which orientation and raster angle plays an important role on mechanical attainment of these components [7]. During the evaluation on mechanical characteristics of PLA composites, the effects of build orientation and printing raster angle on mechanical properties were examined in this study through flexural and tensile test. The graphical representation for wood is presented in table 1, respectively [8,9]. As demonstrated, for PLA and its composites, the stress-strain curves, in the starting stage, follow the Hook's law (stress is directly proportional to strain) until it reaches ultimate yield stress. Once it reaches ultimate yield point, negligible amount of decrease in cross section (necking) occurs due to tensile deformation. This necking continued until the brittle fracture occurred without visible strain hardening. Through the results, it could be concluded that flexural and tensile properties are firmly depend on the variation of build orientation as well as raster angle. Regarding tensile and flexural properties between PLA and its composites with different filler materials, an obvious difference of mechanical behavior would be perceived [10]. To quantify and facilitate the analysis of flexural and tensile properties, ultimate strength, modulus and strain break were calculated and compiled in table1. Filler materials are so sensitive to tensile and flexural properties [11,12]. The FGM sample is built in a single machine according to the American society for testing and materials (ASTM) standard. Using CAD software, the samples are designed, followed by slicing software which shows layer-by-layer differentiation on the designed model. Dimensions are adjusted relatively and applied it for further development. Some manufacturing industries prefer this CAD software for designing and CURA as slicing software

Density	Elastic Modulus	Strength to Weight Ratio	Ultimate Tensile Strength	Thermal Expansion
1.25 g/cm^3	3.2 GPa	45.56 KN-m/kg	55 MPa	65.2 µm/m-k

Table 1. Mechanical properties of PLA

Sample I.D	Tensile Strength, MPa									
	Sample -1		Sample-2		Sample-3		Sample-4		Sample-5	
	1	2	1	2	1	2	1	2	1	2
Ultimate tensile stress, MPa	45.93	47.35	52.21	55.29	57.13	60.91	62.18	65.90	68.38	73.80
Yield stress, MPa	52.36	56.59	61.78	64.88	64.33	51.45	54.79	58.02	64.61	69.48
% of Elongation	26.56	25.32	77.88	31.48	24.16	24.96	24.96	24.96	25.44	25.48

Table 2: Sample mechanical properties

MATERIALS AND METHODS:

Filaments like Neat-PLA and WFRP were supplied by WOL3D with a diameter of 1.75mm. FDM-based 3D pinter (Model: Pratham 3.0) was used to fabricate functionally graded material the required details are entered in table 3. Process variables of 3D printer are shown in table 3-Dimensional tolerance of the printer is ± (0.1-0.5) mm which is an important parameter for printing a product. It is versatile and had an immense features like auto adjusting bed level, high infill speed, silicon-preheated bed, wi-fi connectivity and power failure protection. Before feeding the filaments, a material size of 200×75×2 mm^3 was developed in CATIA V5 R20 and sorted in Standard Tessellation Language (STL) format. Through exporting STL file to ULTIMAKER CURA, the designed product was sliced in several layers using this software and G-code was created. According to the G- code, set of instructions are fed to the FDM printer so that the process would execute to fabricate a product. In initial stage an adhesive agent was sprayed on the silicon preheated bed to ensure that, perfect bonding between base layer and the bed should attain to provide proper dimension of FGM. The quality of fabricated product using FDM technique was mainly depends upon various parameter [13,14,15]. The standard process parameter was determined from numerous trial and error experiment for the fabrication of FGM. During process parameter, neat PLA and WFPC were preferably accumulated with a thickness of 4.55 mm and the built orientation along horizontal plane (x-axis) were made. PLA act as a base material, which is used to attain better bonding with printer bed compared to WFPC. Mechanical experimentation samples were fabricated in accordance with ASM standards (ASTM xxx for compression, ASTM xxx for flexural, ASTM xxx for tensile). The printed FGM samples were gently removed after cooling process. The mechanical test was performed using a Universal Testing Machine (UTM): Tinius Olsen, with maximum load capacity of 50N and a constant strain rate (22). All the test were conducted until the samples get fractured. Yuzuki durometer was used for measuring the values of shore “D” hardness of the sample. During shore “D” hardness testing, xxx indentations with an interval of xxx mm were made along the built direction and the hardness values were taken in terms of shore “D”. Finite Element Analysis (FEA) was used to predict the mechanical behavior of FGM samples such as performance, strength and initial stage causing fracture using a software called ABAQUS. Using Scanning Electron Microscope (SEM) the microstructure changes of failed samples are analyzed. Followed by optical microscope buckling of layer, void of the samples, magnified image of interlayer bonding and fracture surface were observed. The samples of PLA and WFPC were used in this test and made an experimentation process on them, the outcomes were reported in results and discussion

