Fabrication of Biomaterials for Bone Repair and Regeneration

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Abstract

Bone defects, both congenital and acquired, are serious and costly impairments. Bone defects beyond a critical size are not able to heal without further medical intervention. An effective treatment method is to implant a biodegradable scaffold at the injured site to promote bone repair and regeneration by attracting cells to the area. Using 3D printing technology, biomaterial scaffolds can be fabricated to meet the specific needs of patients. In this study, scaffolds with different infill patterns were fabricated from various biocompatible polymers. The mechanical properties of these scaffolds were characterized using compression tests to determine the yield stresses and compressive Young's moduli. These results were compared with yield stresses and moduli of different trabecular bone tissues at multiple anatomical locations.

Introduction

Bone defects are the lack of bone tissue in the body where tissue should be. They arise due to congenital and acquired conditions (i.e., fractures).[1]

Critical-sized bone defects can not heal spontaneously despite surgical stabilization and requires further intervention[2]. The critical-sized bone defects are those:

- Greater than 1-2 cm
- Greater than 50% loss of the bone circumference

Biomaterial scaffolds have structures that mimic the architecture of the host site to provide essential framework for cell attachment and regeneration. Critical parameters for bone scaffolds include biocompatibility, biodegradability, porosity, and mechanical properties,[3] which are important for cell viability and proliferation.

Advantages of using 3D printing for scaffold fabrication[4]. In addition to its affordability, it also has ability to

- Allow manufacturing patient-customizable scaffolds
- Create complex geometries with desired porosity
- Incorporate nutrients for cell viability and proliferation
- Mimic the mechanical strength of host bone tissues

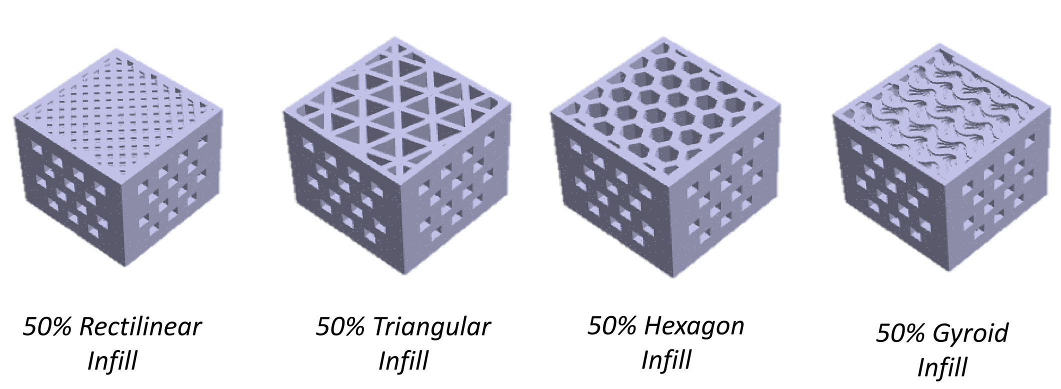


Figure 1. CAD design for 3D printing polymer scaffolds.

