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Influence of Process Parameters and Filament Material of 3D Printing FDM on Flexural Property of PLA and PLA Composites

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Abstract-3D printing is a promising digital manufacturing technique that produces parts, layer by layer. Different from other 3D printing techniques such as selective laser sintering (SLS), stereolithography (SLA), three-dimensional printing (3DP), and laminated object manufacturing (LOM), the fused deposition modeling (FDM) technology is widely used in aerospace, automobile making, bio-medicals, smart home, stationery, and training aids, and creative gifts for its easy use, simple operation, and low cost. Polylactic acid (PLA) is a material most extensively applied in FDM technology for its low melting point, non-poison, non-irritation, and sound biocompatibility. The properties of FDM-produced parts are significantly influenced by the processing parameters. This paper investigates the effect of process parameters on the flexural property of specimens produced by FDM technique. The study is carried out on PLA, PLA Plus, wood, and carbon fiber composite PLA material, by using the full factorial design of the experiment to analyze the effects of control factors on the flexural property of the FDM specimens. For the investigation, three control factors printing orientations, layer thickness, and filament material are considered. From the investigation, it is observed that among the considered factors, (Printing orientations and filament material) significantly influenced the flexural property of the FDM specimens. Further, the effectiveness of each parameter is investigated by using ANOVA and drawn out the set of parameters that gives superior results for better mechanical properties of PLA.

Keywords-*Fused Deposition Modeling (FDM), Polylactic Acid (PLA), Three-Dimensional Printing (3DP)*

I. INTRODUCTION:

Rapid Prototyping (RP) is also known as 3D printing (3DP) is already used in the production of various components. This is due to mainly the fact that certain products simply cannot be produced by other conventional manufacturing processes [1]. This is mostly due to the number of possible advantageous that 3D printing can offer compared to conventional energy-intensive techniques: the ability to fabricate complex geometries as a single unit/part with no joints, lower material and labor cost, good surface finish, lower energy demand, single step processing temperature, less process complexity (CAD model-Print-Install), near-net-shape finish, quick production time, short lead time, the less overall cost compared to the conventional technologies, and so forth[2].

Among the different AM techniques, 3D printing based on fused filament fabrication (FFF)-using thermoplastic polymers that require low melting temperature and rapid solidification times-is widely adopted for the simplicity of the method and its relatively low cost and low material wastage [3,4,5-7]. FFF forms a 3D geometry through the deposition of successive layers of extruded thermoplastic filament. Currently, fused deposition modeling (FDM) is not only used to produce visual aids, conceptual models, and prototypes, but it is also used to produce functional parts such as drilling grids in the aerospace industry [8] and edentulous mandible trays [9]. such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polypropylene (PP), or polyethylene (PE).

Therefore, proper selection of process parameters must be done to create a product with high quality to fulfill customer requirements. These process parameters available on the FDM machine will change the final product's mechanical properties such as tensile and flexural properties. Sood et al. [10] have studied the impact of five main process parameters such as part orientation, layer thickness, air gap, raster angle, and raster width on mechanical properties of the test specimen. The experiment result shows the number of layers in a product relies on the part orientation and layer thickness. Increasing the number of layer thickness improves the strength of the parts. A small raster angle also improves the quality of the parts. Chacón et al. [11] studied the effect of build orientation, layer thickness, and feed rate on the tensile and flexural properties of Polylactic acid (PLA) material and concluded that upright orientation resulted in the poorest mechanical performance, whereas the edge and flat orientations resulted in the highest strength and stiffness. Motaparti et al. [12] investigated the effect of parameters on the flexural properties of ULTEM 9085 parts with solid and sparse build styles. Their investigation revealed that the vertical (edge) build direction could result in greater flexural yield strength.

In this study, commercially available polylactic acid (PLA), PLA Plus, wood, and carbon fiber PLA composite filaments were used to manufacture different specimens by the FDM technique using a 3D printer. The flexural properties, in terms of three-point bending performance, are evaluated. The effect of material and process parameters such as build orientations and layer thickness are analyzed. A comparison of the flexural strength between virgin PLA and PLA composites samples is also conducted. Finally, an ANOVA process will be done for finding the best factor which shows greater impact compared with other control factors.

