The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #42985

Exploring the Relationship Between Infill Ratio, Infill Pattern, and Material in 3D-Printed Part Performance

Ms. Ayla Acuña, California State Polytechnic University, Pomona

Undergraduate at California State Polytechnic University, Pomona for Bachelor of Science in Manufacturing Engineering. Currently a Junior and expects to graduate December 2025.

Dr. Moe Rabea, California State Polytechnic University, Pomona

Extensive experience in applied research and development in material and manufacturing engineering for improving properties of diverse types of material surfaces. In-depth experience of fabricating nanostructured materials for supercapacitor energy storage.

Exploring the Relationship Between Infill Ratio, Infill Pattern, and Material in 3D Printed Part Performance

Abstract

There are many factors to consider when choosing the best manufacturing process and material. This paper reviews how strength, hardness, and surface finish were tested for three-dimensional (3D) printing. Engineering students are taught how to find, measure, and calculate compressive strength and hardness. Students also learn the importance of each of these factors and what can lead to defects. Many studies tend to focus on the properties of just a singular material, but it is important that students explore all types of materials and manufacturing processes they could end up working with. Polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and carbon fiber (CF) are used for 3D printing. Mechanical properties like compressive strength, hardness, and surface roughness were measured to investigate the resulting products from additive manufacturing. To test each material, different infill ratios (30%, 50%, 70%) and patterns (linear, triangular, honeycomb) will be printed resulting in 27 different specimens for comparison. Hardness is a measure of the resistance a material has to deformation in the form or indentation, a shore durometer was used to test the hardness of each material. Compressive strength is the resistance to deformation under constant compressive force, and universal materials testing equipment is a great teaching aid that can help measure various mechanical properties, a compression force can be applied to each specimen while data is recorded and graphed. Surface finish is an important quality that can affect dimension accuracy and lead to defects from uneven force distribution, precision surface roughness gauges contain a fine probe to measure the quality of the surface. After concluding each test, it was found that carbon fiber with 70% linear infill performed the best for strength and hardness. ABS material produced the smoothest surface. Educators may find it valuable to invest in 3D printing material that will better demonstrate these mechanical properties that are often desired in industry. If engineering students understand which combination of material and infill ratio can produce which mechanical properties, they can compare and decide that production could be transferred to 3D printing while maintaining the same mechanical properties required for the part.

Introduction

3D printing is an additive manufacturing process involving laying down softer or liquid materials in layers that then harden or cured into a solid structure. Plastic filament is fed through a nozzle that heats up to melt the material. The melted material is then deposited as the next layer of the part. This process repeats until the entire model is complete. Printing each of the individual layers takes a lot of time, material, and precision. However, the labor and maintenance involved is minimal, making 3D printing a great cost effective option for manufacturing design mockups and other plastic parts [1-2]. 3D printing creates less waste because material is being added to manufacture the part instead of removed.

In addition to increasing efficiency, manufacturing engineers must consider how to reduce manufacturing cost. Some ways to achieve this is by reducing the amount of material needed or by reducing the amount of labor time per part. Using an infill pattern instead of printing a solid part addresses both of these methods. The layers cover less area and therefore takes up less time and material to complete each layer of the part. It is important to minimize the amount of material used while maintaining the structural integrity and properties of the part.

Acrylonitrile butadiene styrene (ABS) is a common type of plastic used for 3D printing. The material has a high dimensional accuracy due to the fact ABS has a small shrinking ratio during cooling. ABS has a multitude of useful properties such as being heat resistant, having a high tensile strength, and hardness [3]. ABS is easy to come by and cheaper than some other comparable materials. While the material isn't particularly strong in any one property, it is very well rounded and mulit-functional.

Polylactic acid (PLA) is a type of plastic material that is derived from natural materials like corn that have lactic acid. This material is often used in agriculture or other food industries because of its greener source. PLA and ABS are often compared to each other due to their similar cost, properties, and uses [4].

