Tuning 3D Printed Resorbable Scaffold Strength and Resorption

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Introduction

Predictable and reliable resorption of scaffolds to treat bone defects is needed if remodeling of the tissue is required to enable the growth of neo-tissue. This neo-tissue must provide mechanical strength, vascularization, and defect site compartmentalization prevention. Thus, 3D printing resorbable scaffolds creates an optimization and control problem for material properties. First, it is necessary to have sufficient “green strength” (i.e., scaffold strength prior to post-fabrication curing) for adequate rendering and to clear unpolymerized polymer from the porous space without destroying the scaffold. Second, it is necessary for the scaffold to be weak enough to resorb by the time the neo-tissue filling the defect site must remodel.

Materials and Methods

Poly(propylene fumarate) (PPF) was prepared as previously described. Diethyl fumarate, the monomer precursor to PPF, was used as a solvent in a 1.5:1 PPF:DEF ratio. These were combined with 3% Irgacure® 819 (BASF, Florham Park, NJ) and 3% Irgacure 784 (BASF). Cylinders (3 mm diameter, 6 mm length) were rendered in an envisionTEC (Dearborn, MI) Perfactory Micro EDU via Continuous Digital Light Processing (cDLP). These cylinders were 3D printed using 90 (N=1), 180 (N=3), and 210 (N=5) seconds exposure per layer and set aside for mechanical testing without post-curing. One specimen (6 mm diameter, 12 mm length) was post-cured in a 3D systems (Rock Hill, SC) ProCure™ 350 UV chamber. Compression testing utilized an Instron (Norwood, MA) 8501.

Results

Cylinders as in Figure 1 were 3D printed (Figure 2a) to varying degrees of yield.

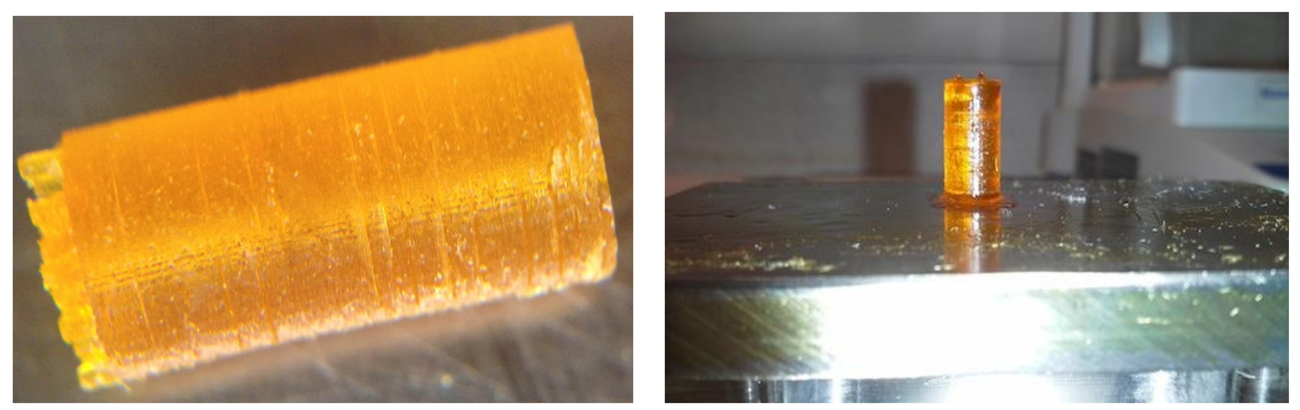


Figure 1. (left) Example 3 x 6 mm 3D-printed cylinder. Note that the supports have not yet been removed. (right) Example 6 x 12 mm cylinder attached to build platform just after printing.

Specimens were tested to failure in an Instron rigged with a self-aligning fixture (Figure 2b). Load was recorded through a load cell and strain was recorded using an externally mounted extensometer due to the specimen being too small to attach directly to. Figure 3 shows results of this testing, which plots load versus displacement. From the slope, stiffness can be examined, which can then be correlated to modulus though knowing the cylinder cross-sectional area.