PROCESS VARIABLES	VALUES
Nozzle temperature (^{0}C)	210^0
Bed temperature (^{0}C)	60^0

Infill pattern %	100%
Layer height (mm)	0.3 mm
Infill density %	30%
Printing speed	60 mm/s
Raster angle (degree)	45^0

Table 3: Process variables

FINITE ELEMENT ANALYSIS:

Finite element analysis (FEA) is an analytic method, which is performed on product to reduce the number of trials require to improve its efficiency. FEA is an analysis technique use to determine the failure of product design. It is widely utilized for illuminating complex problem that developed on the product. The output quality of FEA, always depends on the input quality of material and boundary condition which was applied to fabricate a product. The mechanical behaviour of polymer depends greatly on processing condition, which could be a best input for constitutive model. The main objective of analysis is to validate the proposed formulation through experimental data, obtained from the mechanical test of samples in order to achieve a suitable application in engineering industries. Abaqus is a commercial software which was utilized to perform the analysis process using finite element condition [16]. It is a user defined software that consist of wide range of elements, providing effective sets of tools for solving various types of problem. This software could claim the materials property in an adequate way and problems were defined to offer appropriate characteristics solution for each element. The samples were involved in multiple tests, through evaluating them under different loading conditions (tensile, compression) results are formulated. Compression and tensile test are designed as per ASTM standard. Thus, a material linked together to form a structural element must have either elastic property or complete mechanical behavior. At initial condition yield stress and strain should be zero for the plastic property of material. The obtained result for young's modulus of WPC is 4200 MPa. Feeding improper boundary conditions (BC) would lead to an error convergence of values in simulation, so this boundary condition plays a major role in Abaqus. During simulation two types of boundary conditions are widely used for tensile. BC-1 is Symmetry/ Antisymmetric / Encastre, D. selection of region, E. ENCASTRE (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0), which means that the bottom end of the sample is fixed when it undergoes tensile and compression test. This boundary conditions are provided in common when the required samples are to be fixed for both experimental values as well as for simulation. Other side of the plate region is enabled to move in Y-axis. Encastre signifies that the movements were arrested at all direction including unidirection (U1, U2, U3) as well as rotational direction (UR1, UR2, UR3), hence degree of freedom are zero.–{BC2}-. Mesh is a critical component in simulation which is used to determine the stress induced in finite particle of the specimen, after applying it in a different loading condition the stress that exhibits in each and every single element were analyzed accordingly to produce an accurate result. The output of the mesh depends upon size of the mesh in which the fine mesh would lead to an accurate result with permissible time, whereas a coarse mesh is used to observe the stress induced on specimen in a mass structure elemental view and certifies it in a reasonable calculation time. Decreasing the size of the mesh, would increase the accuracy of the simulation results. Mesh convergent research is carried out in order to improve the balance between minimum error as well as runtime of the simulation. Objects with infinite degree of freedom, would make it complicated to solve the problem manually. In Finite Element Simulation (FES), using mesh we separate the region into a specific number of elements and the results are processed by Abaqus in addition to that post-processing is performed. The total number of mesh element used to mesh the sample and compress the plate for compression test is 3500 and 592, respectively. Linear brick with 8 nodes, contain limited integration and hourglass control. For the sample and compression plate, 4-node 3-D bilinear stiff quadrilateral mesh types were employed.

RESULTS AND DISCUSSION:

Mechanical test such as tensile, compression and flexural test were carried out in UTM to assess the performance of newly designed FGM samples. The wood PLA composite demonstrated promising mechanical properties, with tensile strength and flexural strength within acceptable ranges for various applications. However, further improvements are necessary to enhance its performance, particularly regarding impact resistance and thermal conductivity.

