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EFFECT OF FILLING RATIO-PATTERN PARAMETERS ON MECHANICAL PROPERTIES OF PLA FILAMENTS USED IN 3D PRINTING

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Abstract: This research primarily focuses on the mechanical properties of specimens produced using Polylactic Acid (PLA) through the Fused Deposition Modeling (FDM) technique, a method of 3D printing. Within the scope of this study, specimens were fabricated using various fill percentages and different infill patterns. The simultaneous effect of variable parameters on mechanical properties is a challenging task, and it is aimed to rank the importance of the parameters, model the process, and finally validate the models using tensile and bending experiments. The results show that samples with a Concentric pattern and 95% fill rate exhibited the highest tensile strength with an average of 48.67 MPa. In contrast, the Triangle pattern with 20% infill ratio showed the lowest tensile strength with an average of 14.15 MPa. When evaluating flexural strength values, the Concentric design with a 95% fill ratio stood out once again, recording an average peak value of 79.94 MPa. Meanwhile, the Honeycomb pattern at 20% infill ratio exhibited the lowest strength value measured with an average of 23.3 MPa. Scanning Electron Microscope images taken according to infill rates confirm each other with the voids formed and mechanical performance outputs. These findings underscore that the mechanical attributes of PLA specimens produced using 3D printing technology can significantly vary based on the chosen fill rate and pattern.

Keywords: Polylactic acid, Fused deposition modeling, 3D printer, Fill ratio, Fill pattern, ASTM D638

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1. Introduction

Fused deposition modeling (FDM) three dimensional (3D) printing is a type of additive manufacturing (AM) process that uses thermoplastic filaments to create objects layer by layer. FDM is one of the most widely used and affordable 3D printing technologies, suitable for rapid prototyping and various applications. FDM can print parts with complex geometries and internal cavities, thanks to the use of soluble support materials that can be dissolved after printing. FDM can print parts with different colors and materials, depending on the capabilities of the printer and the extruder. FDM can print parts with different levels of resolution and accuracy, depending on the nozzle size, layer height, infill density, and other parameters. The mechanical properties of PLA filaments in 3D printing are significantly influenced by the filling ratio and filling pattern parameters.

The filling ratio, often termed as infill percentage or density, denotes the material volume inside a 3D printed component. A higher filling ratio typically makes parts more robust and rigid, but it also lengthens the printing duration and uses more material.

On the other hand, the filling pattern, sometimes referred to as the infill or raster pattern, describes the internal geometry of the printed item. It plays a pivotal role in determining the part's strength, stiffness, and manner of failure. Various patterns like Concentric, Triangular, Honeycomb, Hilbert curve, and others, each offer distinct mechanical characteristics. For instance, parts printed with a Concentric pattern tend to have superior tensile strength when the pattern aligns with the stress direction, whereas triangular patterns excel in strength for lighter structures. Conversely, the Honeycomb pattern can reduce strength due to its spacious voids, but Hilbert curve patterns can enhance strength at high filling ratios. However, it's essential to remember that these effects are also modulated by other variables such as the part's orientation during printing, the thickness of each layer, nozzle dimensions, extrusion temperature, printing pace, and cooling speed, all of which impact the final quality and interplay between the printed lines and layers.