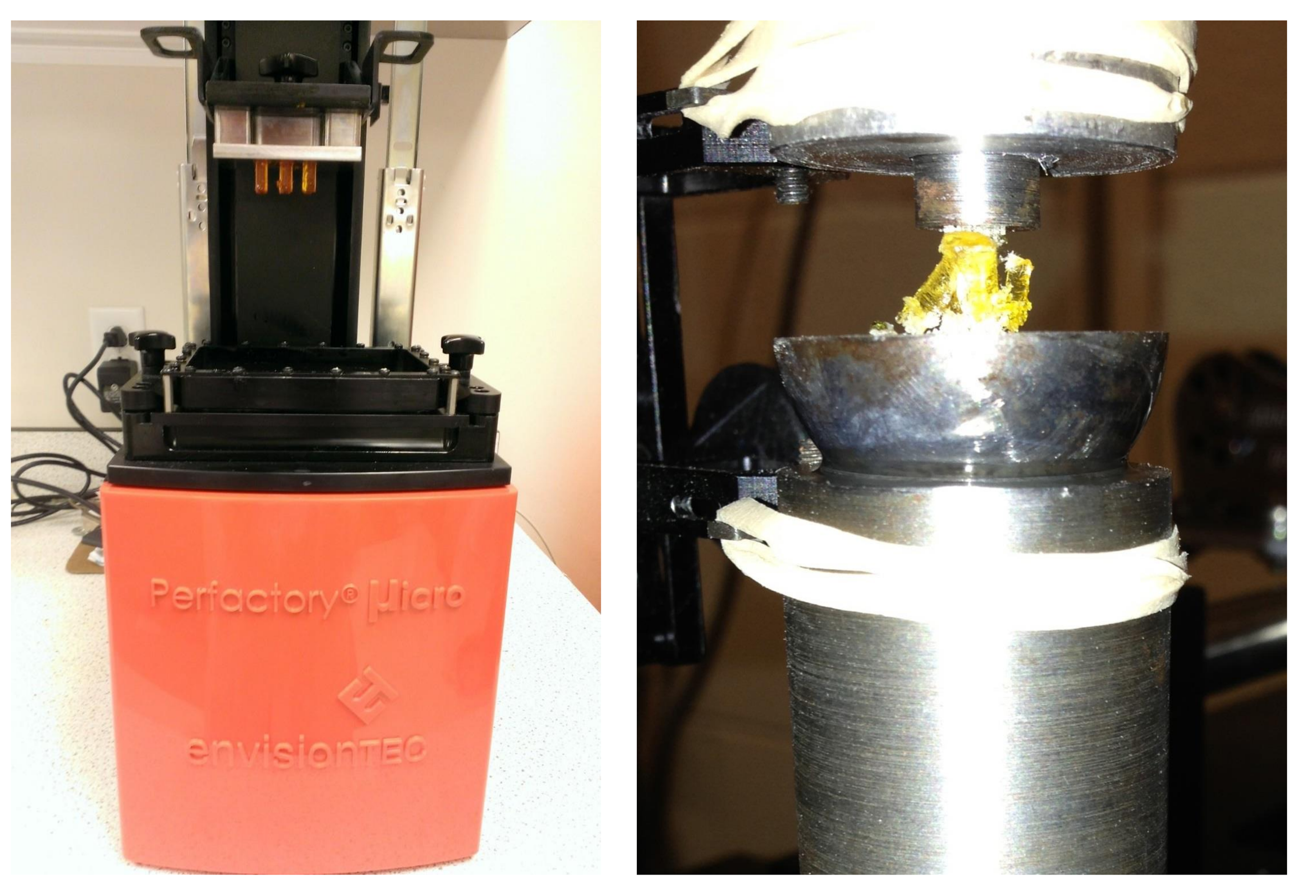
