From Waste Glass to High-Value 3D Porous Glass Ceramics: A Sustainable Additive Manufacturing Pathway

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Abstract

Global glass recycling rates remain low, particularly for products such as fiberglass and pharmaceutical glass, due to stringent quality standards and the high energy required for remelting. Their silica and alumina-rich composition makes these glasses ideal for synthesizing alkali-activated binders at mild conditions (25–80 °C) with lower CO_2 emissions, which are sustainable alternatives to Portland cement-based binders. These binders produce lightweight, porous, and durable materials for next-generation construction. Combining this with additive manufacturing, particularly Direct Ink Writing (DIW), offers design flexibility but requires overcoming rheological challenges caused by rapid hardening and viscosity changes over time. Addressing these issues enables the development of sustainable, high-performance 3D-printed materials aligned with circular economy principles.

In this work, we present the development of printable inks derived from waste fiberglass, activated with low-molarity alkaline solutions (<5 M NaOH) and printed using the DIW technique. The formulated inks exhibited excellent extrudability, shear-thinning behaviour, and rapid viscosity recovery after extrusion, enabling the stable fabrication of 3D structures. The structures achieved densities in the range of 0.9 –1.2 g/cm^3 with designed porosities of 55 – 60%, resulting in compressive strengths between 1.2 and 5 MPa, values that are well-suited for lightweight construction applications. To further optimize the printability and mechanical properties, additional waste streams were introduced, including alumina-Zirconia-Silica (AZS) refractory from dismantled glass furnaces and glass microspheres produced via flame synthesis of soda-lime glass.

Thermal treatment was applied to the 3D printed samples to expand their potential applications. Firing at 800°C induced expansions of the filaments, yielding highly porous glass-ceramic structures. Notably, the incorporation of AZS refractory and glass microspheres stabilized the structures during firing, preventing extreme expansion and ensuring that the original 3D geometry was retained. The resulting porous glass ceramics exhibited hierarchical porosity levels of 80–90%, with densities ranging from 0.27 to 0.4 g/cm^3, while maintaining compressive strengths up to 5 MPa. This strength-to-density trade-off surpasses that of conventional glass foams, while the 3D geometries provide advanced design flexibility. Such materials demonstrate strong potential for high-value applications, including thermal insulation, filtration, and gas separation, highlighting a novel and sustainable pathway for transforming unrecyclable glass waste into functional, lightweight, and structurally versatile products.

Keywords: 3D printing, alkali activation, direct ink writing, rheology, waste glass.