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Influence of Infill Pattern, Infill Ratio on Compressive Strength and Hardness of 3D Printed Polylactic Acid (PLA) Based Polymer

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Abstract

In this article, the influence of infill ratio and infill pattern on the compressive strength and hardness of 3D printed polylactic acid (PLA) based polymer are studied. The fused deposition modelling (FDM) technique was used to produce the 3D-printed samples. In the current work, three specimens of each type have been tested with selected infill ratios (30, 50, and 70%) and infill patterns (line, gyroid, and trihexagon). A compression test was done using the general-purpose (EN772-1) manual compression testing machine for blocks, cubes, and cylinders by the standard specification (ASTM D695), and hardness shore-D was tested by using a hand-held durometer (Shore Instruments, Type D), by ASTM D2240-05 (2010) type D. The data were collected and processed. The results showed that the 70 percent infill ratio with a linear pattern had the highest compressive strength. On the other hand, the hardness test shows that the maximum hardness value was found at the base side of the specimens.

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1. Introduction

3D printing is one of the manufacturing techniques, where the pieces are manufactured by dividing their 3D designs into very small layers using computer programs. The manufactured then used 3D printers through printing one layer upon the other until the final shape is formed. This system differs from the CNC manufacturing, injection molding or sculpting systems, which reduce waste between 70% and 90% of the wasted material used in manufacturing. Some of the 3D printing uses are in Automobiles, Jewelry making, Spare & Replacements Parts, the sport-footwear industry, Model making and many other uses. 3D printers are usually Environmentally Friendly, more economical, and easier to use than other manufacturing technologies. This technique gives developers the ability to print complex nested parts, which can be made from different materials with different mechanical and physical specifications and then assembled. Advanced 3D printing technologies produce models that closely resemble the look, feel, and function of a product prototype. Many kinds of research were carried out in the last decade in an attempt to improve the efficiency of 3D printing. V. D. Sagias et. al. studied the tensile strength of 3D printed polymers, using three infill patterns (diamond, cross, and honeycomb). The study also included the effect of other printing factors like layer thickness, print strength, and placement (whether the printing is horizontal or perpendicular). The researchers found that all of these parameters had influenced the ultimate tensile strength of the printed specimens, and the specimen printed according to the combined effects of the 70µm thickness, 45° placement on the printing platform, and honeycomb and solid printing, had the highest tensile strength of all specimens [1]. A study was carried out by Rismalia et.al. to study the effect of infill density of 3D printed objects on the tensile properties (tensile strength and the stress-strain relation). The researchers used polylactic acid as a material and different infill patterns (grid, tri-hexagon, and concentric), with an infill density (25, 50, and 75%). The tensile strength increased during increasing density, sequentially with Young's modulus value. The concentric infill pattern also gave the highest tensile strength and young's modulus compared to the tri-hexagon and grid pattern [2]. Harshit K. Dave et. al. studied the influence of the printing parameters on the mechanical properties of the printed samples. Namely: the layer height which was in the range (0.1, 0.2, and 0.3 mm), infill density (0.6, 0.7, and 0.8 %), and print speed (30, 40, and 50 mm/min). Polylactic acid (PLA) in fused deposition modelling (FDM) was used as a printing material. Compressive test as a mechanical property was inspected, which showed that the sample with (0.2 mm layer height, 80% infill density and 40 mm/min. print speed) was the strongest [3]. In this study, compression test specimens were printed using a 3D printer of polylactic acid (PLA) as a polymer material. Different infill ratios (30, 50, and 70 %) and infill patterns (line, gyroid, trihexagon) were employed. This study aimed to find the best combination of infill and ratio to obtain the highest possible compressive and hardness properties.

2. Method/ Experimental Work

2.1. Materials

Polylactic acid (PLA) is aliphatic polyester commonly made from α -hydroxy acids, which include polyglycolic acid / polymandelic acid, and is a biodegradable and compostable polymer, in addition to its high-strength and high-modulus of elasticity. PLA can be degraded by simple hydrolysis of the ester bond, as it undergoes thermal degradation at temperatures above 200°C (392°F) [4]. It also has a glass transition temperature (55°C) and melting temperature of about 175°C. The required processing temperatures when it is printed by 3D technique is 190–220°C. PLA also has a high molecular weight and it is colorless, glossy, stiff, with properties similar to polystyrene as shown in Table 1 [4].

Table 1: Material Properties of Polylactic Acid (PLA) [5][6].