Carbon fiber is another 3D printed material, known for its strength from reinforcement fibers. The material is more expensive to produce than other 3D printing materials, but that is just the cost of having an extremely strong material. The fibers in the material distribute the load evenly throughout the part, allowing it to take on a larger load [5].

To decrease total print time and decrease material used, an infill pattern can be used in place of solid material in the middle. The goal of using an infill pattern is to use less material while still maintaining the structural integrity of the part. Linear infill pattern consists of two sets of diagonal lines in the opposite direction. Triangle infill pattern consists of a zig-zag pattern that is sectioned off to create triangular sections. Honeycomb infill pattern consists of hexagons nestled neatly next to each other. These infill patterns have a significant number of intersections so the load is distributed evenly across the part. Infill patterns can occupy a set percentage of space to increase or decrease the amount of material being used. This percentage variable is referred to as infill [pattern] density. The percentage measured the amount of the total space being occupied by solid material [6-7].

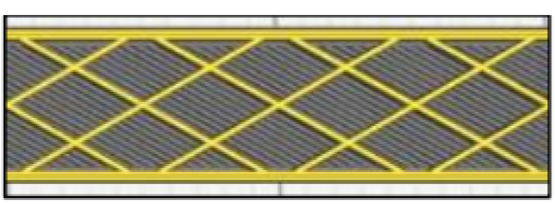

Fig 1. Linear infill pattern [4]

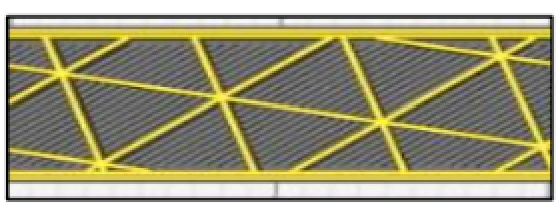

Fig 2. Triangle infill pattern [4]

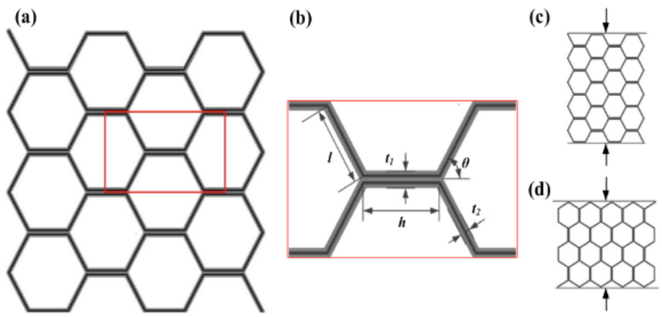

Fig 3. Honeycomb infill pattern [5]

Materials possess a great number of different properties such as strength and hardness. Understanding these properties allow engineers to utilize materials to their full potential. An important property to understand is how much stress (or force) a material can withstand before failing. A stress vs strain graph is a common way to graph the strength of a material. The linear section of this graph is known as the elastic region. Within the elastic region, a part will return to its original shape and dimensions after the force is removed. The ratio between stress and strain in the elastic region is referred to as young's modulus which is measured in Newtons per millimeter squared (N/mm^2). This is the maximum force that can be applied to the cross sectional area. Tensile strength measures a material's resistance to deformation when two forces pull away from each other. These forces pull and stretch the material until it fractures.

The compressive strength of a material is the resistance to deformation when two forces work towards each other, into the part. These forces cause the part to buckle and spill on the sides to the point of fracture. Compressive strength is measured in megapascals (MPa) [8-9].

Hardness is the material quality of resistance to deform. Hardness is tested by using a certain amount of force to indent the material with a very hard material such as hardened steel. The smaller the resulting indent is, the more resistant and more hard a material is. There are two different scales and instruments to measure hardness. Rockwell has a higher scale meant for really hard materials. For the purpose of this experiment, Shore will be used to test the specimens [10].