BONDING CHARECTERISTICS OF FGM SAMPLE:

A key technique for determining the materials mechanical characteristics is microstructure observation. FGM sample undergoes an Optical Microscope (OM) analysis to observer the micrographs of inter-layer bonding at the interface of two polymer. During fabrication the inter layer was partly overlapped with one another in FGM samples. In untreated condition the samples were viewed under OM which reveals an unsatisfied result. In order to obtain a better observation, the samples were abraded using sandpaper which avoids uneven surface, also treated with acetone to remove the foreign particles that present in-between the layers of FGM samples [17,18]. Grit paper helps to increase proper surface finish of the layer. From micrographs of raw sample and surface treated sample, it is clearly understood that the grit paper abraded samples render a clear image of inter-changing layers by removing the well diffused outer most wall. Major defects were not observed whereas acceptable level of voids and porosity had marginal influence on mechanical characteristic of the FGM samples.

TENSILE TEST:

To measure ultimate tensile strength and young's modulus of the printed FGM samples, tensile test was conducted. Through analyzing the behavior of FGM samples under tensile load, results for FGM samples were observed [19,20]. Due to the formation of maximum crystallinity and bonding, FGM samples possess high tensile strength. The semi crystalline structure in the FGM sample, is due to formation of stereo complex crystallization (SC) that occurred during fabrication. This formation of SC on FGM samples would result in increasing of strong bonds between molecules. The FGM samples which consume semi-crystalline nature would possess good thermal resistance. This thermal resistance of material causes the FGM sample to retain the mechanical properties even at high temperature. Fractographs was represented in figure 1, it is obtained from the sample which undergoes load displacement. And the graph is shown in figure 2.

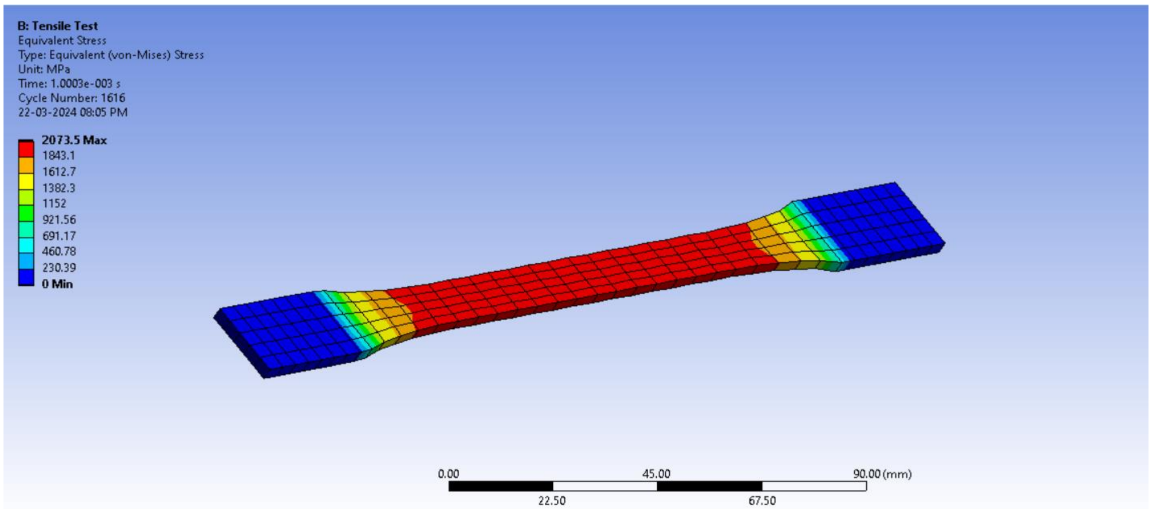
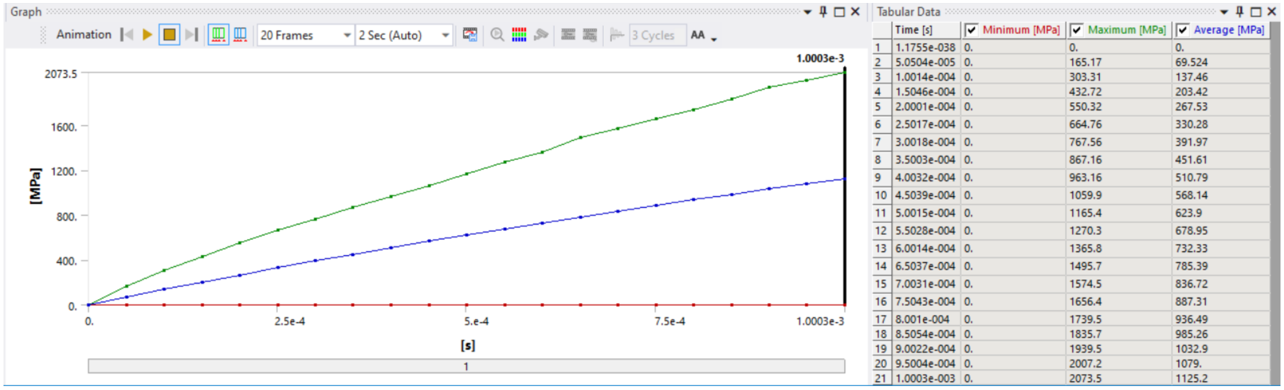