Properties	Units	Value
Melting point	°C	190-220
Density	g/cm^3	1.2-1.25
Diameter of filament	mm	1.75
Tensile yield strength	MPa	62.63
Elongation at break	%	4.43
Flexural strength	MPa	65.02
Flexural modulus	MPa	2504.4
Impact strength	KJ/m^2	4.28

2.2. Method

Fused deposition Modelling (FDM) is a 3D printing process that uses filament (PLA White) of a thermoplastic material. The filament is fed through a moving, heated printer extruder head, and is deposited on the Printer bed. The print head moves under computer control to define the printed shape. The samples first were designed in a 3D modelling software (Fusion 360) with a size of (20×20×40) mm and with different infill patterns (Line, gyroid, trihexagon) and infill ratios (30, 50, and 70 %). The specimens were then sliced using a (Cura) 3D design slicer, and the file was saved as a STL file and sent to the printer. To finalize the process, the samples undergo a finishing stage. The printed specimens are shown in Figure 1 below. After that testing can be done [7].

2.3 Tests

2.3.1. Compression Test

The compression test was done using a general-purpose (EN772-1) manual compression testing machine for blocks, cubes, and cylinders [8] shown in Figure 2. The test was done according to the standard specification (ASTM D695) [9]. The values of compressive strength were calculated by dividing the maximum load by the cross-section area of the specimen to get the maximum compressive load under which the material fails.

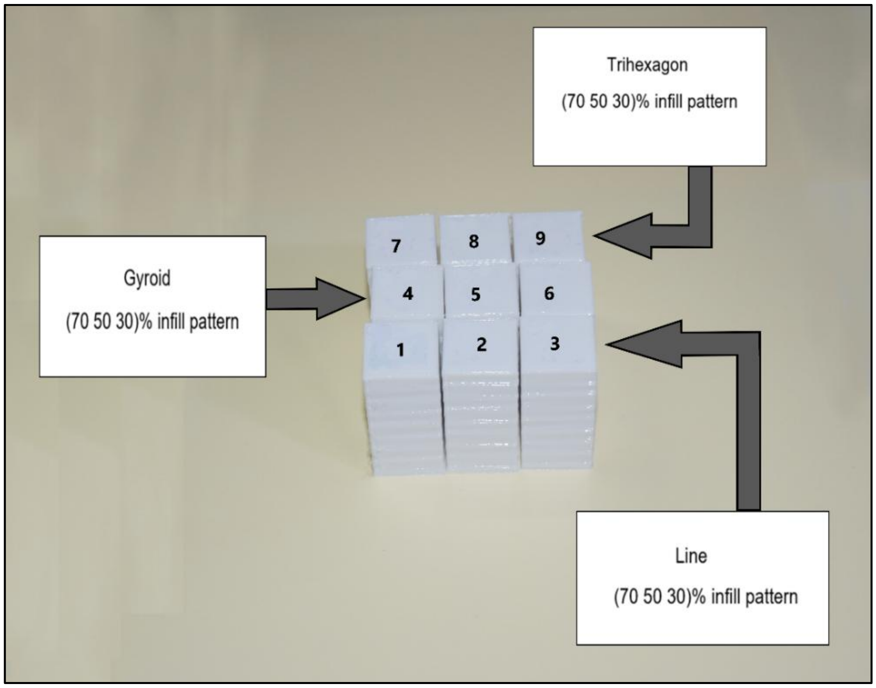

Figure 1: Compressive strength samples, (1) Line 30%, (2) Line 50%, (3) Line 70%, (4) Gyroid 30%, (5) Gyroid 50%, (6) Gyroid 70%, (7) Tri-hexagon 30%, (8)Tri-hexagon 50%, (9)Tri-hexagon 70% .

Figure 2: Compressive strength test machine.

2.3.2. Hardness

The hardness test was done using a hand-held durometer (Shore Instruments, Type D), shown in Figure 3, by ASTM D2240-05 (2010) type D [10]. Hardness measurements were recorded when complete indentation had occurred to mitigate against the relaxation of an elastomeric material that can occur between (5 s and 10 s). After indentation, the process was averaged across the sample surface to ensure homogenous hardness measurements.

Figure 3: Hardness test device.

