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Performance Evaluation of Conventional Lattices Additively Manufactured Using PCL for Bone Scaffold Applications

Noorhafiza Muhammad[1]*, Muhammad Bilal[2], Kuang Yee Ng[1], Adleen Natasha Adnan[1],
Mohd Shuhidan Saleh[1], Tariq Jamil[2], and Kamalakanta Muduli[3]

[1]Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis, Arau 02600, Perlis, Malaysia.
[2]Department of Mechanical Engineering, NED University of Engineering and Technology, Karachi, Pakistan.
[3]Department of Mechanical Engineering, Papua New Guinea University of Technology, Lae PMB 411 Morobe Province, Papua New Guinea.

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ABSTRACT

The internal architecture of the bone scaffold is crucial for bone tissue engineering; i.e., the bone scaffold must be high-strength and lightweight. Besides architecture, materials are also influential parameters in designing the bone scaffold. This study aims to investigate the impact of different pore shapes on mechanical properties, which will exclusively apply to bone scaffolds. Dog-bone specimens made of Polycaprolactone (PCL) with four different porous structures, i.e., triangular, circular, hexagonal, and square, were tested on a Universal Testing Machine (UTM). These specimens were additively manufactured through the Fused Deposition Modelling (FDM) technique. Tensile and compression tests on a universal testing machine revealed that the hexagonal lattice specimen can sustain and bear more load under compression than the triangular and circular lattices. While under tensile load conditions, circular lattices can bear more load than triangular and hexagonal lattice specimens. The square-lattice specimen was found to be the least favorable for tensile and compressive loads. Hence, this research will aid in selecting the lattice structure for the bone scaffold design.

Keywords: Fused Deposition Modelling (FDM), Scanning Electron Microscope (SEM), Bone Scaffold, Conventional Lattice Structure.

1. INTRODUCTION

Bone tissue engineering has been progressively adapted by the surgeons and doctors due to the convenience of fabrication methods, designs and materials [1]. These materials, which can be exploited in bone tissue engineering, must be biocompatible, bioactive, biodegradable and have appropriate mechanical properties [2]. Bone tissue engineering involves engineering insights to provide physical support and bioactive stimulation for cell adhesion, proliferation, differentiation, and the formation of new bone by constructing a 3D scaffold that mimics the natural microenvironment of bone tissue [3].

Bone tissue engineering has been leveraged with the 3D printing technology due to virtue of its complex design developments. 3D printing technology involves the deposition of sequential layering of molten polymer or metal using a computer numerical controlled heated nozzle, alternatively called the rapid prototyping. It has been adopted due to its ubiquitous nature in applications; for instance, in robotics, it may be used to make miniature designs such as chassis,

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*Corresponding author: noorhafiza@unimap.edu.my

housings, mountings, and supports [4]. In medicinal research, it can be exploited to orthodontics, surgical tools, prosthetics and implants [5].

The selection of biocompatible materials for the bone regeneration process involves evaluating them to use in bone tissue engineering. Polycaprolactone (PCL), a biodegradable polymer, has garnered significant attention for bone scaffolds by virtue of its higher biocompatibility, low degradation rate, and ability to be tailored for mechanical properties [6], [7]. PCL scaffolds can be developed using 3D printing, allowing control over design, pore size, and interconnectivity can be accommodated, which are important factors for tissue regeneration. Unlike traditional fabrication methods, 3D printing allows customization of scaffold designs to meet specific patient needs, reduce production costs, and enhance the efficiency of the development process [8].