II. EXPERIMENTAL PROCEDURES

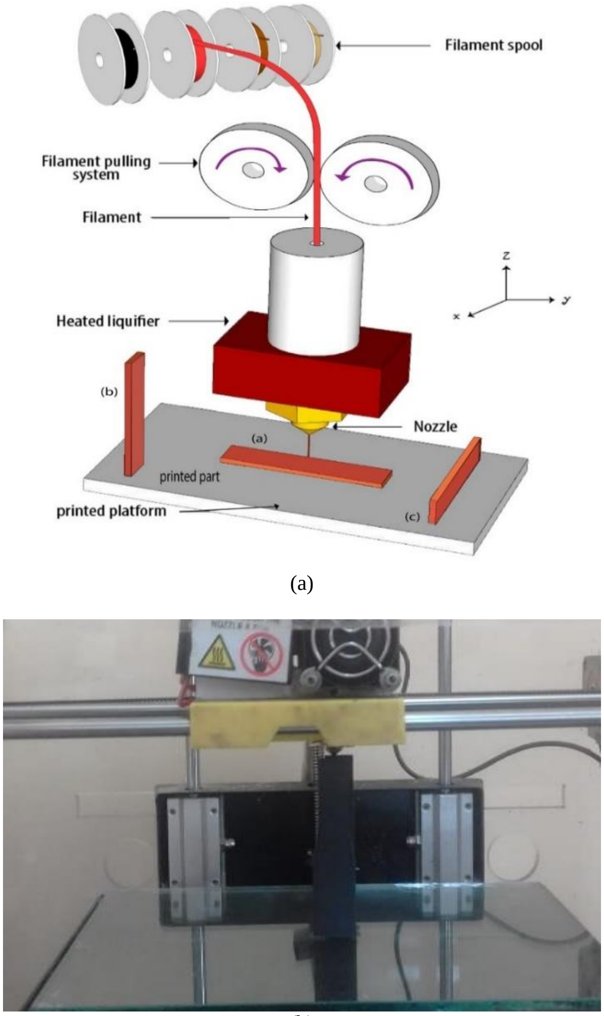
A. *Filament material*

Polylactic acid (PLA) has been selected for the fabrication of specimens. Poly (lactic acid) material is a biobased, biocompatible and biodegradable polymer that is generally produced from renewable sources (e.g., corn, sugar cane, wheat, and rice). The production of poly (lactic acid) is environmentally advantageous since it is obtained from natural sources and due to the consumption of large amounts of carbon dioxide gas during its production.

- Filament diameter: 1.75 mm
- The density of the Filament: 1.25 g/cm^3.
- Favorable Working Temperature: 210 °C.
- Bed Temperature to be maintained: 60˚ C.

B. *Fused deposition modeling (FDM)*

A spool of one of the following thermoplastic type filament (PLA, PLA Plus, wood, and carbon fiber PLA composites) is fed into the heated extruder through the driven pulleys as shown in Figure 1 and the filament material melted down to its printed temperature which adjusted in the programming code. The thermoplastic filament was driven by pulleys, in those pulleys, one was the driver pulley and another one is the driven pulley. The heated temperature for filaments will be adjusting. Based on these filament materials there existed various nozzle materials such as brass, steel alloy, etc. For PLA material, a brass nozzle would be sufficient for fabrication. Filament material after passing by extruder a molten state thin substance coming out through nozzle hole and this thin substance form thin layers (0.1,0.2 and 0.3 mm) one over the other with raster angle 45° until the specimen completely fabricated. Fabrication of FDM specimens with flat and upright orientation doesn't need support material. For on-edge orientation, an extra filament material for supporting the structure named as support material was used.



(a)

(b)

Figure 1. a) The schematic of the Fused Deposition Modeling (FDM) method, b) flexural specimen printed in upright.

C. *Specimen preparation*

To study the PLA material Flexural property, there is a need for fabrication of specimens; this can be achieved with the help of a 3D Printer of FDM type. To understand the Flexural property deeply, the processing parameters of the material will be varied while fabricating specimens on an FDM printer. Varying the process parameters could be achieved using slicing software of ''simplify 3d version'' where we include or introduce or change the processing parameters values such as layer thickness printing orientations.