Figure 1: Tensile test of WFRP



	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	1.1755e-038	0.	0.	0.
2	5.0504e-005	0.	165.17	69.524
3	1.0014e-004	0.	303.31	137.46
4	1.5046e-004	0.	432.72	203.42
5	2.0001e-004	0.	550.32	267.53
6	2.5017e-004	0.	664.76	330.28
7	3.0018e-004	0.	767.56	391.97
8	3.5003e-004	0.	867.16	451.61
9	4.0032e-004	0.	963.16	510.79
10	4.5039e-004	0.	1059.9	568.14
11	5.0015e-004	0.	1165.4	623.9
12	5.5028e-004	0.	1270.3	678.95
13	6.0014e-004	0.	1365.8	732.33
14	6.5037e-004	0.	1495.7	785.39
15	7.0031e-004	0.	1574.5	836.72
16	7.5043e-004	0.	1656.4	887.31
17	8.001e-004	0.	1739.5	936.49
18	8.5054e-004	0.	1835.7	985.26
19	9.0022e-004	0.	1939.5	1032.9
20	9.5004e-004	0.	2007.2	1079.
21	1.0003e-003	0.	2073.5	1125.2

Figure 2: Tensile test graph of WFRP

COMPRESSION TEST

Compression test was performed on fabricated material to analyze its strength under compression load. Average of three test was conducted on three FGM samples of different dimension each specimen was tested in UTM and the experimental setup is shown in figure. In figure 3 the average results were marked. Hence from the result it is transparent that compressive strength of WFRP is maximum with 6449.7 MPa and minimum with 0 MPa. The graph is shown in figure 4.