Parts with tight dimensional tolerances or parts that need a specifically level surface are often manufactured in metal and milled to achieve precision. In the case of 3D printing, the part cannot be milled as the part would melt from the heat of the friction, possibly damaging equipment. Having material with minimal surface roughness decreases variability in your measurements. Parts with high surface roughness do not have a lot of surface area of contact when fastened adhered to another part. Low surface area of contact, decreases the strength of the bond and the overall strength of the part [11-12].

Materials have their own known strength when the parts are solid or have a known cross sectional area. Infill adds internal strength to the part while saving on material. The two variables of infill are pattern and percent density. For example, a strong infill pattern with a low density might have the same strength as a weak infill pattern with a high density.

Procedure

Using a Flash Forge Creator Pro 3D printer, 54 specimens were printed, two of each combination of material, infill pattern, and infill density as listed in Table 1. The shape as shown in Fig. 5 and 6 is called “dogbone” which is common for tensile testing.

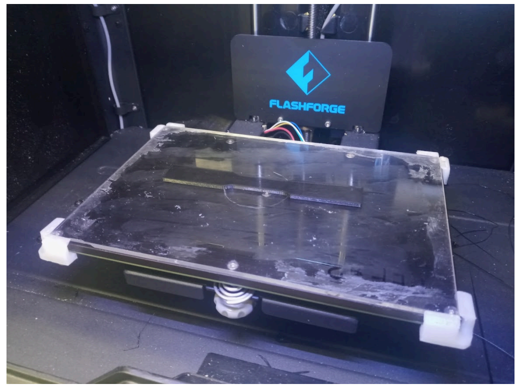

Fig 4. Dogbone specimen being 3D printed.

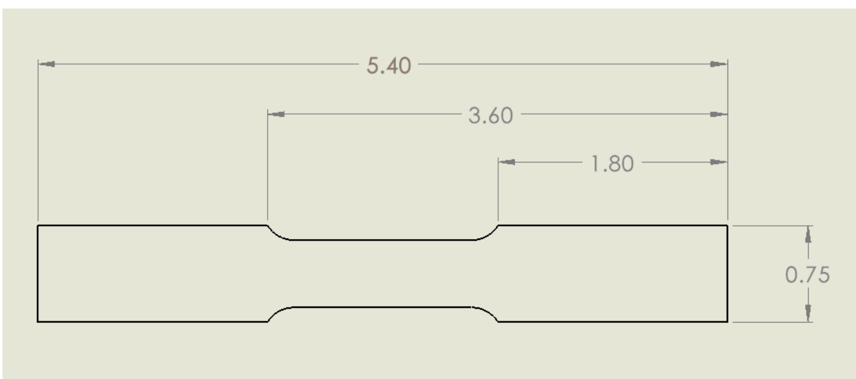

Fig 5. Dimensions of the dogbone shape.

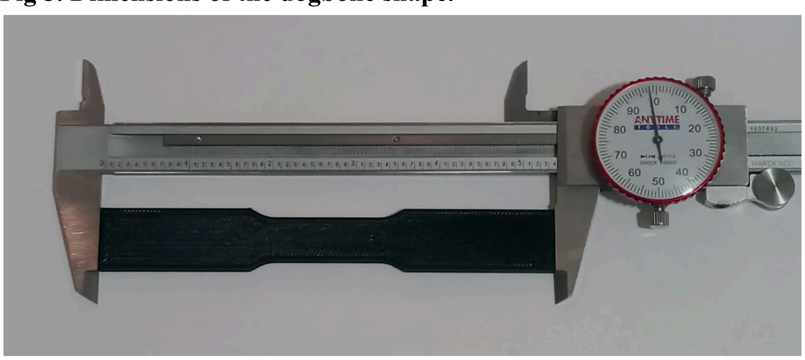

Fig 6. Profile of dogbone specimen displayed in a caliper.

Table 1. Complete list of all 27 combinations material, infill pattern, and infill percentage.

