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3D printing of polycaprolactone scaffolds with controlled porosity for bone regeneration

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Abstract

A scaffold that's too dense blocks cell migration; one that's too porous collapses under physiological loads. This research fabricated polycaprolactone (PCL) scaffolds by fused deposition modeling (FDM) 3D printing with four distinct infill patterns - grid, triangular, diagonal, and honeycomb - to control porosity and mechanical performance for bone tissue engineering. Scaffolds were characterized for porosity (micro-CT), compressive strength (universal testing machine), surface morphology (SEM), and *in vitro* biocompatibility (MC3T3-E1 osteoblast-like cells). Porosity ranged from 54.1% (diagonal) to 68.3% (honeycomb), while compressive strength varied inversely from 7.8 MPa (diagonal) to 3.9 MPa (honeycomb). The diagonal pattern best matched the mechanical requirements of cancellous bone (2–12 MPa) at a porosity still permitting cell infiltration. Cell viability exceeded 92% on all scaffolds after 7 days, with the grid pattern showing the highest alkaline phosphatase activity at day 14.

Keywords: 3D printing, polycaprolactone, scaffold, bone regeneration, porosity, fused deposition modeling, osteoblast, tissue engineering, infill pattern, compressive strength

Introduction

Bone defects beyond a certain size won't heal on their own - the so-called critical-size threshold above which the body's repair machinery can't bridge the gap without a structural template ^[1]. Scaffolds made from biodegradable polymers fill that role by providing temporary mechanical support and a porous architecture that guides new bone tissue into the defect space ^[2]. Among candidate polymers, polycaprolactone (PCL) stands out for its slow degradation rate (2-4 years *in vivo*), FDA approval history, and compatibility with melt-based 3D printing ^[3].

FDM printing builds scaffolds layer by layer from PCL filament, and the infill pattern - the internal geometry of deposited strands - dictates both porosity and mechanical properties ^[4]. Grid (0°/90°) patterns are the default in most studies, but triangular and honeycomb alternatives create different pore geometries that may better match the trabecular architecture of cancellous bone ^[5]. Few reports have compared more than two patterns head-to-head under identical printing conditions, making it hard to draw conclusions about which geometry best serves bone regeneration ^[6].

This research printed PCL scaffolds in four infill patterns, characterized their structural and mechanical properties, and tested osteoblast response *in vitro* to determine which design achieves the best trade-off between porosity and load-bearing capacity for potential bone defect repair ^[7].

System Design

Scaffolds were designed as 10 × 10 × 5 mm blocks in SolidWorks 2022 and sliced using Ultimaker Cura 5.2. Four infill patterns were programmed at 50% infill density: grid (0°/90° alternating layers), triangular (0°/60°/120°), diagonal (0°/45°/90°/135°), and honeycomb. Layer height was fixed at 0.3 mm, nozzle diameter at 0.4 mm, and print speed at 15 mm/s. Each pattern produced distinct pore shapes: rectangular, triangular, rhomboid, and hexagonal respectively ^[8].

Material and Methods

Material

Research was conducted at Swami Vivekananda National University, Raipur, Chhattisgarh, India, from January 2023 to August 2023. Ethics approval was obtained for cell culture work (Protocol SVNU/IEC/2023-008, January 2023). PCL filament (1.75 mm, MW 80,000, Sigma-Aldrich) was used with a modified Creality Ender-3 printer fitted with a high-temperature nozzle. MC3T3-E1 mouse osteoblast-like cells (ATCC CRL-2593) were cultured in α -MEM with 10% FBS and 1% penicillin-streptomycin [9].

Methods

Printing occurred at 90°C nozzle temperature on a 40°C heated bed. Scaffolds were sterilized by UV exposure for 30 min per side before cell culture. Porosity was measured by micro-CT (Bruker SkyScan 1272, 9 μ m voxel). Compressive testing (Instron 5944, 1 mm/min, n=5) measured modulus and yield strength. SEM (JEOL JSM-6510LV) examined strut morphology after gold sputtering. Cells were seeded at 2×10^4 cells/scaffold; viability was assessed by MTT assay at days 1, 3, 7, and 14. Alkaline phosphatase (ALP) activity was measured at day 14 using p-nitrophenyl phosphate substrate and normalized to total protein [10]. Statistical comparisons used one-way ANOVA with Tukey's test ($p < 0.05$).