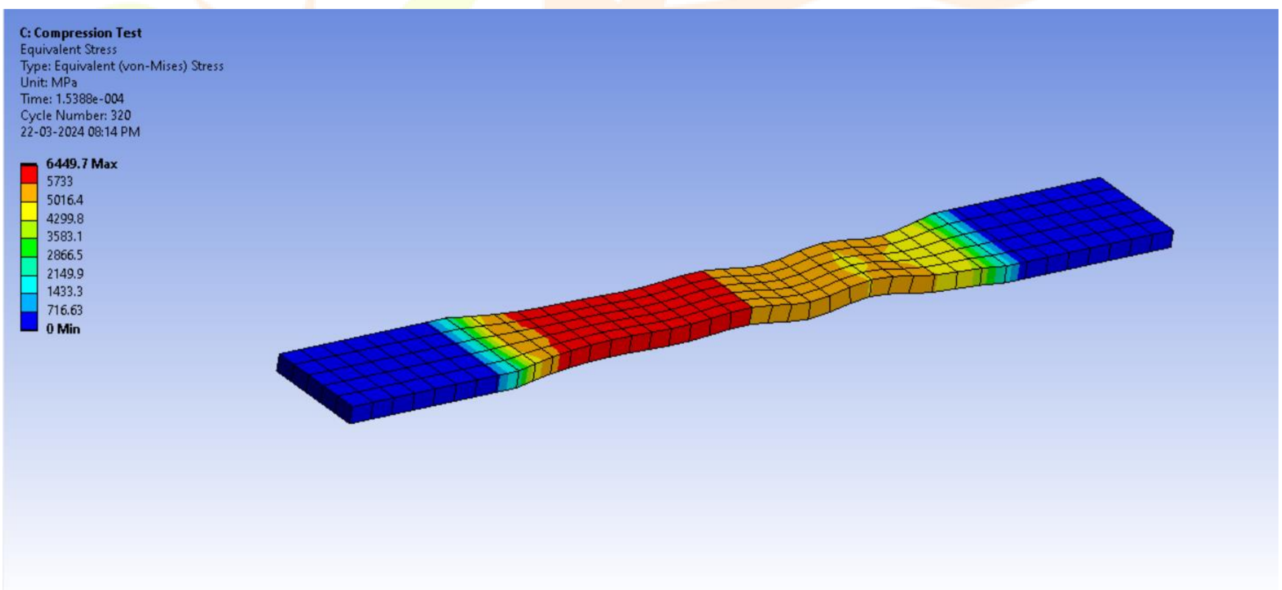
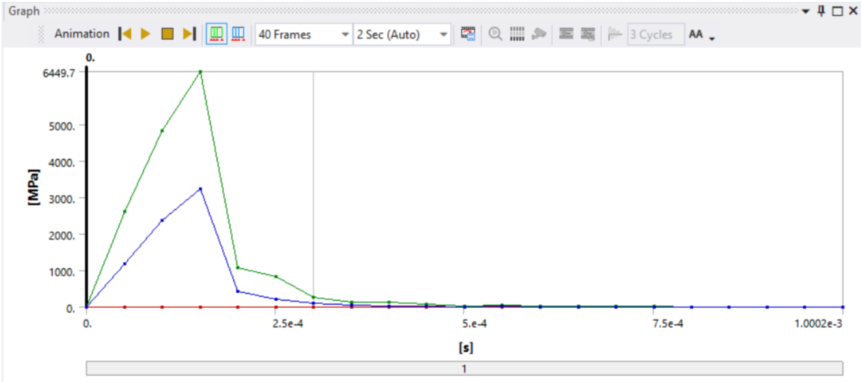


Figure 3: Compression test on WFRP



Tabular Data

	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	1.1755e-038	0.	0.	0.
2	5.0222e-005	0.	2613.7	1196.
3	1.0001e-004	0.	4832.4	2384.4
4	1.5004e-004	0.	6449.7	3240.7
5	2.0022e-004	0.	1092.	427.97
6	2.5019e-004	0.	839.84	222.27
7	3.0021e-004	0.	257.09	109.94
8	3.5025e-004	0.	148.25	45.584
9	4.0028e-004	0.	145.02	31.722
10	4.5001e-004	0.	69.066	15.874
11	5.0005e-004	0.	33.96	13.038
12	5.5009e-004	0.	43.14	18.855
13	6.0013e-004	0.	16.916	6.7742
14	6.5017e-004	0.	16.041	7.0331
15	7.0022e-004	0.	19.256	7.6181
16	7.5027e-004	0.	14.035	5.2359
17	8.0001e-004	0.	13.324	5.2181
18	8.5006e-004	0.	12.712	5.0012
19	9.0011e-004	0.	12.578	4.8276
20	9.5017e-004	0.	12.272	4.5583
21	1.0002e-003	0.	12.379	4.4574

Figure 4: Compression test graph of WFRP

FLEXURAL TEST

The flexural test, also known as the bend test or the three-point bending test, is a mechanical test used to determine the flexural properties of materials such as wood PLA (Poly Lactic Acid) composites. This test measures how a material behaves when subjected to bending forces, providing valuable information about its stiffness, strength, and ductility under bending loads. In the context of wood PLA composites shown in figure 5, the flexural test involves applying a bending load to a standardized specimen of the composite material until it deforms or fractures. The specimen is typically a rectangular beam-shaped sample with specific dimensions according to standards such as ASTM D790. With result graph in figure 6.