Lin, PLA, 30%	Tri, PLA, 30%	HC, PLA, 30%
Lin, PLA, 50%	Tri, PLA, 50%	HC, PLA, 50%
Lin, PLA, 70%	Tri, PLA, 70%	HC, PLA, 70%
Lin, ABS, 30%	Tri, ABS, 30%	HC, ABS, 30%
Lin, ABS, 50%	Tri, ABS, 50%	HC, ABS, 50%
Lin, ABS, 70%	Tri, ABS, 70%	HC, ABS, 70%
Lin, CF, 30%	Tri, CF, 30%	HC, CF, 30%
Lin, CF, 50%	Tri, CF, 50%	HC, CF, 50%
Lin, CF, 70%	Tri, CF, 70%	HC, CF, 70%

Testing surface roughness is nondestructive, so this was tested first. A spectrometer is used to measure the differences in the surface. A light is projected over the surface of the specimen and the spectrometer measures how many photons are captured on the other side. Multiple data points are captured and compiled into an average Ra value in millimeters (mm). Each specimen was used and recorded in this manner.

Testing hardness only uses a small portion of the specimen, and therefore the specimen can be used again for future testing. This recycling minimizes waste to be cost effective. Using a digital Shore D durometer, the larger, end section of the specimen is measured on the flat surface. The durometer uses an indentation needle with a 0.1 mm diameter. The same force is applied each time, resulting in an indent on the specimen. The diameter of the resulting indent is measured and compared to the Shore scale.

Tensile testing is destructive to the specimens. Using the Instron 3367 Universal Testing System, the two ends of a specimen are secured into the jaws and stretched. The top jaw pulls away with up to 30 kN of force. The machine continues to apply the force until the part fractures. As the test is executed, data is collected, stored, and graphed onto an integrated computer system. The computer automatically pulls relevant information from the resulting stress vs strain curve. The young's modulus in N/mm^2 was recorded for each test.

Fig 7. Dogbone specimen set up in the Universal Testing system for a tensile strength test.

Compressive testing uses the Universal Testing System, but applies a force inward instead of an outward force. The specimen is secured into the jaws and the top jaw pushes down with a gradually increasing force up to 30 kN. The computer records the force needed to create a failure in the part. Compressive strength in megapascals was recorded for each test.

Results

Overall, triangle was the least effective infill pattern. In Table 2, carbon fiber with 70% infill density out-performed by a landslide with 732.25 N/mm² and 787.1 N/mm². Carbon fiber with 50% infill density has the next best strength but has an average of a 81.775 N/mm² difference. Linear and honeycomb infill patterns were used for this data. Triangle infill pattern with 70% infill density and CF underperformed, resulting in 612.3 N/mm².

Table 2. Resulting data from tensile and compressive strength tests.

Infill Pattern	Material	Infill Percent	Young's Modulus (N/mm²)	Compressive Strength (MPa)
Linear	PLA	30%	366.12	181.1
Linear	PLA	50%	441.27	210
Linear	PLA	70%	691.21	229
Linear	ABS	30%	317.22	164
Linear	ABS	50%	391.7	171
Linear	ABS	70%	587.33	190
Linear	CF	30%	512	217
Linear	CF	50%	667.1	241
Linear	CF	70%	**732.25**	**291**
Triangle	PLA	30%	331.71	170
Triangle	PLA	50%	390.7	191
Triangle	PLA	70%	521.1	221
Triangle	ABS	30%	298.8	160
Triangle	ABS	50%	299.7	165
Triangle	ABS	70%	476.6	181
Triangle	CF	30%	481.6	205
Triangle	CF	50%	522.7	232
Triangle	CF	70%	612.3	231
Honeycomb	PLA	30%	382.7	192
Honeycomb	PLA	50%	467.6	221
Honeycomb	PLA	70%	698.7	237

Infill Pattern	Material	Infill Percent	Young's Modulus (N/mm²)	Compressive Strength (MPa)
Honeycomb	ABS	30%	337.3	168
Honeycomb	ABS	50%	410.02	178
Honeycomb	ABS	70%	601.1	198
Honeycomb	CF	30%	521.7	237
Honeycomb	CF	50%	688.7	251
Honeycomb	CF	70%	**787.1**	**298**