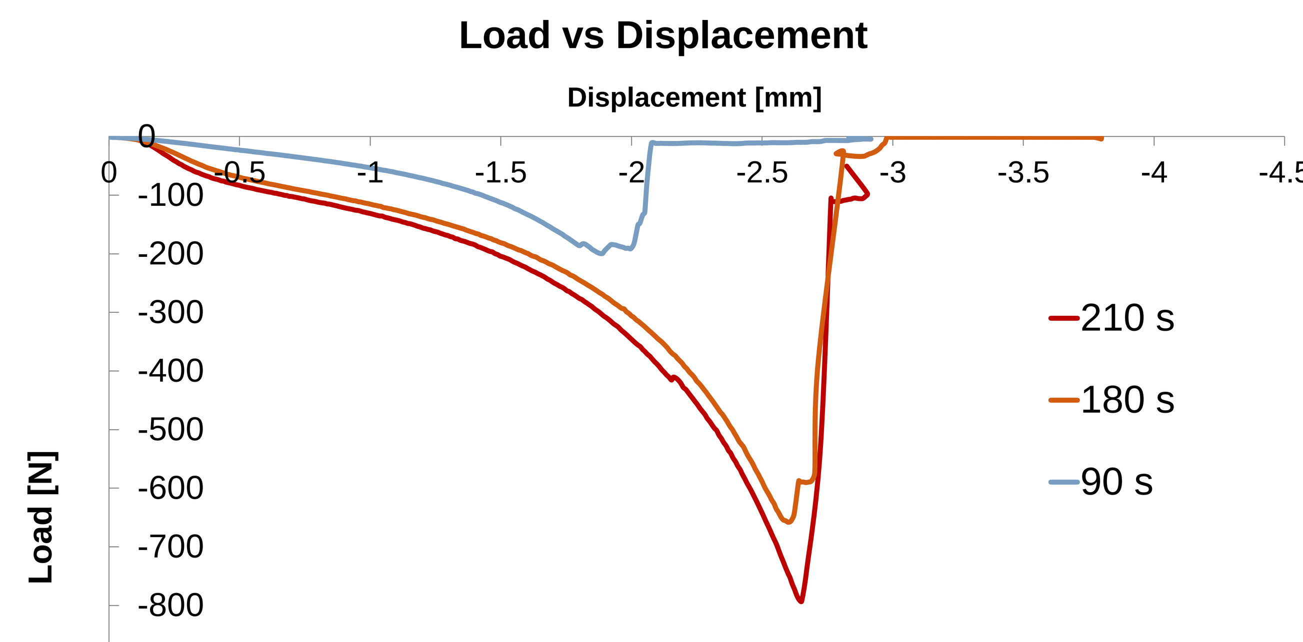