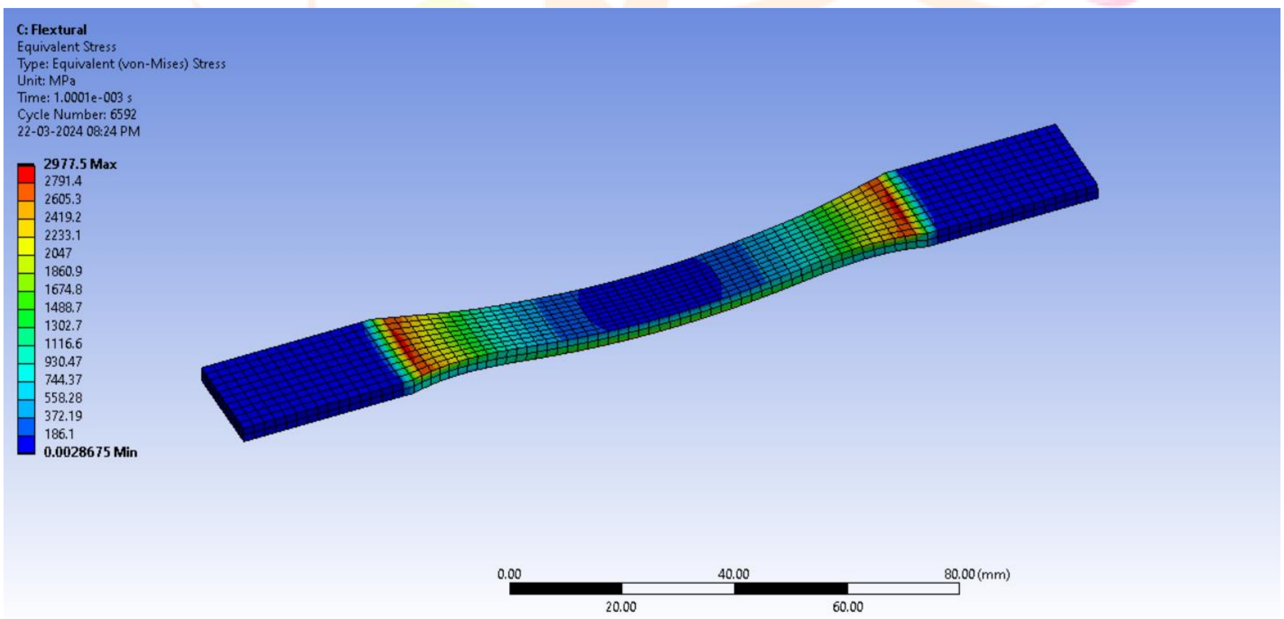


Figure 5: Flexural test of WFRP

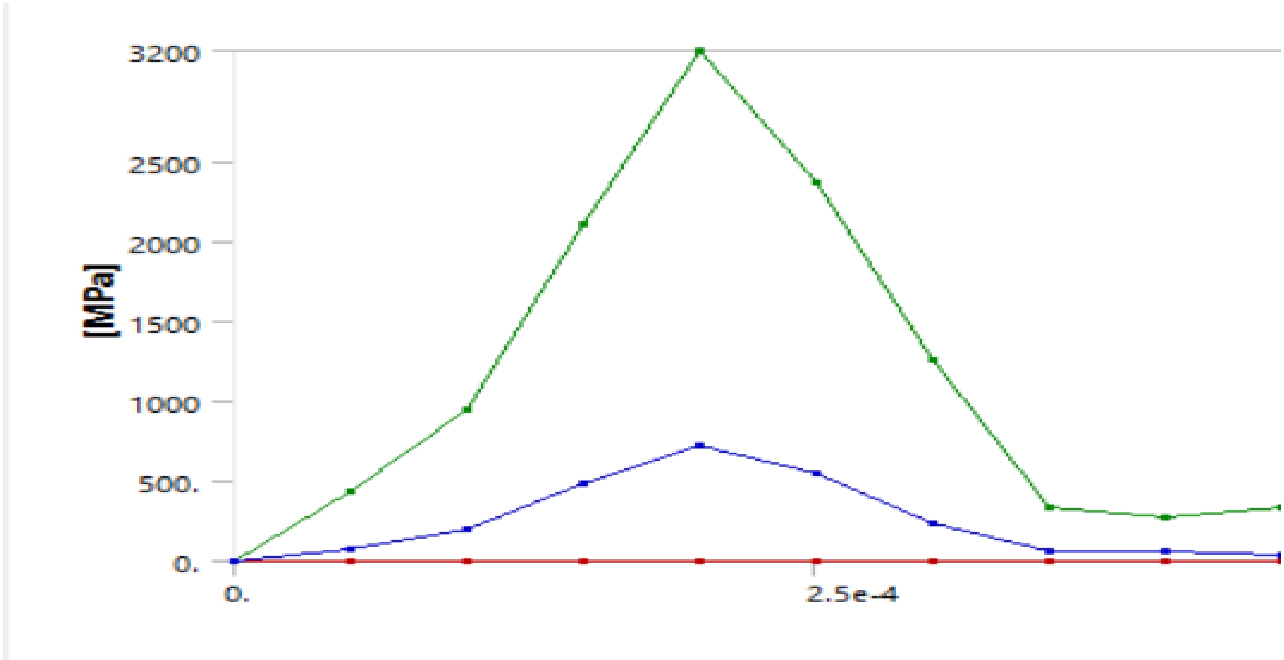


Figure 6: Flexural test graph WFRP

CONCLUSION

In conclusion, this research paper has delved into the realm of enhancing the mechanical properties of Poly Lactic Acid (PLA) composites through wood reinforcement, providing a comprehensive investigation into this intriguing area of study. The synthesis of PLA-based composites reinforced with wood fibers or particles has garnered significant attention due to the unique combination of properties offered by both materials. Through a meticulous exploration of various factors including material selection, processing techniques, and mechanical characterization, this study has shed light on the potential of wood reinforcement in augmenting the performance of PLA composites across different applications. One of the key findings of this research is the significant improvement observed in the mechanical properties of PLA composites upon the incorporation of wood reinforcements. Through meticulous experimentation and analysis, it has been demonstrated that the addition of wood fibers or particles contributes to enhancements in tensile strength, flexural strength, impact resistance, and thermal stability of the resultant composites. Moreover, the synergistic effects arising from the unique combination of PLA and wood constituents have been elucidated, highlighting the potential for tailored material properties to meet specific application requirements. Furthermore, this study has explored the influence of various parameters such as wood particle size, aspect ratio, content, and surface treatment on the final properties of PLA composites. By systematically varying these parameters and analyzing their effects on the composite performance, valuable insights have been gained into the optimization of wood-reinforced PLA