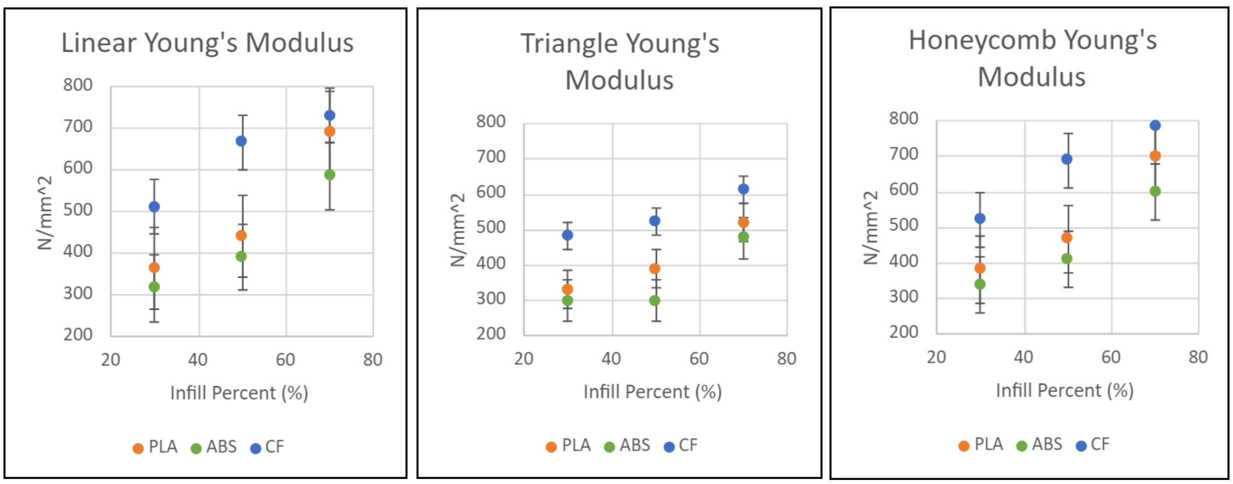

Fig 8. Graphs comparing material performance of tensile strength for a linear, triangle, honeycomb infill pattern.

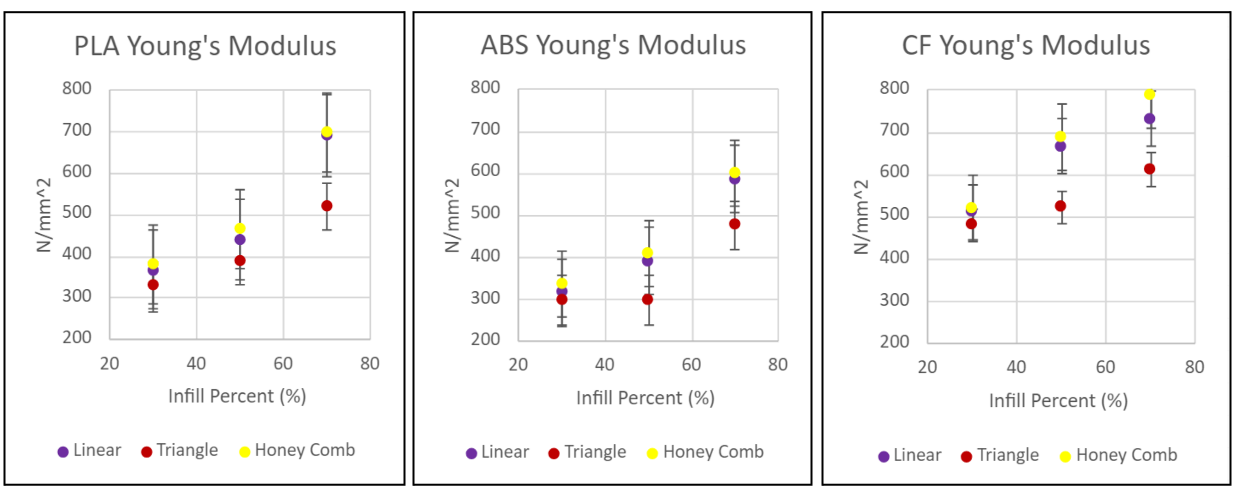

Fig 9. Graphs comparing infill pattern performance of tensile strength for materials PLA, ABS, and CF.