In their study, Dudescu and Racz (2017) examined the effects of different raster angles (0°, 30°, 45°, 90°), filling rates (20% to 100%) and patterns on the mechanical properties of 3D printed parts using ABS material. In their study, Wittbrodt and Pearce (2015) evaluated the mechanical performances obtained from 3D printing of PLA materials of different colors at different processing temperatures. Özsoy et al. (2022) improved the temperature effect problem on the parts by detecting the correct coolant type at a rate of 95% through image processing and machine learning, using the FDM method to produce parts on a 3D printer. Özsoy and Aksoy (2022) created a user guide on the mechanical properties of 3D printed parts using image processing and real-time big data analysis. Benamira et al. (2023) investigated the effect of printing parameters on the mechanical and damage properties of 3D printed PLA. Kechagias et al. (2023) evaluated the process in which the mechanical response of PLA in 3D printing with the FDM method depends on many parameters. Kartal and Kaptan (2023) examined the effect of 3D printer nozzle diameter on the mechanical properties of PLA printed parts. Hamat et al. (2023) evaluated the effects of filament production parameters (extrusion temperature and rotation speed) on tensile strength. Bian et al. (2023) discussed the effect of the morphology and feed rate of FDM printed PLA on the mechanical properties at the time of exit from the nozzle during the hot extrusion process. Pandzic et al. (2019) focused on the effects of 3D printed samples with PLA material on the tensile strength depending on the filler type and ratio, while Lalegani Dezaki et al. (2021) focused on the effects of the filler pattern on surface roughness and tensile strength. Wu et al. (2015) comparatively examined the mechanical properties of layer thickness and raster angle in 3D printed materials. Moradi et al. (2021) have conducted experimental research on the mechanical characterization of 3D printed PLA produced by FDM.

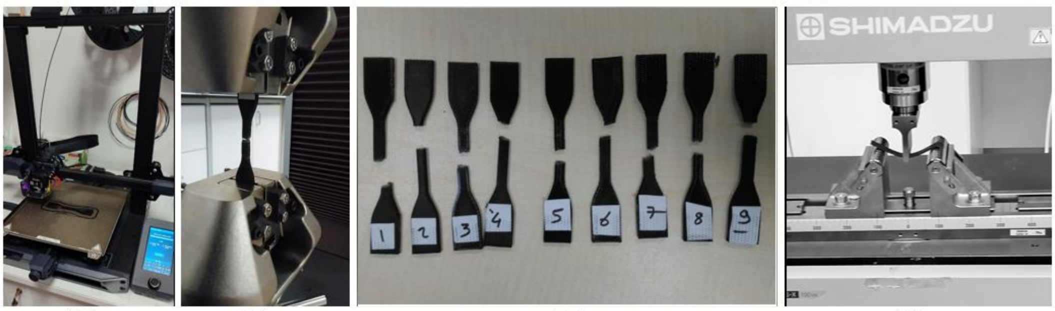
In literature research, there does not appear to be a study that comprehensively examines the mechanical properties of parts printed with PLA materials according to 5 different filling percentages and 4 different filling patterns. This study aims to fill this knowledge gap by delving deep into the combined effect of fill rate and pattern on the mechanical behavior of PLA. Within this paper, detailed insights will be provided on the mechanical properties of PLA specimens produced using 3D printing techniques, with various fill rates (20%, 40%, 60%, 80%, and 95%) and infill patterns (Triangle, Rectilinear, Honeycomb, and Concentric). Specifically, the tensile and flexural strength values will be thoroughly examined. The results are discussed to elucidate why the selection of printing parameters is so critical in determining the mechanical performance of the printed objects.

2. Materials and Methods

The filament properties and printing parameters used in this study are seen in Table 1. These parameters are the most commonly preferred values for manufacturing 3D printed parts with PLA material. Specimens were prepared taking into account various fill rates (20%, 40%, 60%, 80%, and 95%) and infill patterns (Triangle, Rectilinear, Honeycomb, and Concentric). A minimum of 5 samples were printed for each combination. Figure 1.a shows the sample printing on the Ender 3 S1 Pro printer, and Figure 1.b shows the tensile test of printed sample. Figure 1.c shows the broken samples at the end of the tensile test. For tensile tests, specimens were produced in accordance with ASTM D638 type IV standard dimensions, while for the flexural tests, they adhered to ASTM D790 standard sizes. Tensile tests were carried out using a universal testing machine with a capacity of 5 kN (Figure 1.b). Specimens were stretched at a constant rate of 5 mm/min. Flexural tests were conducted on the same testing machine under a three-point bending arrangement, where the loading rate was also set at 5 mm/min (Figure 1.d). All acquired data were analyzed using appropriate software to determine statistical parameters such as standard deviation and variance. Additionally, various graphs were generated to discern the impact of fill rate and pattern on mechanical properties.