Figure 2. (a) Cylinder test specimens after being 3D printed in Perfactory Micro. (b) Specimen after being tested to failure under compression.



Exposure Time	Layer Thickness	Avg. Modulus (sample size)
90 s	120 micron	23.7 MPa (1)
180 s	150 micron	124.8 MPa (3)
210 s	180 micron	188.5 Mpa (5)

Figure 3. Mechanical Testing of 3D Printed PPF Cylinders: Strength vs. Exposure Time. MPa = megapascal.

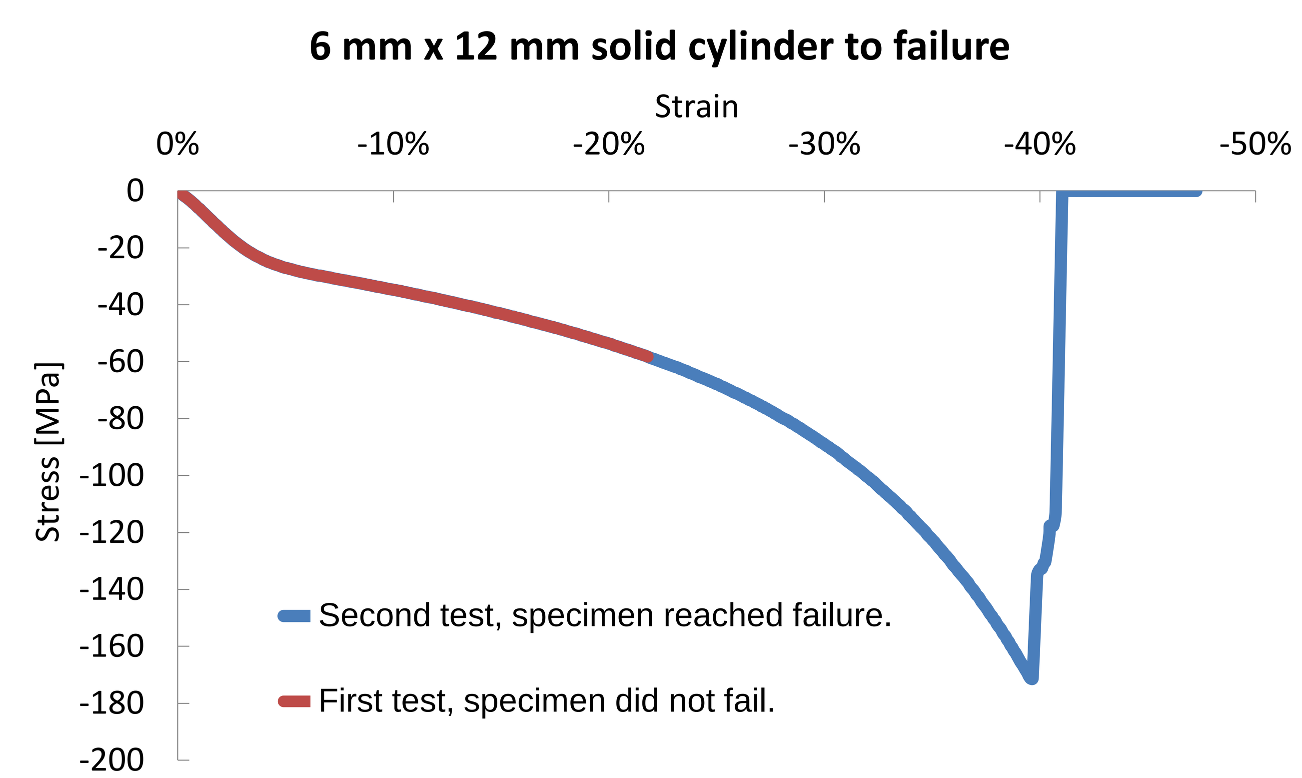


Figure 4. Compression testing of a 480 min post-cured 6 x 12 mm PPF cylinder. Initial linear slope corresponds to 868 MPa.

Figure 4 shows the compression testing of the one 6 x 12 mm solid cylinder produced. The initial test was surprising as the specimen did not fail at maximum test-strain. Therefore the test was repeated with the maximum test-strain doubled. Failure was found at 40% strain with a maximum stress of 171 MPa. The initial linear slope corresponding to the linearly elastic region yielded a modulus of 868 MPa, which may be the highest ever recorded for a PPF formulation. The average modulus was 334 MPa, a 77% increase over the highest green strength modulus.

Discussion

The interaction of resin components, especially polymer, initiator, and dye, is critical to scaffold green strength, post-cured strength, and resolution. Irgacure 784 appears to act primarily as a dye during 3D printing allowing highly accurate scaffold fabrication. After clearing the pores, Irgacure 784 appears to act as an initiator during post-curing. Exposure time is correlated with gradually increasing green strength, thereby allowing us to tune the scaffold's strength and, as we expect, its resorption profile.

References

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Disclosures

DD, EJM, MOW, AS, and JPF have submitted patent applications on these topics. DD received compensation from, and has an ownership stake in, Osteoplastics LLC.

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