According to the graphs in Fig. 7 and 8, no matter the infill pattern or density, CF has the greatest tensile strength, followed by PLA, then ABS with values of 787.1 N/mm², 698.7 N/mm², and 601.1 N/mm² respectively.

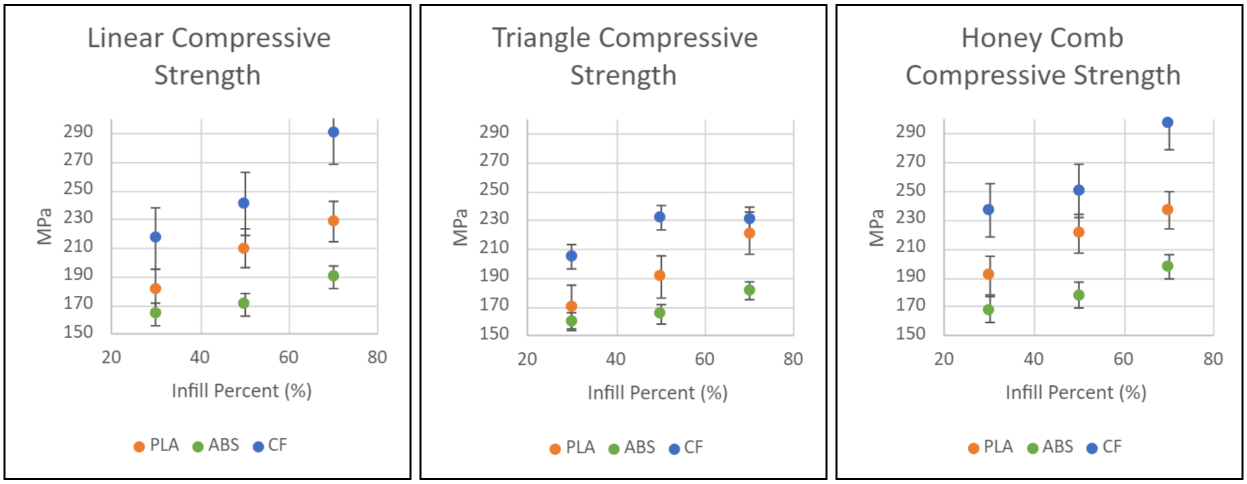

Fig 10. Graphs comparing material performance of compressive strength for a linear, triangle, honeycomb infill pattern.