TABLE I. KEY PRINTING PARAMETERS USED IN THIS WORK

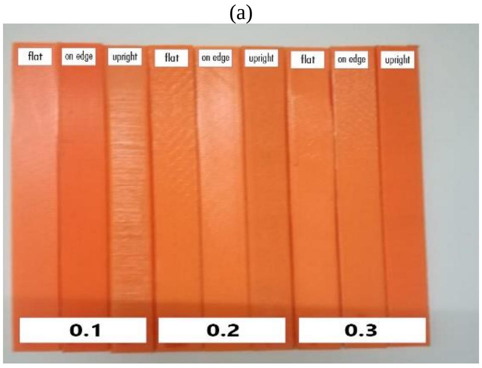
Nozzle Temperature	210˚
Printing speed	60mm/min
Nozzle diameter	0.4
Object Infill density	100%
Raster angle	45˚/-45˚

The changes in the process parameters were given to the CAD design which was created or generated by the CAD software ‘‘SOLIDWORKS 2016” as per ASTM standards. Once the CAD model is generated, it will be saved as in the format of ‘.STL’ and further, the parameters have been included in the ‘‘simplify 3d version” software. Finally, the saved G-code file will be run by the FDM printer to get the fabricated ASTM 790 standard specimens. The specifications and parameters included in the fabrication process of the specimen were listed in Table1.

D. *Design of experiments*

Figure 2 shows the fabrication of the specimen within the ASTM 790 standards on FDM printer. For study influence of three control factors on fabrication and flexural property of FDM specimens used full factorial case. Two processing parameters such as Layer Thickness and printing orientations have been considered and these two factors and filament material factor by full factorial design outcomes 36 specimens each for a flexural test. Table 2 shows process parameters and their levels. The following figures visualize the process of fabrication.

(a)



(b)

Figure 2. Flexural specimens with a) a-flat, b-on-edge, and c-upright orientation of different materials, b) Virgin PLA with various printing orientations and layer thickness

TABLE II. CONTROL FACTORS AND THEIR LEVELS FOR EXPERIMENTAL DESIGN.

S.No.	Control Factors	Levels			
		1	2	3	4
1	Material(PLA)	Virgin	PLUS	Wood	Carbon
2	Orientations	Flat	On-edge	Upright	
3	Layer thickness	0.1	0.2	0.3	

E. *Flexural test*

To examine the flexural property of the specimens will find out by doing a three-point bending test. A three-point bending test will conduct on Universal Testing Machine (UTM) performed on the ASTM D790 standard specimen. The flexural strength is measured where the specimen is loaded in the center while resting on two supports. The specimens are made with 125 mm length, 13 mm width, and 3 mm thickness. Overall, 36 specimens were tested for flexural strength of the specimen at each factorial case.