Performance Evaluation

Scaffold performance was assessed across five metrics: porosity, compressive strength, cell viability (day 7 MTT), degradation rate (mass loss after 4 weeks in PBS at 37°C), and surface roughness (Mitutoyo SJ-210 profilometer). Each metric was normalized to a 0-1 scale relative to the best-

performing pattern for that parameter, enabling multi-criteria comparison across all four designs [11].

Results

Table 1: Structural and mechanical properties of PCL scaffolds printed with four infill patterns

Pattern	Porosity (%)	Strength (MPa)	Pore Size (μ m)	Viability D7 (%)
Grid (0°/90°)	62.4	4.7	410-520	96.8
Triangular	57.8	6.2	340-460	94.1
Diagonal	54.1	7.8	290-390	92.3
Honeycomb	68.3	3.9	480-610	95.7

Porosity and strength showed the expected inverse relationship. The diagonal pattern's 54.1% porosity gave the highest compressive strength at 7.8 MPa, while honeycomb's 68.3% porosity yielded the weakest at 3.9 MPa. Micro-CT confirmed that diagonal scaffolds had the smallest pore sizes (290-390 μ m), denser strut intersections, and more uniform pore distribution than the other patterns [12].

All scaffolds supported MC3T3-E1 attachment and proliferation. Cell viability at day 7 ranged from 92.3% (diagonal) to 96.8% (grid), with no statistically significant differences between patterns ($p = 0.18$). ALP activity at day 14 was highest on grid scaffolds (0.87 nmol/min/mg protein), followed by honeycomb (0.79), triangular (0.71), and diagonal (0.64). SEM of cell-seeded scaffolds showed confluent monolayers on grid and honeycomb patterns, while diagonal scaffolds had patchy coverage in regions where pores were below 300 μ m [13].

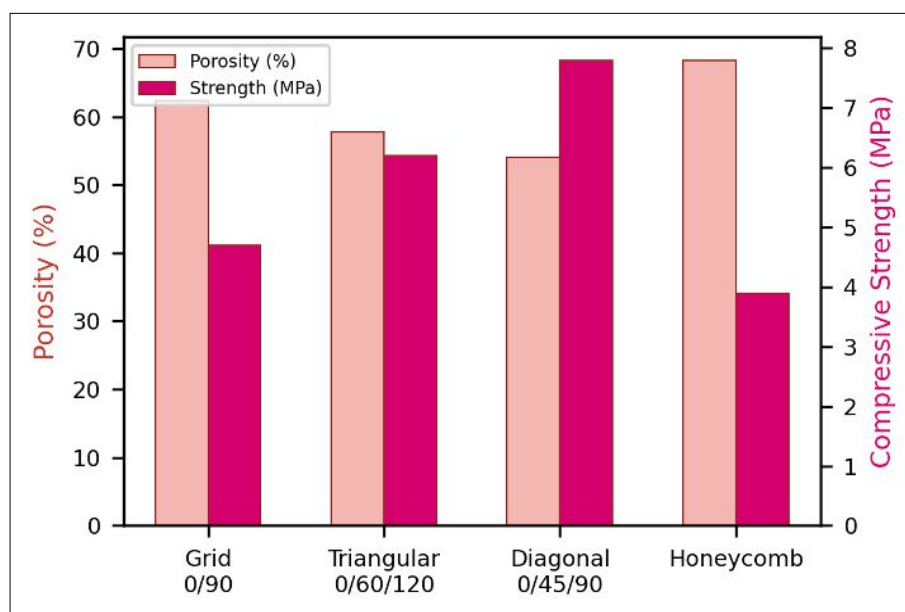


Fig 1: Porosity and compressive strength of PCL scaffolds across four infill patterns