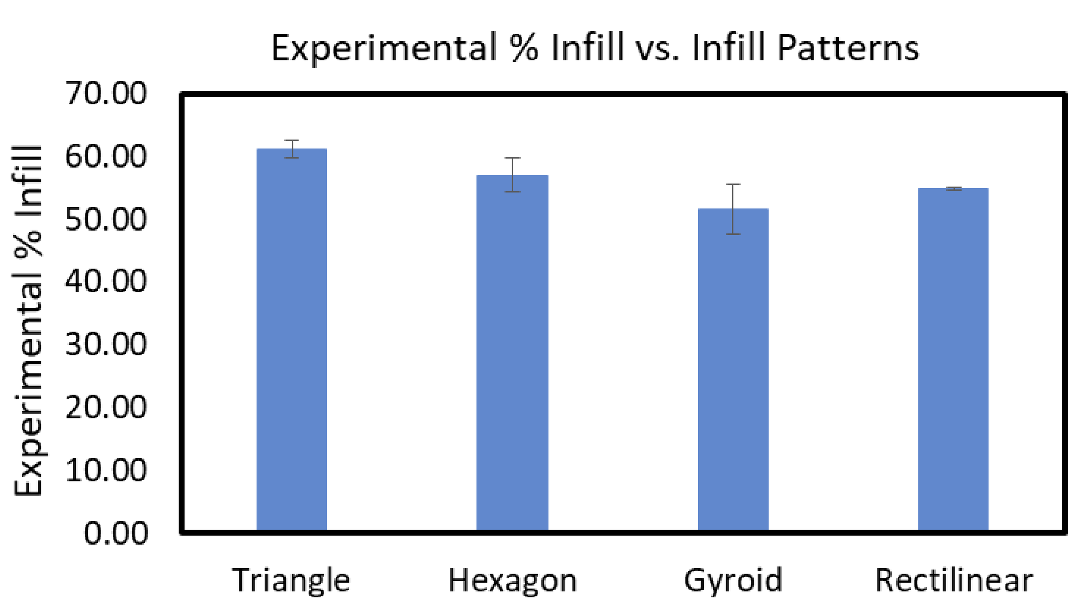


Figure 6. Experimental percentage infill comparison of various 50% geometric patterns (triangle, hexagon, gyroid, rectilinear) for PCL scaffolds.

Materials and Methods

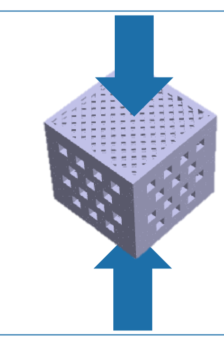
Onshape, a CAD development software, was used to design scaffold samples with various infill patterns. Cubic samples (10mm x 10mm x 10mm) were printed using Flashforge Dreamer 3D Printers by using a variety of polymer filaments: polylactic acid (PLA, MatterHackers Inc.), poly(ε-caprolactone) (PCL, 3D4makers), polyvinyl alcohol (PVA, MatterHackers Inc.), olefin block copolymer (OBC, a gift from Dow Chemical Company), and polylactic acid/polyhydroxyalkanoates (PLA/PHA, MatterHackers Inc.). The infill pattern and density of the samples were sliced using Flashprint, a CAD slicing software. These shapes consisted of: rectilinear, triangle, hexagon, and gyroid. The samples were compressed longitudinally and transversely using the MTS Insight 5. The compression rate for the samples was 1 mm/min. From these compressions, the yield stress (the point at which 2% plastic deformation occurs) and compressive Young's modulus (the slope of the stress over the strain during the Hookean region) were determined. Weibull analysis (a two-parameter, continuous probability distribution that is utilized for failure and life data analysis) was performed to find the probability of failure for triangle infill samples prepared using a variety of materials.

Results

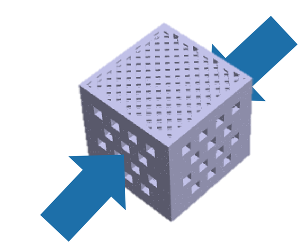
Poly(ε-caprolactone) (PCL) **Olefin Block Copolymer (OBC)** **Polylactic Acid (PLA)** **Polylactic Acid/Polyhydroxyalkanoates (PLA/PHA)** **Polyvinyl Alcohol (PVA)**