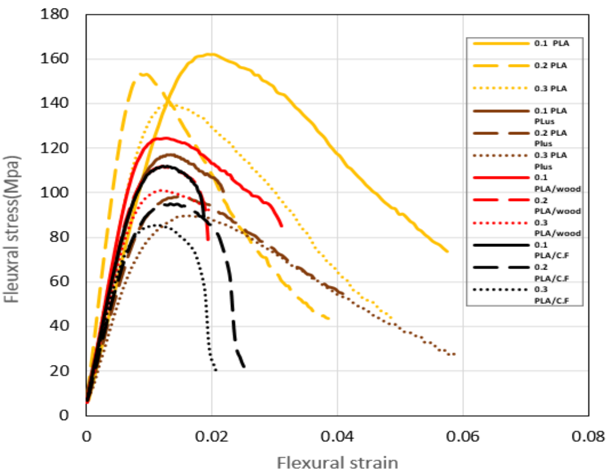
II. ANALYSIS AND RESULTS

A. Stress-strain curves of flexural test

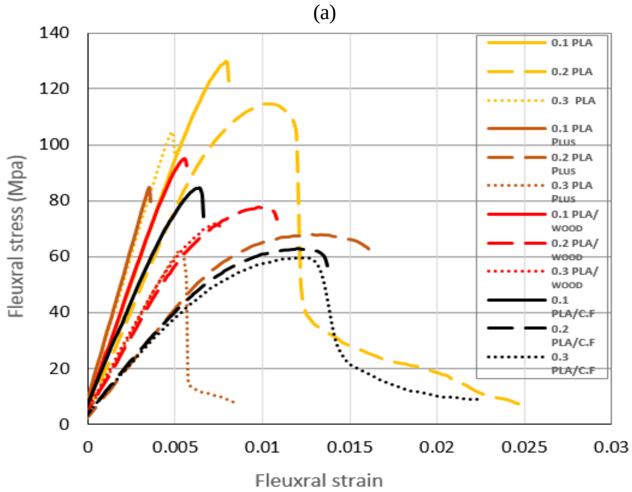
To study the flexural property of FDM specimens, the effect of filament material and process parameters as printing orientations and layer thickness were analyzed in this study through a flexural test. The stress-strain curves for a flexural test of FDM specimens of PLA and PLA composites materials printed with a layer thickness (0.1, 0.2 and 0.3 mm) in different orientations are presented in Fig.3. As shown, for PLA and its composites, the stress-strain curves, in the initial stage, follow Hooke’s law (strain proportional to the stress) until ultimate yield stress. After the ultimate yield point, negligible necking continued until the brittle fracture occurred without visible strain hardening. Moreover, from stress-strain curves, it can conclude that the flexural strength of FDM specimens is higher influenced significantly by filament material and printing orientations compared to layer thickness. It is cleared from Fig. that the optimum flexural strength of FDM specimens printed in on-edge orientation with 0.1 mm layer thickness of Virgin PLA material. Results have demonstrated a high flexural strain of FDM specimens printed in flat and on-edge orientation than printed in an upright orientation. Moreover, wood fiber PLA composite is low flexural strain material.

B. *Influence of control factors on flexural strength*

Figure 4(a) shows a variation of average flexural strength of FDM specimens with different levels of layer thickness (0.1, 0.2 and 0.3 mm) printed with PLA and PLA composites materials. It has been found that the average flexural strength varies between 156 and 88 Mpa. It is clear from Fig. that increasing layer thickness of FDM specimens printed with PLA and PLA composites in (flat, on-edge, and upright) orientations decrease average flexural strength. it can conclude that decreasing in layer thickness from 0.1 to 0.2 mm decreases the average flexural strength more than decreasing layer thickness from 0.2 to 0.3 mm for all filament materials. For example, FDM specimens of virgin PLA material printed with a layer thickness of (0.1, 0.2, and 0.3 mm), exhibited average flexural strength of 156,144 and 135 Mpa, respectively.



(a)



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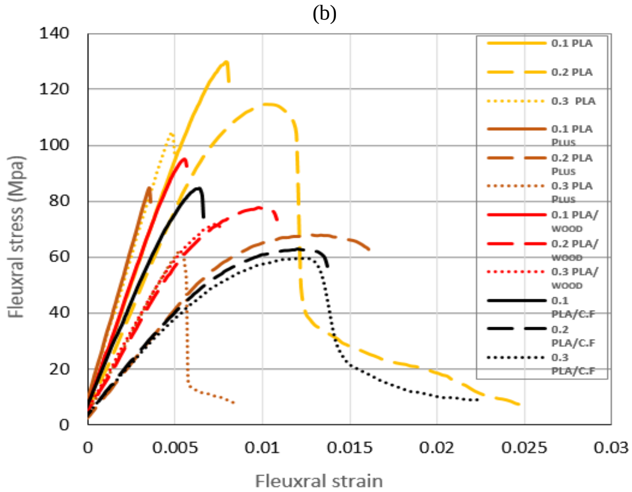
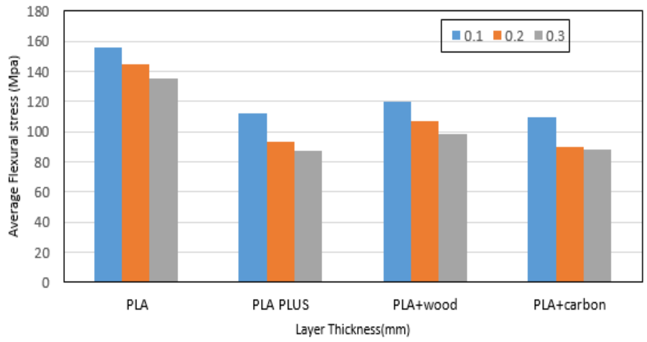
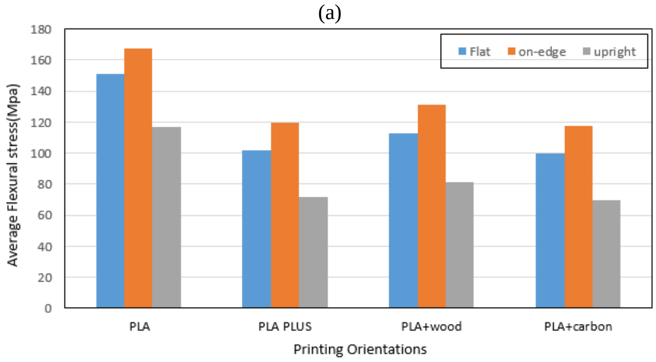