Table 1. Specification of PLA filament and printing parameters

Specification	Units	Value
Density	g/cm^3	1.24
Melting temperature	°C	190-220
Bed temperature	°C	60
Nozzle temperature	°C	220
Printing speed	mm/s	60



(a) (b) (c) (d)

Figure 1. (a) PLA material samples printed using Ender 3 S1 pro printer (b) Tensile test (c) Broken tensile specimens (d) Flexural test.

3. Results

3.1. Tensile Characteristics

The tensile strength of various samples with different infill ratios and patterns was meticulously studied. The values given in the study are the average values obtained from 5 samples. The results for the 20% infill ratio indicate significant differences based on the pattern used. For instance, the Concentric pattern demonstrated the highest tensile strength at 19.88 MPa. In contrast, the Triangle pattern exhibited the lowest tensile strength, registering at 14.15 MPa. This can be attributed to the fact that the Triangle pattern contains more gaps compared to the Concentric pattern, which tends to be fuller and parallel to the fracture direction. Furthermore, the Rectilinear, Honeycomb, and Concentric patterns all showed a noticeable increase in tensile strength as the infill ratio increased, with the Concentric pattern achieving the highest tensile strength of 48.67 MPa at a 95% infill ratio. In comparing these findings with those of past studies, the trends identified by Pandzic et al. (2019) and Lalegani Dezaki et al. (2021) were somewhat consistent. They found that the Concentric pattern generally exhibited higher tensile and yield strengths, especially for PLA filaments with a 90% infill ratio. It should also be noted that the flexural strength results showcased the potency of each pattern at various infill ratios, highlighting the robustness of materials like the Concentric pattern, which reached a peak flexural strength of 79.94 MPa at a 95% infill ratio. In conclusion, the choice of infill pattern plays a pivotal role in determining both the tensile and flexural strengths of 3D printed objects, with the Concentric pattern consistently outperforming its counterparts at higher infill ratios. According to Table 2 and Figure 2, the concentric pattern consistently showcases superior tensile strength, especially as infill ratios escalate, achieving its zenith at 48.67 MPa at 95% infill. This implies that for heightened tensile demands, the concentric pattern coupled with higher infill ratios might be the optimal choice. At the outset, with a 20% infill, the Triangle and Honeycomb patterns exhibit nearly identical tensile strengths, hovering around 14 MPa. However, as the infill ratio expands, their trajectories diverge. By 95% infill, the Honeycomb pattern registers a tensile strength of 36.63 MPa, outpacing the triangle pattern's 25.89 MPa. Notably, the Rectilinear pattern depicts a uniform ascent in tensile strength corresponding to rising infill percentages, denoting a predictable performance spectrum across diverse infill scales. To sum up, Table 2 underscores that both the choice of infill pattern and its proportion wield a substantial influence on the tensile strength of PLA samples, highlighting the necessity of judicious selection in tailoring 3D printed components to meet specific mechanical benchmarks. Additionally, the Rectilinear pattern steadily augments in tensile strength with each increment in infill percentage, indicating its stable and predictable response across varied infill gradations. Conclusively, the choice of infill design and proportion profoundly impacts the tensile strength of PLA specimens. A nuanced understanding of these nuances is imperative for customizing 3D printed items to distinct mechanical prerequisites, prompting an avenue for future research to unpack the foundational reasons behind these performance metrics and their practical connotations.