Mechanical Testing

Longitudinal Compression



compression rate: 1 mm/min



Transverse Compression

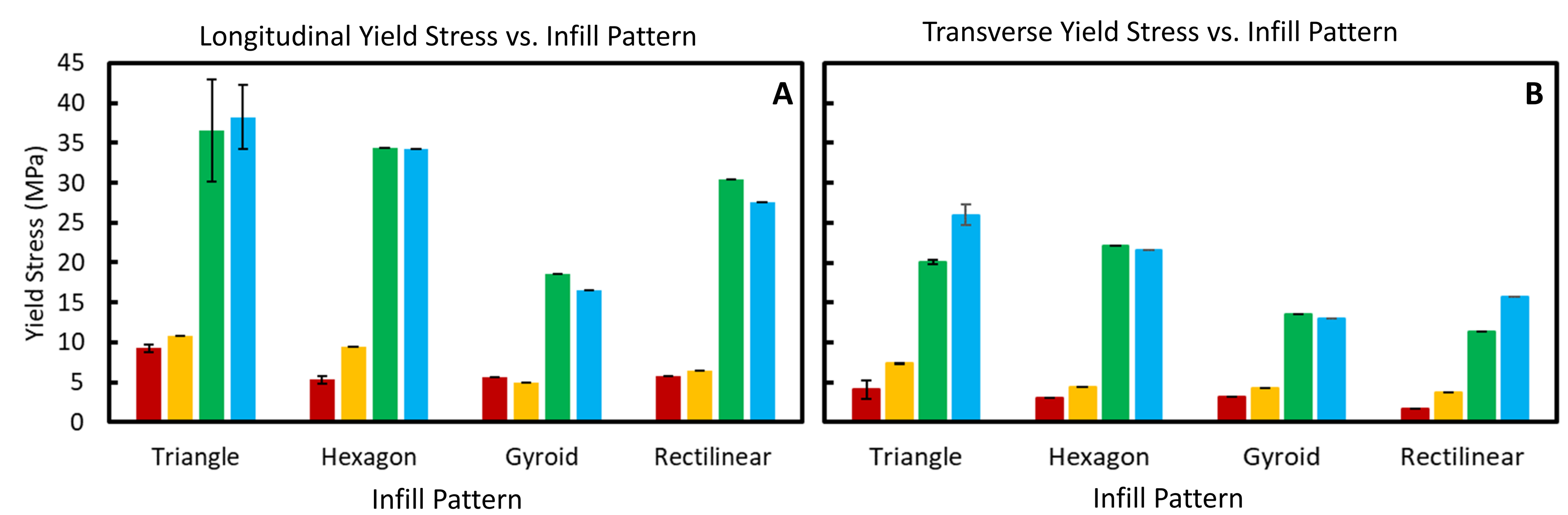


Figure 2. (A) Longitudinal and (B) transverse yield stresses versus infill patterns for scaffolds with 50% theoretical infill density prepared using a variety of polymers

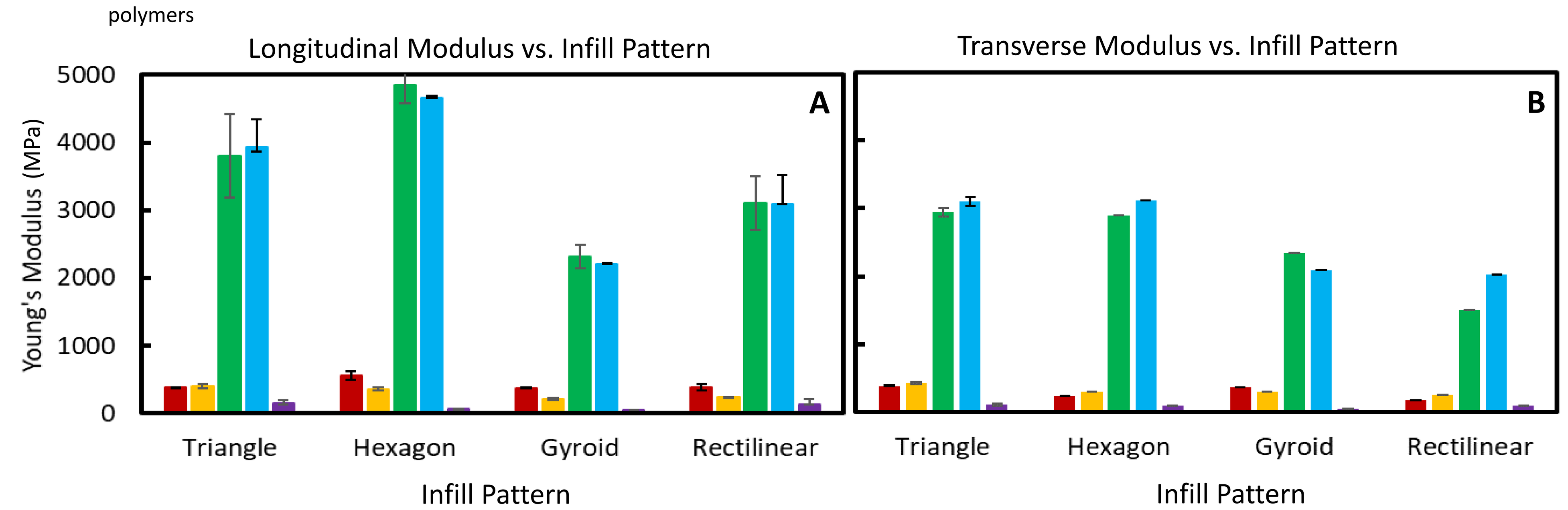


Figure 3. (A) Longitudinal and (B) transverse moduli versus infill patterns for scaffolds with 50% theoretical infill prepared using a variety of polymers.