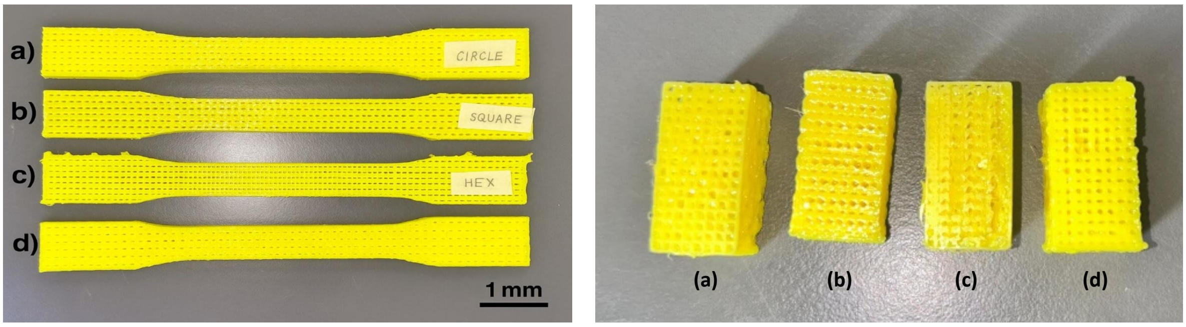
The mechanical characteristics of bone scaffolds, such as durability and flexibility, are mostly evaluated based on their geometry, including pore size, shape, and interconnectivity. These characteristics must be enhanced to enable the scaffold to replicate the mechanical strength of real bone while providing optimal conditions for cell growth. For uses involving bone tissue engineering, scaffold design should be improved. This research will examine the influence of different geometric configurations on the mechanical properties of 3D-printed PCL scaffolds [9], [10].

2. METHODOLOGY

The specimens of PCL were designed on CATIA V5 and printed using Fused Deposition Modelling (FDM) technology. Since PCL is a thermoplastic polymer which is both biodegradable and safe for medical purposes. It has been widely used as bone scaffold for regeneration of bone. Its non-toxicity makes it safe for medical use. Four porous specimens were designed to maintain a characteristic length of 1mm, i.e., triangular, circular, hexagonal, and square, as shown in Figure 1. Keeping in mind the thermal properties of PCL [11], [12], the printing parameters were chosen as listed in Table 1.

Table 1: Key printing parameters used in the present study.

Variables	Values
Nozzle temperature (°C)	174.0
Build Plate Temperature (°C)	30.0
Print Speed (mm/s)	100.0
Layer Height (mm)	0.2
Infill Density (%)	0.2



(a) (b)

Figure 1: Additively manufactured sample of the (A) tension and (B) compression tests.

Standard-compliant specimens were chosen to undergo testing: rectangular for the compression test (ASTM D695) with dimensions of 25.4 mm × 12.7 mm × 12.7 mm, and dog-bone for the tensile test (ASTM D638) with dimensions of 165 mm length, 19 mm width, and 3 mm thickness. The recurring pore structures formed the core cross-section of the dog-bone shape, and the test nozzles were gripped ends retained as solid to provide a secure clamp during the test. This shape has been selected so that a clear stress concentration area will be available in the centre, where failure is likely to occur, to easily observe tensile behaviour[13]. These specimens were evaluated using a Scanning Electron Microscope (SEM) and a Universal Testing Machine (UTM). The SEM was used to analyze surface morphology and internal structure, including pore size, pore shape, and porosity, which are important for bone regeneration. Table 2 below shows the specifications of the SEM machine. UTM (as detailed in Table 3) was used to measure and analyze the tensile, compressive, and elastic properties of the bone scaffolds.

Table 2: Specification of the scanning electron microscope.

Specifications	Details
Magnification	15x ~ 30000x
Resolution	30nm
Acceleration Voltage	5kV~15kV
Detector	Backscattered Electron Detector (BSED)
Maximum Sample Size	50mm diameter, 20mm thickness

Table 3: Specification of the universal testing machine.

Specifications	Details
Test Types	Tensile and Compression
Maximum Load Capacity	5kN~100kN
Crosshead Speed	0.001~1000 (mm/min)
Stroke	500mm~1200mm
Control Software	TRAPEZIUM X