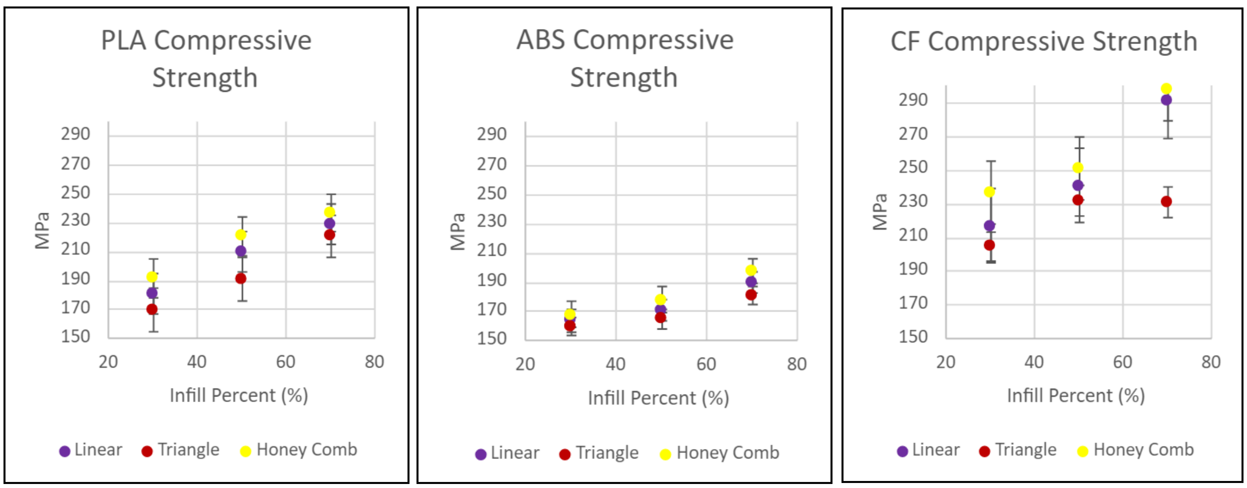

Fig 11. Graphs comparing infill pattern performance of compressive strength for materials PLA, ABS, and CF.

As shown in Fig. 9 and 10, ABS has the lowest compressive strength with a range of 160-198 MPa. Within each material, on average, there is no noticeable difference between the effectiveness of the infill pattern. Greater infill density resulted in greater compressive strength. CF had the greatest compressive strength with a range of 205-298 MPa.

Table 3. Average hardness for each material.

Material	Hardness
PLA	85
ABS	76
CF	92

Data for each specimen of the same material were very similar, so data was averaged. The infill pattern and density of 3D printed material has no effect on the hardness of the part. It is clear that CF possesses a great many desirable properties. The greatest young's modulus was 787.1 N/mm² and the greatest compressive strength was 291 MPa. According to Table 3, the hardness of CF is a 92.

Table 4. Average surface roughness for each material.

Material	Surface Roughness (mm)
PLA	1.55
ABS	1.40
CF	1.51

Data for each specimen of the same material were very similar, so the data was averaged. The values recorded are the average difference in the surface. Table 4 shows ABS has the best surface with only a 1.40 mm difference. This is followed by CF with 1.51 mm and PLA with 1.55 mm.

Discussion

Infill affects many aspects of a part such as weight and type of failure. Smaller infill density means less material used and a less heavy and less dense part. Depending on the density and mass of the part, there might be enough buoyant force to keep the part afloat. A lighter part is beneficial for engineering fields such as aerospace and automotive where less weight means greater stability and speeds. All material has a failure point, so it is good to plan for how the material will fail and how that failure can affect the overall part. Honeycomb infill will collapse on itself, but will not fracture. This means the part can still hold the force applied to it.

It seems that harder and stronger materials solidify faster when being 3D printed. This can cause a rough surface finish. No matter what material is used, when 3D printing, surface roughness will be noticeable. A tradeoff for a better surface finish, if to reduce the strength of the part by using ABS.

Conclusion

The results from the data can be useful in a variety of ways. No matter which material, infill pattern or infill percent you use, the Young's Modulus will always be greater than 200 N/mm². For educational and demonstrative purposes, that is strong enough for students to learn about tensile testing, stress vs strain graphs, and young's modulus. For educational purposes, the cheapest material with the least infill density will suffice.

Honeycomb infill has the highest tensile strength but is on par with linear infill for compressive strength. While a lot of the comparative data had very short ranges, triangle was the weakest infill pattern as it consistently was the lowest data point in each cluster.

While infill pattern and density play a large role in the tensile and compressive strength of the part, material is the only factor for the hardness and surface roughness of the part. Carbon fiber consistently outperformed the other materials in those respects. Carbon fiber might not be the most practical or accessible material for educational purposes. Instead, PLA should be the preferred material over ABS.

In conclusion, honeycomb is the best infill pattern and carbon fiber is the best material for mechanical performance. 70% infill density results in the greatest material strength. However, 30% and 50% infill densities perform just as well as 70% infill density. This is important to note if cost is a factor and material is to be conserved.