Table 2. The tensile strength of various samples with different infill ratios and patterns

	Tensile strength (MPa) according to infill ratio				
Pattern	20%	40%	60%	80%	95%
Triangle	14.15	17.32	19.24	23.35	25.89
Rectilinear	18.63	23.43	26.56	34.18	38.15
Honeycomb	14.68	22.63	26.25	30.84	36.63
Concentric	19.88	28.26	36.47	40.32	48.67

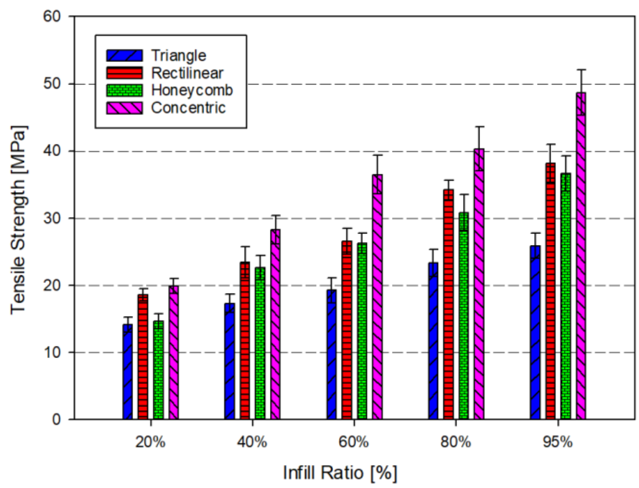


Figure 2. The tensile strength of various samples with different infill ratios and patterns.

3.2. Flexural Characteristics

The flexural test was conducted to further assess the mechanical properties of the samples, shedding light on their resistance to bending (Figure 1.d). Specimens with varying infill ratios and patterns were fixed at their ends, and a specific load was applied from their midpoints, providing insights into their load-displacement, flexural strength, and flexural strains. Analysis of the fractured sections clearly indicated that both the infill ratio and pattern significantly influence the mechanical performance of the samples. For the 20% infill ratio, the results, illustrated in Figure 3, align with observations from the tensile test. The Concentric pattern demonstrated superior resistance to flexural loads, outpacing other patterns in terms of its load-bearing capacity. Among the patterns studied, Concentric, Rectilinear, and Triangle achieved the highest flexural strength values, with the Concentric pattern being particularly outstanding, reaching 31.03 MPa at the 20% infill ratio. Conversely, even though the 3D Honeycomb pattern showed commendable resistance against tensile forces, it lagged in flexural strength, especially when compared to the other patterns. The Honeycomb's strength started at 23.3 MPa for the 20% infill ratio but improved considerably as the infill ratio increased. Notably, the Concentric pattern exhibited the highest flexural modulus, further emphasizing its exceptional mechanical properties. In summary, the choice of infill pattern and ratio is crucial in determining the flexural strengths of 3D printed objects, with the Concentric pattern consistently proving to be the most formidable across multiple infill ratios. According to Table 3 and Figure 3, which delineates the flexural strength of various patterns at different infill percentages. Concentric pattern's dominance, the concentric pattern indisputably leads in flexural strength, especially as the infill percentage grows. Its strength peaks at a significant 79.94 MPa at 95% infill. This makes it evident that the concentric pattern, when paired with higher infill percentages, is superior in terms of flexural strength, potentially making it ideal for applications demanding higher bending resistance. Both the Triangle and Rectilinear patterns show an increase in flexural strength as infill percentage rises. However, the Rectilinear pattern significantly outperforms the Triangle pattern, especially at higher infill percentages, reaching 62.49 MPa at 95% infill compared to the Triangle's 39.22 MPa. Honeycomb's plateau, starting at a modest 23.3 MPa at 20% infill, the Honeycomb pattern sees a sharp increase as infill rises, but interestingly plateaus around the 51 MPa mark from 60% infill onwards. In conclusion, the infill pattern and its percentage crucially determine the flexural strength of PLA samples. Table 3 elucidates the need for careful consideration of these parameters when seeking to optimize the bending resistance of 3D printed materials for particular applications. Future research can explore the structural peculiarities of these patterns that contribute to such performance outcomes.