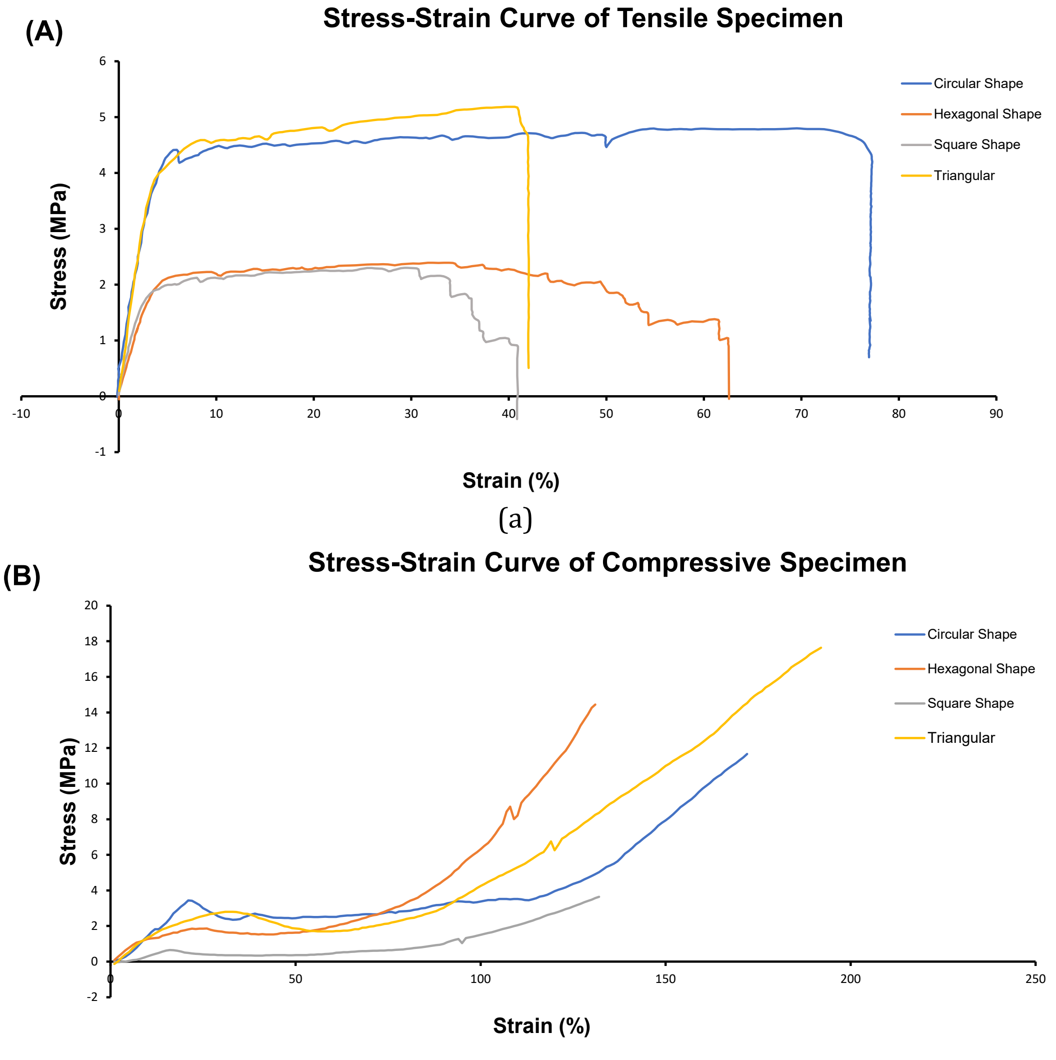
Tensile and compressive tests were used to evaluate the scaffold geometries; the specimen shapes used in tensile tests were different from those used in compressive tests, but the infill used in both specimen shapes was the same to facilitate the assessment. To assess how well the 3D-printed PCL bone scaffolds withstand load, a set of mechanical tests was conducted. These tests revealed the stiffness, yield strength, and ultimate strength for every pattern. The findings showed exactly how the different internal shape effects under different loading conditions; these insights would be needed to conduct the cause-and-effect analysis if the scaffolds are to work in real bone-issuing gineering cases [5], [14].

3. RESULTS AND DISCUSSION

3.1 Stress-Strain Curve of Compression and Tensile Test

The stress-strain curve is the fundamental graph of the material to familiarize oneself with the properties of any material. The stress-strain curves of specimens with different intercellular structures indicate that circular-shaped pore specimens are more reliable and resilient, with high yield strength, while triangular-shaped pore specimens show the highest ultimate tensile strength. Both the hexagonal pores specimen and the square pores specimen showed approximately the same yield strength but the resilience and toughness of the hexagonal pores specimen are more than those of the square shape under tensile loading conditions, as illustrated in Figure 2.

Likewise, under compressive loading conditions, hexagonal pores are found to be more resilient, with the highest fracture stress. Triangular pore shapes exhibit the highest strain, indicating the highest toughness and resilience. The circular pore shape showed the highest yield strength, while the square pore specimen did not produce the expected results.