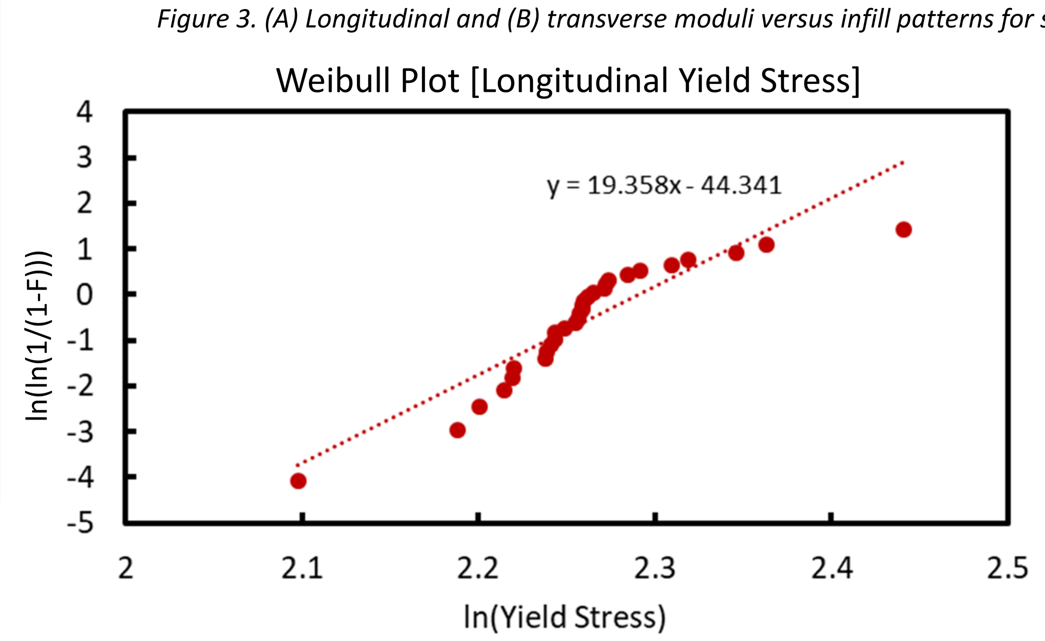


Figure 4. Weibull plot for longitudinally compressed PCL scaffolds (50% triangle infill, shown as an example).

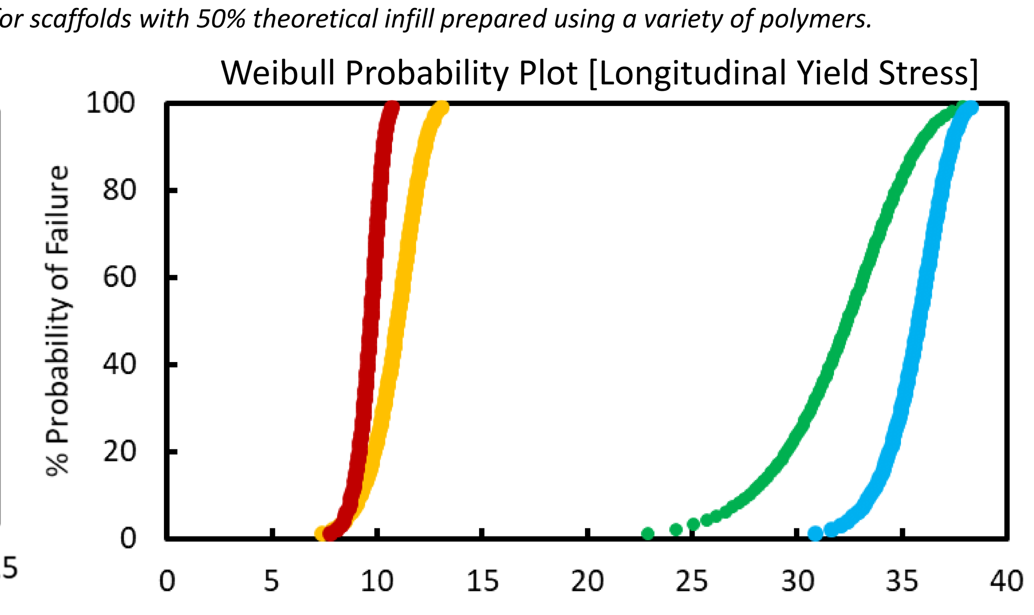


Figure 5. A failure probability graph for 50% triangle infill scaffolds.