(c)

Figure 3. Flexural stress-strain curves of FDM specimens of PLA and PLA composites printed with different layer thickness combinations under different printing orientations: (a) flat, (b) on-edge, (c) upright.



(a)



(b)

Figure 4. Variation of average flexural strength of FDM specimens of PLA and PLA composites printed with various: (a)layer thickness, (b) printing orientations.

Figures 4(b) show the variation of average flexural strength of FDM specimens printed in (flat,on-edge, and upright) printing orientations with PLA and PLA composites materials. It has been found that the average flexural strength varies between 151 and 69 Mpa. It is clear from Fig. that FDM specimens printed in flat and on-edge orientations exhibited higher average flexural strength when compared with those printed in an upright orientation. For example, FDM specimens of wood and carbon fiber PLA material printed in (flat, on-edge, and upright) orientations, exhibited average flexural strength of 100, 117, and 69 Mpa, respectively, for carbon fiber PLA composite and 113,131 and 81.5 Mpa, for wood fiber PLA composite. The maximum flexural strength of 167 Mpa was obtained for on-edge orientation for virgin PLA specimens.

Figures 5 shows the variation of average the flexural strength of FDM specimens printed with (PLA, PLA PLUS, wood, and carbon fiber PLA composite) filament materials under different process parameters (layer thickness and printing orientations). It has been found that the average flexural strength varies between 145 and 96 Mpa. It is clear from Fig. that specimens printed in Virgin PLA material exhibited higher average flexural strength when compared with those printed with different PLA composites materials. For example, FDM specimens of Virgin PLA and PLA PLUS material printed with different process parameters, exhibited average flexural strength of 145 and 98 Mpa, respectively.

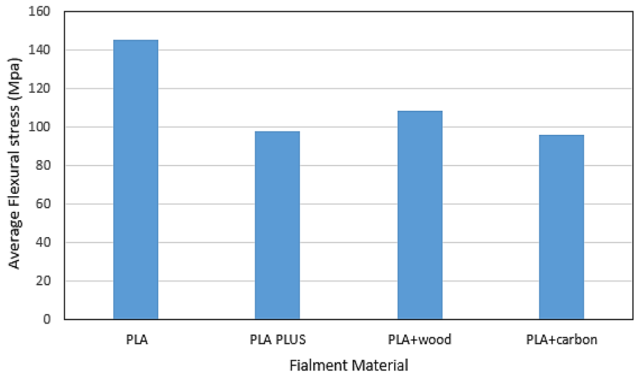


Figure 5. Variation of average flexural strength of FDM specimens of every material with all process parameters variation.

TABLE III. THE ANOVA RESULTS FOR FLEXURAL STRENGTH OF FDM SAMPLES.

Source of variation	DF	Adj SS	Adj MS	F-Value	P-Value	P_c
Layer thickness	2	3148.4	1574.21	232.16	0.000	9.69
Printing orientations	2	14892.6	7446.28	1098.16	0.000	45.86
Filament Material	3	14238.7	4746.22	699.96	0.000	43.85
Residual	28	189.9	6.78			100.00
Total		32469.5				
R^2 = 99.42%						

DF, degrees of freedom; SS, sum of squares; MS, mean square; F, F-test, P, Statistical significance, P_c; percentage of contribution.