(a)

(b)

Figure 2: Stress-strain curve results obtained from the universal testing machine (A) for tensile specimen (B) for compressive specimen.

3.2 Influence on Mechanical Properties

The intercellular structure of the specimen substantially affects the mechanical properties; the best-performing structure was found to be the hexagonal one, i.e., 18.5 MPa under compressive loads, indicating an enormous load-bearing capacity. It also showed a smooth and ductile deformation behavior, making it a reliable structure to absorb compressive loads without sudden failure. The triangular pore shape shows a lower maximum stress strength of approximately 18.0 MPa but a higher strain at failure of 85%. It indicates that the shape can withstand large deformation. Yet, its soft yield point shows an earlier plastic deformation. The square pore shape has the lowest maximum stress among to shapes, at around 7.0 MPa. Its sudden change to plastic deformation, while maintaining a long elastic range, indicates a more brittle failure structure under heavy loads. The circular pore shape shows moderate mechanical properties, with a smooth stress distribution and a maximum stress of 13.0 MPa.

The circular-cellular structure performed very well under tensile loading, with a strain of approximately 75% and a maximum tensile strength of about 4.8 MPa. The smooth stress-strain curve makes it the most reliable under tensile loads, as it shows good ductility and the capacity to stretch without fracturing. The square-cellular structure had a lower strain of about 36% and the lowest tensile strength, about 2.4 MPa. After reaching the maximum point, the stress-strain curve for this shape dropped sharply, indicating that it breaks easily and exhibits brittle behavior. This indicates that the square pore shape and inadequate structure makes it unsuitable for supporting tensile loads. Thus, the scaffold's shape greatly influences its performance under tension; square geometry is the least effective, while circular geometry is the most effective. The circular pore shape is therefore the most suitable geometry for bone scaffold applications because of its high strength and flexibility under tension, whereas the square pore shape is least suitable because it shows low strength and brittle failure, as indicated by the tensile test results.

3.3 SEM Analysis of Intercellular Defects

The SEM analysis demonstrates the importance of geometry for 3D print quality, as illustrated in Figure 3. The circular pores achieved superior shape accuracy because their design required gentle nozzle movements, thereby avoiding abrupt directional changes. The material experiences less stress due to this method, leading to decreased layer shifts and incomplete edges. The circular pores generated smooth surfaces and reduced printing defects due to this approach.

The hexagonal pore structure delivered the most balanced operational results. The gradual changes in angle allowed for smoother nozzle transitions, resulting in more accurate pore shapes and cleaner edges. The six-sided structure is symmetrical and stable, helping maintain even material flow during printing. Because of this, the hexagonal pores showed fewer defects and more consistent shapes compared to the triangular and square designs.

Square pore SEM image reveals better printing results compared to the triangular pores with straighter sidewalls and more uniform shapes. But its edges are not perfect and appear somewhat rounded. This could result from rapid deceleration or reorientation of the nozzle at 90-degree turns. Small issues can lead to small gaps or excess material. The flat edges frequently show little printing errors, even with the similar-looking pore shapes. These small errors might affect the printed sample's strength and surface quality.

The triangle shapes were more difficult to print. The sharp-angled design made the nozzle- bearer difficult to operate with pinpoint accuracy, especially in the corners. It is expected that these corners would overheat or at least have material stretching and rounding. The abrupt turns during the printing process also led to incompletely extruded material, resulting in surface roughness or defects in the printed film structure.

In summary, the SEM results indicate that the pore structure affects the surface quality of 3D-printed scaffolds. Symmetrical shapes with smooth curves, like circular or hexagonal, had cleaner edges and fewer visible defects. Meanwhile, the junction between the triangular and square shapes approached a sharp-edged design, which became more difficult to fabricate. These results imply that geometry selection is critical for obtaining high-quality scaffold designs. Designing scaffolds, especially for precision-demanding applications, using simpler to print geometries may help increase overall performance and consistency.