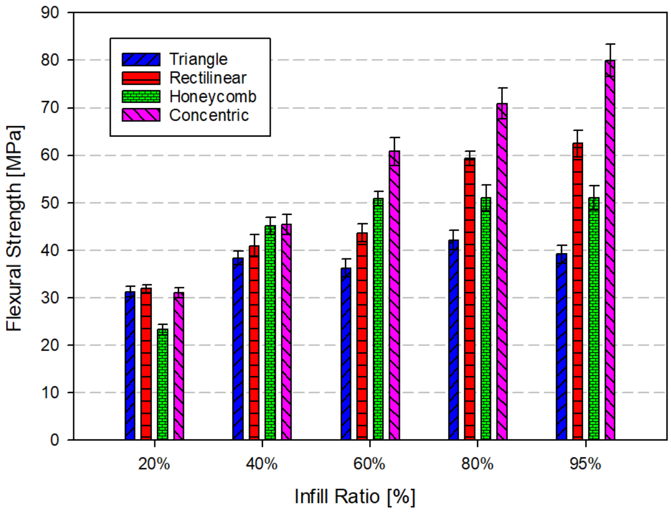


Figure 3. The flexural test properties of the samples.

Table 3. The flexural test properties of the samples

	Flexural strength (MPa) according to infill ratio				
Pattern	20%	40%	60%	80%	95%
Triangle	31.29	38.37	36.27	42.16	39.22
Rectilinear	31.88	40.97	43.68	59.29	62.49
Honeycomb	23.30	45.11	50.94	51.08	51.01
Concentric	31.03	45.50	60.79	70.90	79.94

3.3. Shore D Hardness

Shore D hardness values of the samples were measured with the PCE-D Shore D Durometer device as seen in Figure 4.a. The obtained hardness values are seen in Figure 4.b. Accordingly, the Triangular infill pattern offers hardness values ranging from approximately 85 to 105 Shore D for infill ratios from 20% to 95%, respectively. This reflects the Triangle pattern's tendency to provide high strength and impact resistance. It was observed that the hardness increased with the increase in the filling ratio. The rectilinear fill pattern offers good stability for general use. In this study, an increase from 84 Shore D at 20% infill to 104 Shore D at 95% infill was estimated. This is consistent with the hardness values of PLA reported in the literature, ranging from 77 to 81 Shore D (Mayén et al, 2022). Honeycomb filling pattern balances lightness and strength. In this study, an increase from 83 Shore D at 20% filling rate to 103 Shore D at 95% filling rate was achieved. The flexibility of the Honeycomb structure may result in lower hardness values. The Concentric filling pattern offers hardness values ranging from 82 Shore D at 20% filling rate to 102 Shore D at 95% filling rate. The flexible nature of this pattern may lead to lower hardness values. In the literature, it has been observed that the hardness generally increases as the filler density of PLA increases. In their study, Şirin et al. (2023) based their studies on the values determined as 93.9, 99.9 and 102.6 Shore D for 30%, 50% and 70% filling densities, respectively.

3.4. Scanning Electron Microscope (SEM)

Figure 5.a shows the 3D printed structure with a 20% filling ratio. The large voids and gaps between the printed paths are clearly visible, which would contribute to a lower mechanical strength. This structure is less dense and would be more prone to fractures under stress due to the reduced material continuity. Figure 5.b shows the 3D printed structure with a 60% filling ratio. Compared to the 20% fill ratio, the paths are closer together, and there are fewer and smaller voids. This indicates a better layer adhesion and a potential for higher mechanical strength than the 20% fill ratio sample. However, it's still not as densely packed as a higher fill ratio would be, and thus, would have intermediate strength characteristics. Finally, Figure 5.c with a 95% fill ratio shows a very dense structure with minimal voids. The layers appear to be very tightly packed, which suggests excellent material continuity and strong layer-to-layer adhesion. This structure is expected to have the highest mechanical strength among the three, making it the most suitable for applications that require robust mechanical properties.