3. Results and Discussion

3.1. Compressive Test

Figure 4 shows the effect of the 30, 50, and 70% infill ratio in addition to infill pattern (Line, gyroid, and trihexagon) on the compressive strength. Infill ratio may be defined as percentage of the printed material to the overall volume of the object [11]. It was found that increasing the infill ratio enhances the compressive strength. At 70% infill ratio, the specimens showed the highest compressive strength of all different infill patterns, with the line pattern at 70% infill ratio having the highest compressive strength in comparison to other infill patterns. This agrees with the results obtained by other researchers like Harshit et. al. [3], and Elmrabet [12]. This might be due to the higher amount of polymer employed in the printing process, leading to a higher density and eventually a lower volume of free space inside the printed specimen. This produces a stronger material due to smaller pore size and eventually higher capability of load-bearing. Generally, the compressive strength is directly proportional to the infill ratio [3], [14]. The results are also by Wu et.al [13], [15], who suggest that big gaps can start damage more easily than the highly-packed infills, which inhibit the propagation of flaws and damages, resulting in higher strength. The infill pattern shape is the method by which deposition printed lines fill the inside of the 3D printed specimens. Hence, various infill shapes can be associated with the printing process, like hexagon, cubic, honeycomb, linear, or gyroid, etc., and these patterns determine the mechanical properties of the printed object through controlling the raster and its movement [16]. The results also showed that the infill with the linear pattern gives the highest gained compressive strength when compared to trihexagon and gyroid patterns at an infill density of 50 and 70%. Although, the difference lies in a small range (<10MPa) for all the specimens with the same infill density. The values can be seen in Table 2. The compressive strength obviously was affected by the shape of the infill pattern, besides the infill density. The reason may be the higher volume of the printed infill [16], [17] as in the case with the linear pattern, compared with gyroid and trihexagon patterns. Sequentially, this volume lends to more mechanical strength to the printed object, due to the higher surface area associated with the linear shape. In fact, the effect of the pattern shape was more marked on the mechanical properties compared to the effect on the density [16], [18].

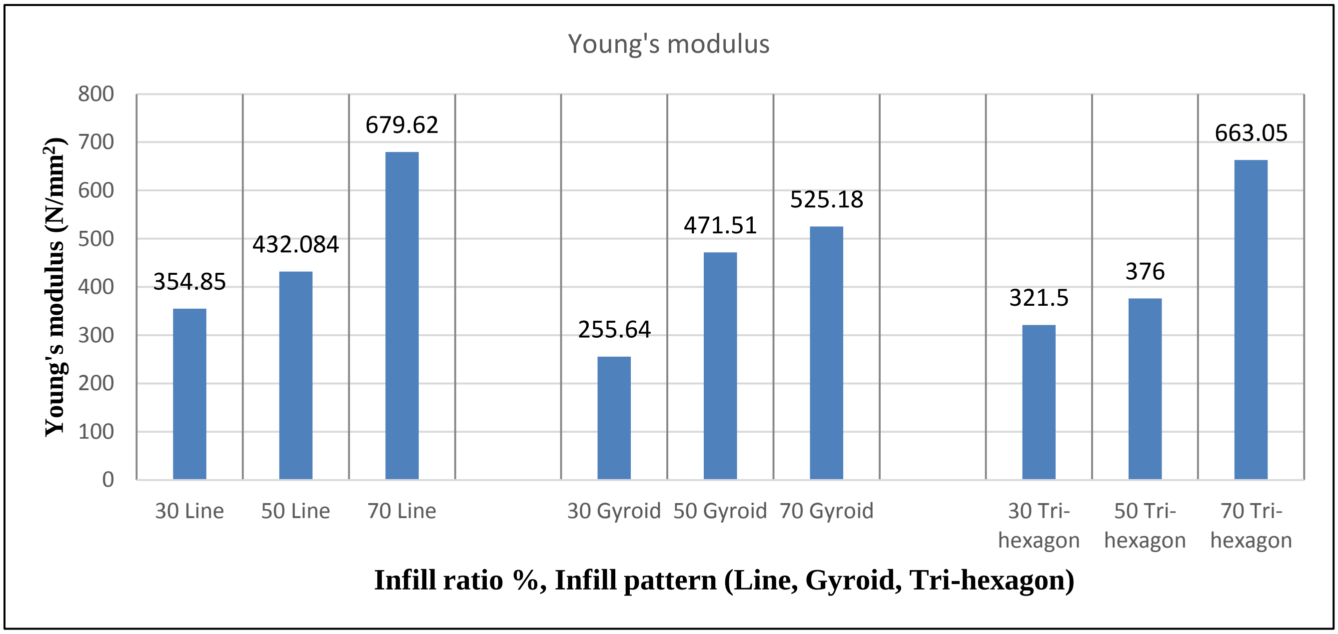

Figure 4: The effect of infill ratio and infill pattern on compressive strength.

Table 2: The values of compressive strengths for 30, 50, and 70 % infill Ratio and for the Linear, Trihexagon and Gyroid infill patterns.

