IMPARTING EXTENSIBILITY TO JAMMED COLLOIDAL INKS FOR DIRECT-INK-WRITING PRINTABILITY

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ABSTRACT

We introduce and test the hypothesis that extensional rheology, as well as yield stress, are the two key rheological properties [1] for jammed colloidal inks used in direct-write 3D printing of implantable lattice-structured bone scaffolds (**Fig. 1.**). Guided by prior observations that yield stress fluids can be engineered with high extensibility [2], and that higher extensibility of emulsion-based yield stress fluids enabled more robust printing [3], we describe an experimental study of these paste-like materials that varies ink formulation and flow conditions to map printability to these rheological properties. The inks consist of an aqueous suspension of hydroxyapatite particles (the main mineral of bone), irregularly shaped and sized 1-10μm, which creates a cementitious paste-like yield-stress fluid. To induce capillarity for better bone growth, we add sacrificial polymethyl methacrylate beads (PMMA, 5.96 ± 2.00μm in diameter) to create microporosity in the final scaffolds. This baseline formulation of ink is difficult to print due to brittle filament rupture if the nozzle speed is not closely matched to the average velocity of the extruded ink. We examine two methods to tune extensibility and yield stress: (i) incorporating polymer additives, and (ii) modulating electrostatic particle interaction. Hydroxypropyl methylcellulose serves as the polymer additive, tested at different loading. Polyacrylic acid and polyethylenimine coat the particles with negative and positive charge, respectively, to modulate yield stress. By mapping printability to the rheological design requirements of extensibility and yield stress, our results show how modulating these two key rheological properties can improve printability.

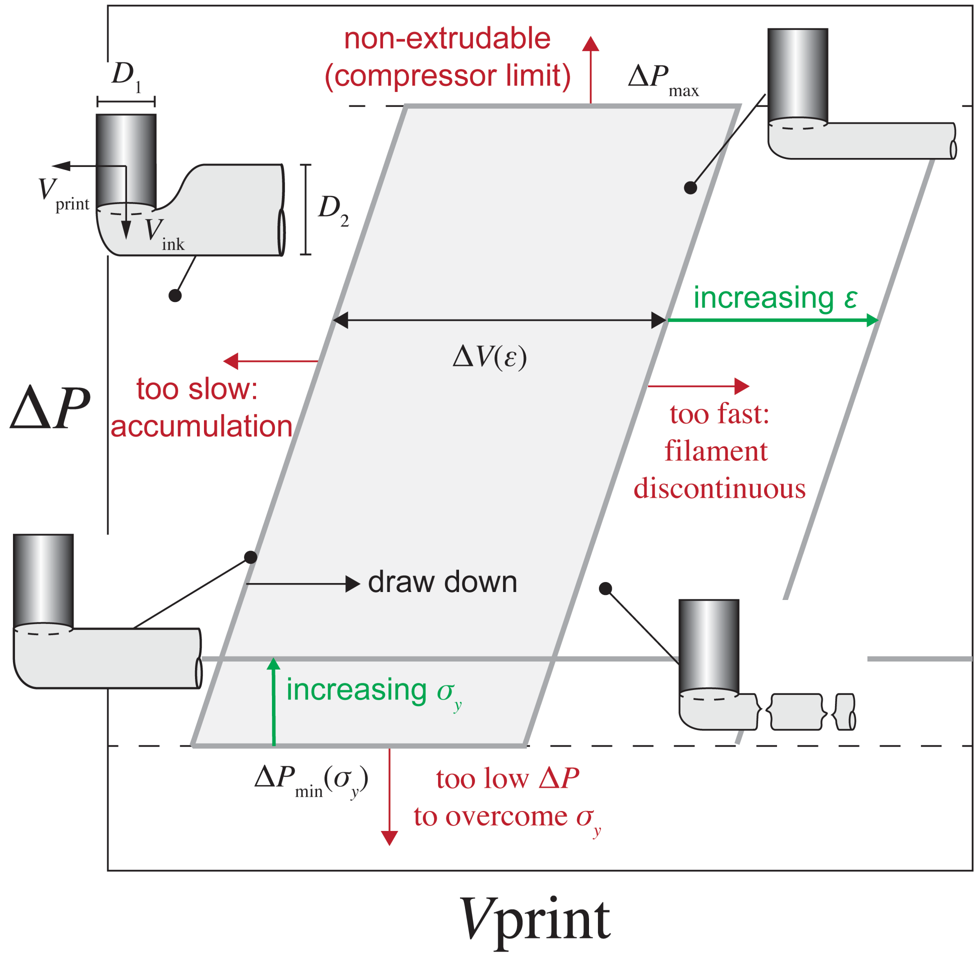

Figure 1: Printability map of direct-ink writing of lattice scaffolds shows four important regimes, depending on the two characteristic speeds: (i) ink accumulation when $V_{\text{print}} < V_{\text{ink}}$ yielding $D_1 < D_2$; (ii) equi-dimentional, $V_{\text{print}} = V_{\text{ink}}$, $D_1 = D_2$; (iii) rod thinning, $V_{\text{print}} > V_{\text{ink}}$, , $D_1 > D_2$; and (iv) rod discontinuous $V_{\text{print}} \gg V_{\text{ink}}$. The rod thinning window can be widened by extensibility.

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