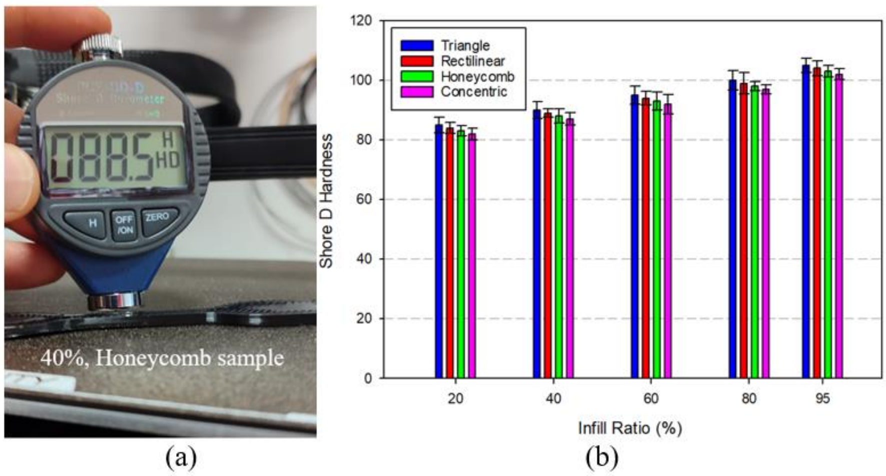


Figure 4. Shore D hardness variation according to filling ratio-pattern.

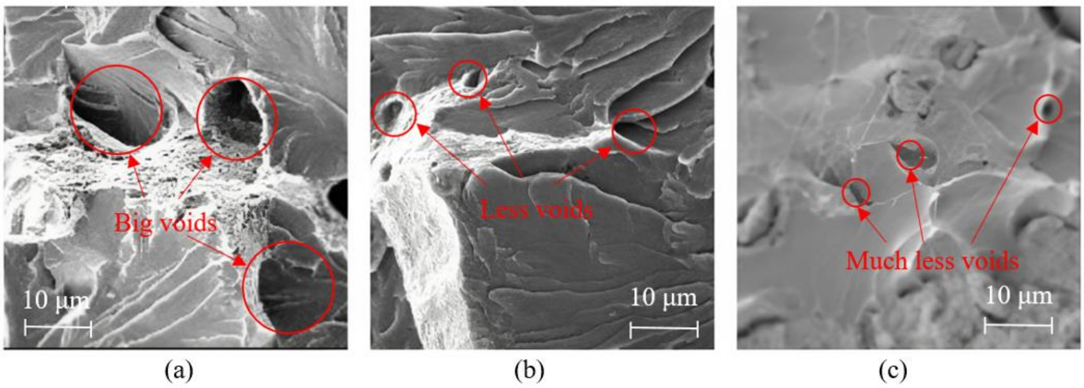


Figure 5. Scanning electron microscope views according to infill ratios of Concentric filling pattern, a) 20%, b.) 60%, c) 95%.