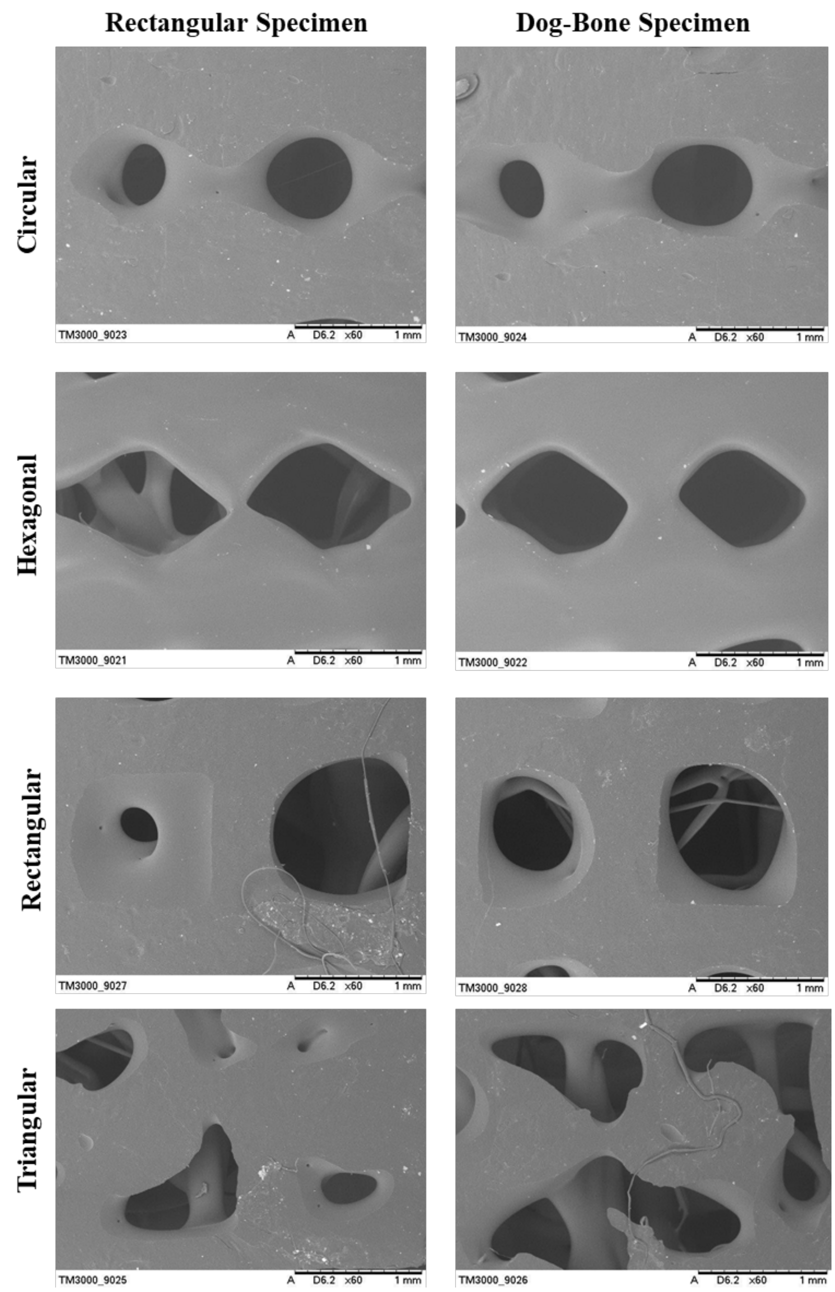


Figure 3: SEM images of samples with different geometric configurations.

4. Conclusion

This study explored the stress-strain curve and diagnosed 3D printing defects during the printing of a PCL specimen with conventional lattices. The following points can be inferred from the above experimental investigation conducted on a PCL specimen printed on conventional lattices, i.e., circular, hexagonal, triangular, and rectangular.

- The hexagonal intercellular PCL specimen would withstand high compressive stresses. It will certainly produce less additive manufacturing defects than those produced by other intercellular shapes.

- The circular intercellular PCL specimen can sustain high strains under tensile loading conditions, producing fewer additive manufacturing defects than other intercellular shapes.
- The triangular and rectangular shapes are not preferred intercellular shapes due to their lower stress resistance and higher rates of manufacturing defects.

Furthermore, this study can be used to validate finite element analysis (FEA), thereby corroborating these results can be corroborated. These insights could assist readers and designers in their way forward and exploitation of bone scaffolds.

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