According to the aforementioned results, it can be concluded that for PLA and its composites, the best flexural property could be obtained when the minimum thickness of layers and printing orientations of printed filaments are oriented longitudinally (e.g. the cases in flat and on-edge orientations). On the contrary, the worse flexural properties could be obtained when the tested specimen is loaded along with the build orientation (e.g. the cases in upright orientations) due to weak interlayer bonding. The results revealed also that FDM specimens printed with Virgin PLA filament material exhibited higher average flexural strength when compared with those printed with a filler or fiber PLA.

C. ANOVA Results

Table 3 lists the ANOVA results for flexural strength of FDM samples. The last columns in the tables show the percentage of contribution (P_c) of each factor on the total variation indicating the influence of the factors on the results. The higher the value of the P_c, the more statistical and physical significant the factor is. From the analysis of Table 3, it can be observed that printing orientations, layer thickness, and filament material significantly affect the flexural strength of FDM samples. The angle orientation and filament material exhibited the highest statistical and physical significance on the flexural strength of FDM samples. The layer thickness exhibited much lower statistical and physical significance when compared with the printing orientations and filament material. The printing orientations and filament material exhibited P_c values of 45.87 % and 43.85%, respectively. for the flexural strength of FDM samples. While the layer thickness exhibited (P_c) values of 9.697 %for flexural strength of FDM samples. From Tables 3, it is clear that the residuals are less than 2%, which indicates that there are no interactions between angle orientation, layer thickness, and filament material.

Figure 6 shows the main effect plot for flexural strength will be structured between printing orientations (O), layer thickness (L), and filament material (M), it is observed that the flexural strength of the material gradually decreases with an increase in its layer thickness. Coming to printing orientations of FDM samples at on-edge orientation increasing flexural strength otherwise flexural strength decreases. Printing orientations had shown good flexural strength at flat and on-edge but upright, the flexural strength of the material has shown downfall.

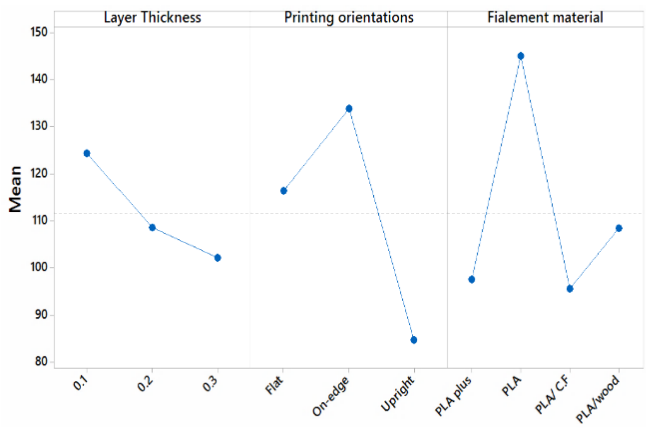


Figure 6. Main Effects plot for Flexural strength.

The following equation is regression analysis equation for the flexural strength, and it gives predicted values for the flexural strength and those values will be tally with the experimented values.

Flexural Strength = 111.731 + 12.684 L_1- 3.097L_2- 9.587L_3 + 4.706 O_1 + 22.222 O_2 - 26.928 O_3 + 33.381M_1- 14.105 M_2 – 3.192 M_3 -16.083 M_4. (1)

1) Analysis of experimented and predicted values of flexural strength:

All the test specimens (36) printed by FDM printer for evaluating the strengths of flexural has been undergone for test and the values obtained were listed in the below Table 4. Predicted values for these tensile strengths were obtained from the equations generated during the ANOVA analysis. And to know the accuracy of the experimentation conducted, there a finding of Error percentage helps in determining the deviation between the obtained and predicted values. The mathematical equation representation was written below here.

Percentage of Error=

$$|(\text{Experimented-Predicted})|/(\text{Experimented}) \quad (2)$$

Error percentage has been calculated and it ranges differently for flexural strength. Coming to tensile strength, error reaches up to 1.691%. By averaging all these percentages of error, the final results were as, for flexural it was 0.97 % i.e., mean error. All the values were mentioned in the following Table 5, where: A, B, C, D, and E refer to Layer thickness, printing orientation, experimented, Predicted, and % Error, respectively. The following bar graphs were drawn by the values taken from Table 4. Graphs were generated between experimented and predicted values of the specimens for flexural strengths. Figure 7 was for comparison between Experimented and Predicted Tensile strength.