formulations. Additionally, the investigation into processing techniques including melt blending, extrusion, and injection molding has provided crucial understanding regarding the fabrication of high-quality PLA composite materials with enhanced mechanical properties. Importantly, the environmentally friendly nature of PLA and wood constituents underscores the sustainability aspect of these composites, aligning with the growing demand for eco-friendly materials in diverse industries. The biodegradability and renewable sourcing of PLA, coupled with the abundant availability of wood resources, present a compelling case for the widespread adoption of wood-reinforced PLA composites as viable alternatives to traditional petroleum-based plastics. In conclusion, this research contributes to the body of knowledge surrounding the development of sustainable and high-performance polymer composites by offering a comprehensive investigation into the enhancement of mechanical properties through wood reinforcement. The insights gained from this study pave the way for further advancements in material science and engineering, with potential applications ranging from automotive components and packaging materials to construction and biomedical devices. As we continue to strive towards a more sustainable future, the exploration of innovative materials such as wood-reinforced PLA composites holds immense promise in addressing the challenges of resource depletion and environmental degradation while simultaneously meeting the ever-evolving needs of modern society as the total results of the wood-PLA test are shown in table 4.

TESTING PERFORMED ON SPECIMEN	MAXIMUM RESULT
TENSILE STRENGTH (MPa)	2073.5
FLEXURAL STRENGTH(MPa)	2977.5
COMPRESSION STRENGTH (MPa)	6449.7
IMPACT STRENGTH (MPa)	4027.9
THERMAL COEFFICIENT (W/mK)	8.52

Table 4: Result and conclusion

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