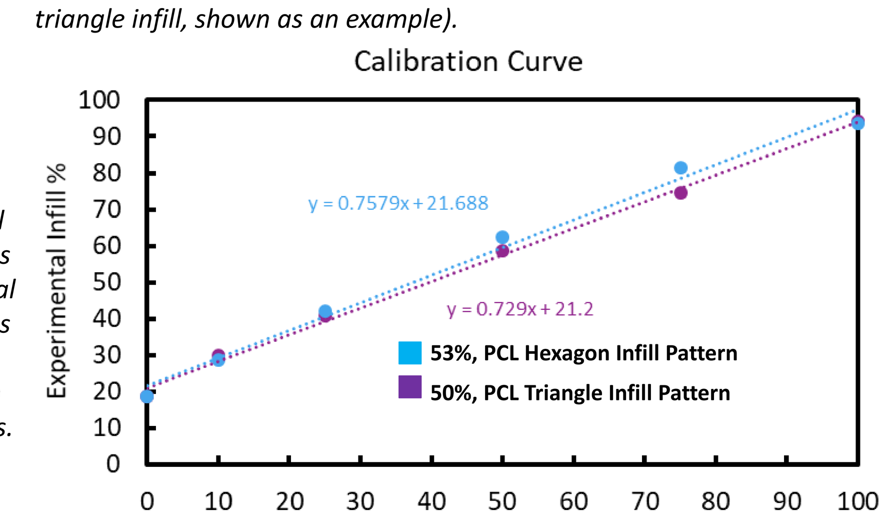


Figure 7. Calibration curves of experimental infill densities vs. theoretical infill densities for triangle and hexagon infill patterns.

Table 1. Weibull analysis results for PCL scaffolds

		Modulus (MPa)		Yield Stress (MPa)	
Shape (%)	Comp.	m	E_0	m'	σ_0
Triangle (50%)	Long.	13.5	649	19.4	9.9
	Trans.	14.1	396.2	13.9	4.4
Hexagon (53%)	Long.	20.9	804	28.4	10.5
	Trans.	4.6	402	8.7	5.0

E_0 = characteristic Young's modulus *σ_0 = characteristic yield stress*
m is Weibull modulus of compressive moduli and m' is Weibull modulus of yield stresses. They were obtained from the slopes of linear Weibull plots.

Table 2. Weibull Analysis Results for 50% Triangle Infill Scaffolds

	σ_0 (MPa)		E_0 (MPa)	
Material	Longitudinal	Transverse	Longitudinal	Transverse
PCL	9.9	4.4	649	396
OBC	11.4	7.8	458	417
PLA	33.4	19.8	3310	3112
PLA/PHA	36.3	28.9	3659	3203
PVA	N/A	N/A	157	106

σ_0 = characteristic yield stress
E_0 = characteristic Young's modulus

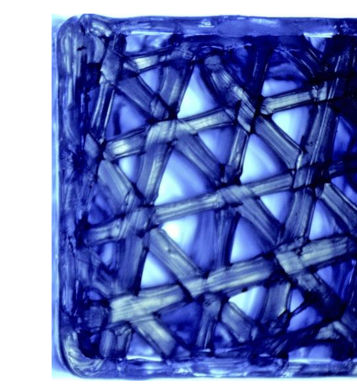


Figure 8. PCL scaffolds with 50% triangle Infill.