References

[1] W.A. Soud, I.A. Baqer and M.R. Ahmed, "Experimental Study of 3D Printing Density Effects on the Mechanical Properties of the Carbon-Fiber and Polylactic Acid Specimens," Engineering and Technology Journal, Vol. 37, Part A, No. 04, pp. 128-132, 2019.

[2] C. Aumnate, A. Pongwisuthiruchte, P. Pattananuwat, and P. Potiyaraj, "Fabrication of ABS/Graphene Oxide Composite Filament for Fused Filament Fabrication (FFF) 3D Printing," *Advances in Materials Science and Engineering*, vol. 2018, pp. 1–9, Nov. 2018, doi: https://doi.org/10.1155/2018/2830437.

[3] H. Yang, F. Ji, Z. Li, and S. Tao, "Preparation of Hydrophobic Surface on PLA and ABS by Fused Deposition Modeling," *Polymers*, vol. 12, no. 7, p. 1539, Jul. 2020, doi: https://doi.org/10.3390/polym12071539.

[4] M. Jasim, T. Abbas, and A. Huayier, "The Effect of Infill Pattern on Tensile Strength of PLA Material in Fused Deposition Modeling (FDM) Process," *Engineering and Technology Journal*, vol. 40, no. 12, pp. 1–8, Sep. 2022, doi: https://doi.org/10.30684/etj.2021.131733.1054.

[5] Y. Cheng, J. Li, X. Qian, and S. Rudykh, "3D Printed Recoverable Honeycomb Composites Reinforced by Continuous Carbon Fibers," *Composite Structures*, p. 113974, Apr. 2021, doi: https://doi.org/10.1016/j.compstruct.2021.113974.

[6] G. Dakhil, R. Salih, and A. Hameed, "Influence of infill pattern, Infill Ratio on Compressive Strength and Hardness of 3D Printed Polylactic Acid (PLA) Based Polymer," *Journal of Applied Sciences and Nanotechnology*, vol. 3, no. 1, pp. 1–7, Feb. 2023. doi:10.53293/jasn.2022.4745.1141

[7] M. Kasim Mehdi and B. Owed, “The Influence of Infill Density and Speed of Printing on the Tensile Properties of the Three Dimension Printing Polylactic Acid Parts,” *Journal of Engineering and Sustainable Development*, vol. 27, no. 1, pp. 95–103, Jan. 2023, doi: https://doi.org/10.31272/jeasd.27.1.8.

[8] D. Pranesh and N. Nandakumar, “Fabrication of PLA Structures using Fused Deposition Modelling and Experimental Investigation on Mechanical Properties ,” *International Advanced Research Journal in Science, Engineering and Technology*, vol. 8, no. 6, Jun. 2021. doi:10.17148/IARJSET.2021.8614

[9] A. Kholil, E. Asyaefudin, N. Pinto, and S. Syaripuddin, “Compression Strength Characteristics of ABS and PLA Materials Affected by Layer Thickness on FDM,” *Journal of Physics: Conference Series*, vol. 2377, no. 1, p. 012008, Nov. 2022, doi: https://doi.org/10.1088/1742-6596/2377/1/012008.

[10]R. Lam, M. Orozco, E. Mendieta, B. Hunter, and J. Seiter, “Compressive Mechanical Properties of Three-Dimensional (3D) Printed Thermoplastics.” [Online]. Available: https://strategy.asee.org/compressive-mechanical-properties-of-three-dimensional-3d-printed-thermoplastics.pdf

[11] Y.-S. Zeng *et al.*, “An Investigation on the Hardness of Polylactic Acid Parts Fabricated via Fused Deposition Modeling,” *Polymers*, vol. 14, no. 14, p. 2789, Jul. 2022. doi:10.3390/polym14142789

[12] K. Jakupi, V. Dukovski, and G. Hodolli, “Surface Roughness Modeling of Material Extrusion PLA Flat Surfaces,” *International Journal of Polymer Science*, vol. 2023, pp. 1–8, May 2023. doi:10.1155/2023/8844626