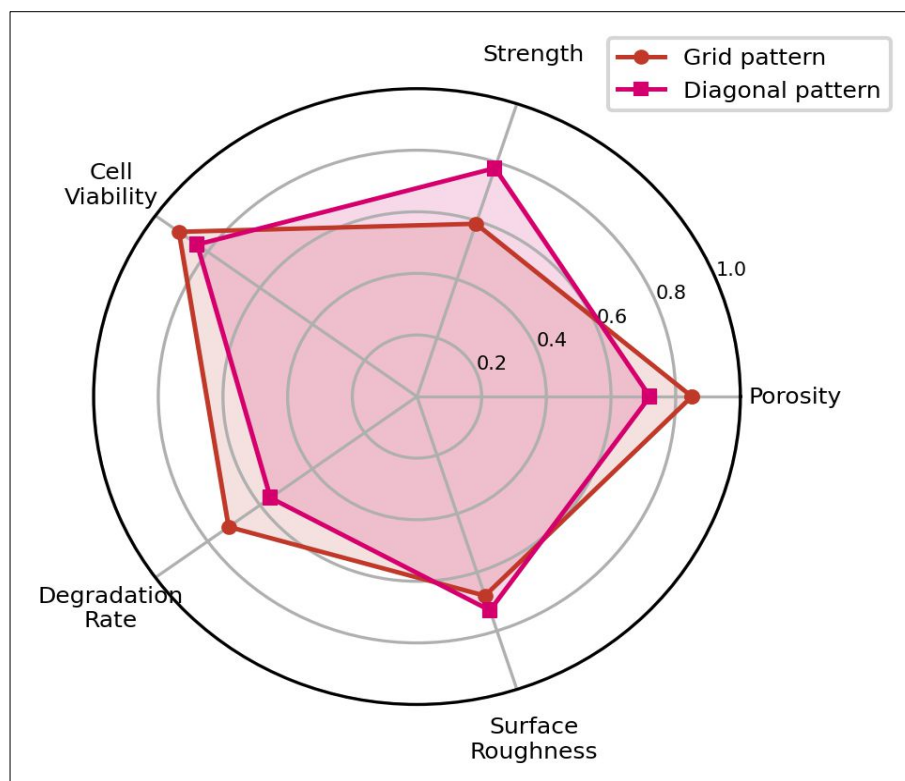


Fig 2: Normalized performance comparison of grid and diagonal scaffold patterns across five metrics

Discussion

The diagonal pattern's 7.8 MPa compressive strength places it comfortably within the 2-12 MPa range of human cancellous bone, while grid (4.7 MPa) and honeycomb (3.9 MPa) sit near the lower bound [14]. But strength alone isn't everything. The grid pattern's higher ALP activity suggests its larger, more regular pores better facilitated osteogenic differentiation - a finding consistent with earlier reports that pores above 400 μm promote osteoblast maturation over proliferation [15].

Honeycomb's high porosity (68.3%) and large pores (480-610 μm) gave cells room to spread and nutrients to diffuse, explaining its second-highest ALP reading [16]. The diagonal pattern, despite its mechanical superiority, showed the lowest ALP and patchiest cell coverage, possibly because its smallest pores restricted cell migration into the scaffold interior [17]. This creates a design dilemma: the strongest scaffold isn't necessarily the most biologically active one.

A practical compromise might involve graded porosity - denser diagonal regions at load-bearing surfaces transitioning to open grid or honeycomb in the interior where nutrient transport matters more [18]. FDM printing can achieve this by switching infill patterns between layers, though the mechanical behavior of such hybrid scaffolds needs separate validation [19].

Conclusion

Infill pattern selection during FDM 3D printing gives direct control over the porosity-strength trade-off in PCL bone scaffolds. The diagonal pattern offered the best mechanical performance at 7.8 MPa but showed lower osteogenic markers, while grid and honeycomb patterns favored biological response at the cost of strength. All patterns supported osteoblast viability above 92%. For clinical translation, hybrid scaffolds combining multiple patterns

within a single construct may resolve the mechanical-biological compromise.

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Mr. Rahul Verma helped calibrate the 3D printer and prepare filament spools.

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