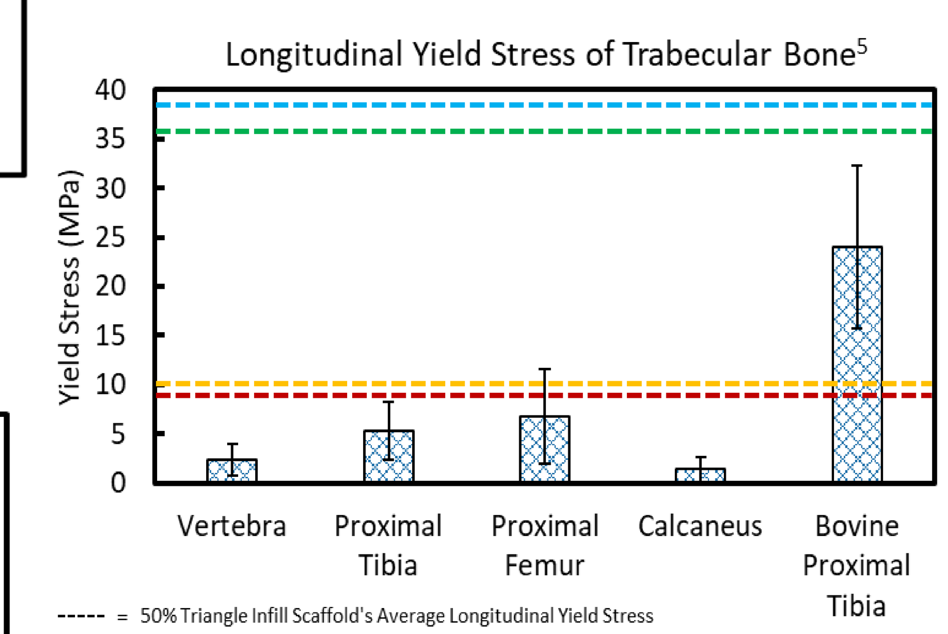


Figure 9. Yield stress comparison of trabecular bones and scaffolds.

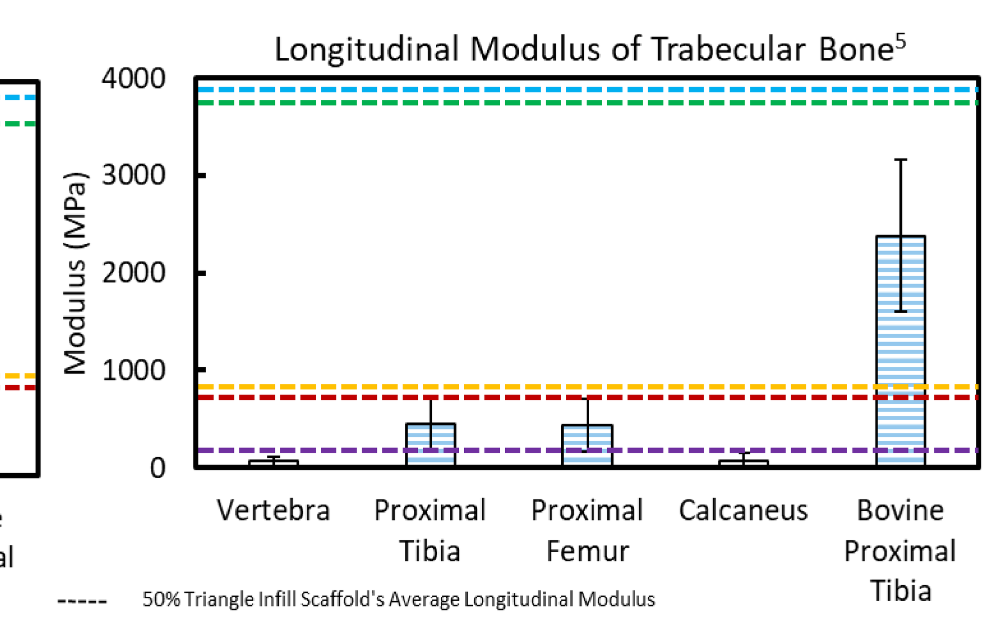


Figure 10. Modulus comparison of trabecular bones and scaffolds.

Conclusion

- PLA, PCL, OBC, PVA, and PLA/PHA scaffolds with different infill patterns and 50% infill density were produced using Flashforge Dreamer 3D printers.
- The compression test results indicate that the longitudinal yield stress of PCL and OBC scaffolds with varying geometric infills fall in the range of 5-10 MPa. In contrast, the PLA and PLA/PHA scaffolds with different geometric infills have longitudinal yield stresses above 15 MPa. The transverse yield stresses of all scaffolds are lower than their longitudinal yield stresses.
- The longitudinal and transverse modulus data showed a similar trend as the yield stress data for all the scaffolds.
- As shown in *Table 2*, 63% of the longitudinally compressed PLA/PHA scaffolds would fail at 36.26 MPa, the highest on average than the rest of the materials. In contrast, 63% of the longitudinally compressed PCL scaffolds would fail at 9.88 MPa, the lowest on average.
  - PLA/PHA was found to have the greatest characteristic yield stress and modulus, while PCL had the least.
  - The most compliant material is PVA, while the stiffest material is PLA/PHA.
- PVA exhibits shape memory property according to preliminary results obtained in this study.
- OBC is light weight with high durability, which could be potentially used as a prosthetic material.
- Due to the appropriate yield stresses and moduli of PCL and OBC scaffolds, they are the closest match to the mechanical properties of trabecular bone.

References

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