Infill Ratio % and Pattern	Compressive strength (MPa)
30 Gyroid	199
50 Gyroid	193
70 Gyroid	214
30 linear	192
50 linear	212
70 linear	223
30 Trihexagon	197
50 Trihexagon	198
70 Trihexagon	212

3.2. Hardness Test

Figure 5 shows hardness results for 3D printed (PLA), from different sides of the sample. Type D Shore Durometer hardness results are generally more similar in value to the standard properties of (PLA) which are in between (67 - 85). The results presented different values of hardness for the same specimen, each of which was taken at a different side so basically, the same specimen gives different values of hardness at each face, despite that the material used for printing is the same. The reason for the variety may be due to the bed temperature, or attributed to the indenter tip geometry and the way it interacts with the surface variation or infill pattern generated by each processing method and machine. Anyway, the hardness values were found to be in the average range for PLA [6], [19]. In the hardness test the results were not affected by the infill density and pattern, as it was noticed with compressive strength, but rather was influenced by the position of the measurement, so the values varied within the same specimen depending on the place it was measured at, rather than geometrical shape and density. 3D printing is known to be an anisotropic process that is largely dependent on the orientation, the angle at which the raster moves, the infill density and pattern, how the sides are laid, and the air gaps. All these factors must be taken into account when designing a 3d printed object, thus the values of various mechanical properties differ according to the above-mentioned factors [20], [21], hence the values of hardness differed according to the position they were measured at, whether at the bottom surface, the sides or the upper surface. The lower surface, which is in contact with the printing plateau showed the highest value of hardness, as it was the thickest part printed throughout the printing course, followed by the sides which showed a medium value between the upper and lower surfaces. The buildup of the printed polymer in a perpendicular direction was probably the reason behind a hardness value that is a little higher than the top surface but at the same time lower than the lower surface. So, when hardness is measured, the indenter is pressed into the vertically built side, thus the value is smaller than the lower surface hardness. As for the upper surface, which is printed at the final stage of the process, the values of hardness were at the lowest point, since the surface is printed over hollow patterns which entrap air and voids, giving a non-solid base for the printed material to settle on, eventually facilitating penetration of the indenter into the surface.

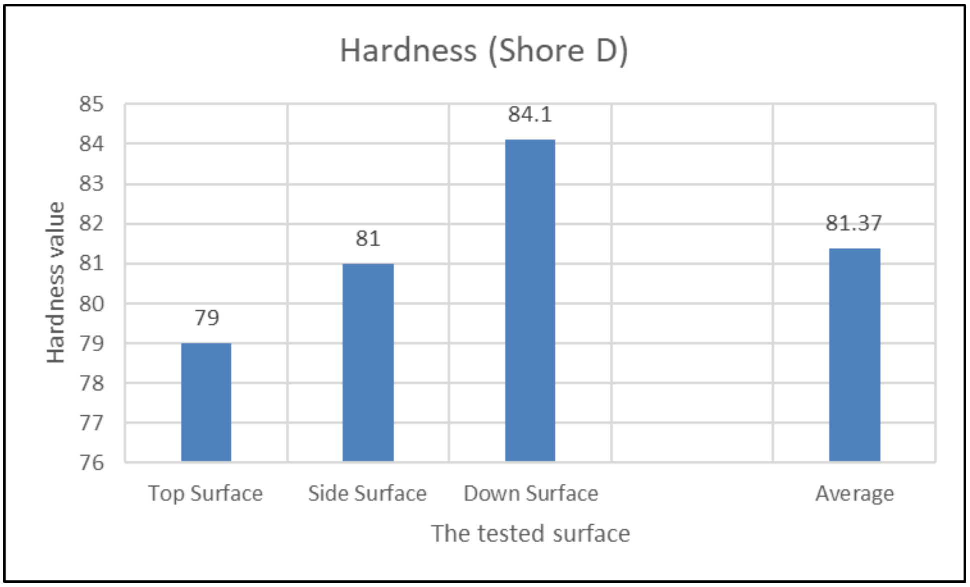

Figure 5: Values of (shore D) Hardness of (PLA) Polymer.

4. Conclusions

Experimental investigation was carried out on the effect of infill pattern and ratio on the compressive strength and hardness of the 3D printed PLA, according to the ASTM D695 standard. Both the different infill pattern and ratio gives different compressive strength. The analysis of the result reveals that increasing the infill ratio caused the increase in compressive strength, interestingly the maximum compressive strength was at 70% infill ratio with line pattern. As for the hardness test, the values were at the maximum on the sample lower side.

Conflict of Interest

The authors declare that they have no conflict of interest.

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