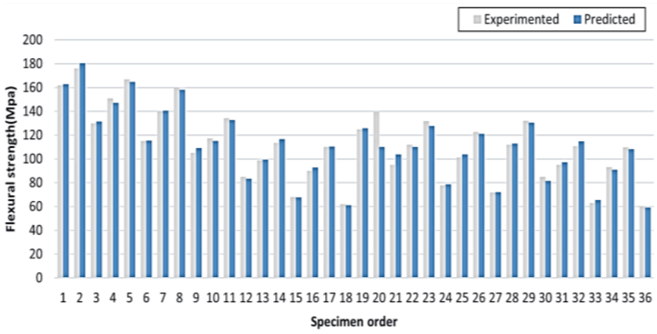


Figure 7. Comparison between experimented tensile strength & predicted tensile strength.

III. CONCLUSIONS

Based on the results presented, the following conclusions can be drawn, the FDM flexural specimens printed in on-edge orientation exhibited higher flexural strength than FDM specimens printed in the flat or upright orientation. While all the samples printed along upright orientation have the weakest flexural strength due to weak interlayer bonding, and can conclude also that the increasing layer thickness of FDM specimens decreasing the strength of specimens. Furthermore, the optimum layer thickness was 0.1 mm. For filament materials, Virgin PLA filament material of 3D printing FDM specimens exhibited better flexural property than those printed with PLA composites filament materials. Filament material and printing orientation exhibited the highest statistical and physical significance effect on FDM specimens. FDM specimens showed that the highest value records at layer thickness 0.1mm printed in on-edge orientation with virgin PLA material.

TABLE IV. FLEXURAL STRENGTH VALUES AT MAXIMUM POINT OF EXPERIMENTED AND PREDICTED.

Specimen No.	Material	Process Parameters		Flexural strength (MPa)		
		A	B	C	D	E
1	Virgin PLA	0.1	Flat	162	162.93	0.6138
2		0.1	On-edge	176	180.45	0.5542
3		0.1	Upright	130	131.3	0.7616
4		0.2	Flat	151	147.15	0.6796
5		0.2	On-edge	167	164.67	0.6073
6		0.2	Upright	115	115.52	0.8657
7		0.3	Flat	140	140.66	0.7109
8		0.3	On-edge	160	158.18	0.6322
9		0.3	Upright	105	109.03	0.9172
10	PLA PLUS	0.1	Flat	117.1	115.02	0.8694
11		0.1	On-edge	134.1	132.53	0.7545
12		0.1	Upright	85	83.382	1.1993
13		0.2	Flat	98.71	99.235	1.0077
14		0.2	On-edge	113.7	116.75	0.8565
15		0.2	Upright	68	67.601	1.4793
16		0.3	Flat	90	92.745	1.0782
17		0.3	On-edge	110	110.26	0.9069
18		0.3	Upright	62	61.111	1.6364
19	PLA/Wood	0.1	Flat	124.9	125.93	0.7941
20		0.1	On-edge	139.6	110.15	0.9079
21		0.1	Upright	95	103.66	0.9647
22		0.2	Flat	112	110.15	0.9079
23		0.2	On-edge	131.9	127.66	0.7833
24		0.2	Upright	77.74	78.514	1.2737
25		0.3	Flat	101.2	103.66	0.9647
26		0.3	On-edge	122.6	121.17	0.8253
27		0.3	Upright	71.89	72.024	1.3884
28	PLA/carbon	0.1	Flat	112	113.04	0.8847
29		0.1	On-edge	132.2	130.55	0.7660
30		0.1	Upright	85	81.404	1.2284
31		0.2	Flat	95.08	97.257	1.0282
32		0.2	On-edge	110.6	114.77	0.8713
33		0.2	Upright	63	65.623	1.5239
34		0.3	Flat	93.13	90.767	1.1017
35		0.3	On-edge	109.9	108.28	0.9235
36		0.3	Upright	60	59.133	1.6911
				Error%		0.9711%

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