4. Discussion

An in-depth examination of tensile strengths across samples with varied infill patterns and ratios revealed insightful trends. The findings from the 20% infill samples highlighted discernible disparities based on patterns; with the Concentric pattern registering the highest tensile strength at 19.88 MPa, while the Triangle pattern lagged behind at 14.15 MPa. This difference could be attributed to the fuller, fracture-direction aligned nature of the Concentric pattern compared to the more gapped Triangle pattern. As infill percentages rose, the Rectilinear, Honeycomb, and Concentric patterns observed significant surges in tensile strength, culminating with the Concentric pattern's 48.67 MPa peak at 95% infill. Aligning with prior studies by Pandzic et al. (2019) and Lalegani Dezaki et al. (2021) the Concentric pattern, particularly with a 90% infill, was found to exhibit superior tensile and yield strengths for PLA filaments. Furthermore, the data from flexural tests underscored the pronounced strength variations across patterns at differing infill percentages. For instance, the Concentric pattern soared to a 79.94 MPa flexural strength at 95% infill. Collectively, these findings emphasize the pivotal role of infill pattern and ratio in determining tensile and flexural strengths in 3D printing. The insights drawn from Table 2 further accentuate the prominence of the Concentric pattern, especially at escalated infill percentages, for applications demanding enhanced tensile durability. Interestingly, while the Triangle and Honeycomb patterns started similarly at 20% infill, they diverged significantly at higher infill levels. This, combined with the consistent growth in the Rectilinear pattern, reaffirms the importance of strategic pattern and ratio selections in 3D printing to meet specific mechanical benchmarks. The flexural testing offered additional clarity on the mechanical prowess of the samples, specifically their bending resistance. When subjected to flexural stress, it became evident that both the infill pattern and ratio were crucial determinants of mechanical performance. The initial observations for the 20% infill, as depicted in Figure 3 echoed the trends seen in tensile tests, with the Concentric pattern emerging superior in terms of load-bearing capability. Notably, despite its tensile strength, the Honeycomb pattern underperformed in flexural strength when juxtaposed against its counterparts. However, as infill percentages increased, Honeycomb's strength saw improvements. The outstanding flexural modulus showcased by the Concentric pattern further underscores its mechanical robustness. Drawing from Table 3, the Concentric pattern's prowess, especially at higher infills, is evident. Conversely, the Honeycomb pattern's performance, though commendable, showcases a plateauing trend post the 60% infill mark. The data underscores the importance of the infill pattern and its ratio in optimizing the flexural performance of 3D printed objects. Potential avenues for future studies could involve dissecting the structural intricacies of these patterns to understand their performance variations better. In Shore D hardness measurements, an increase in hardness values was observed in parallel with the increase in the filling ratio. On the other hand, changing the filling patterns was found to be less affected by the change in the hardness values of the samples. Overall, the SEM images visually support the idea that a higher fill ratio in 3D printing leads to a denser structure, better layer adhesion, and consequently, improved mechanical properties such as tensile strength. The 95% fill ratio with a Concentric pattern is likely to result in the most durable and structurally sound parts suitable for demanding applications.

5. Conclusion

The study presented a comprehensive investigation into the tensile and flexural strengths of 3D printed samples, focusing on varying infill patterns and ratios. The primary takeaways from this research are:

The choice of the infill pattern is paramount in determining both the tensile and flexural strengths of 3D printed objects. The Concentric pattern, in particular, exhibited consistent superior performance in both these categories, especially at higher infill ratios. At an initial 20% infill, while Triangle and Honeycomb patterns exhibited comparable tensile strengths, a clear divergence in their performance was observed as the infill ratio was increased. On the other hand, the Rectilinear pattern demonstrated a steady and predictable growth in tensile strength with rising infill percentages. Flexural tests revealed that, despite Honeycomb's promising tensile strength, it lagged in terms of flexural resistance, especially when juxtaposed against other patterns. However, its strength improved with higher infill ratios. The Concentric pattern, with its outstanding flexural modulus, highlighted its potential as a top choice for applications requiring strong resistance to bending. Aligning with prior studies, the Concentric pattern displayed superior tensile and yield strengths, especially for PLA filaments with higher infill ratios. These findings underscore the significance of strategic pattern and ratio selection in 3D printing to cater to specific mechanical requirements. There's a pronounced need for designers and engineers to be judicious in their selections, especially when aiming to optimize the mechanical properties of 3D printed components. The data suggests intriguing avenues for future research. A deep dive into the structural nuances of different patterns, coupled with real-world application testing, could offer more insights into optimizing 3D printed objects for various purposes.

In essence, this research provides valuable insights for stakeholders in the 3D printing realm. It emphasizes the profound impact of infill patterns and ratios on the mechanical strengths of printed objects, guiding future design decisions and paving the way for further exploration in the domain.

Author Contributions

The percentage of the author(s) contributions is presented below. All authors reviewed and approved the final version of the manuscript.

	F.K.	A.K.
C	50	50
D	80	20
S	25	75
DCP	70	30
DAI	40	60
L	50	50
W	80	20
CR	40	60
SR	65	35
PM	70	30
FA	90	10

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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