AI-Assisted Generative Design of Architected Cementitious Microstructures for Durable and Low-Carbon Construction

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1. Introduction

The global construction sector faces dual pressures to reduce its significant carbon footprint while enhancing the long-term durability of its output. Conventional design approaches often rely on over-engineering and excessive material use to meet performance targets, particularly in aggressive environments where degradation mechanisms like chloride ingress are prevalent [1]. A promising alternative lies in architected materials, where performance is achieved through optimised internal geometry rather than sheer mass. While Triply Periodic Minimal Surfaces (TPMS) have shown high mechanical efficiency in metallic and polymer systems [2,3], their systematic translation into cementitious construction remains largely unexplored. This work proposes an AI-assisted generative design framework to create, optimise, and predict the mechanical strength of architected cementitious microstructures, aiming to provide a scalable pathway toward durable and low-carbon construction — with applications such as marine infrastructure.

2. Research Objectives

The primary objective is to develop an integrated, AI-driven framework for the generative design of 3D-printed cementitious building blocks. This involves: (i) creating a parametric geometry generator for TPMS-inspired structures; (ii) building a multi-objective optimisation loop that incorporates mechanical strength prediction, stiffness, and durability (chloride diffusivity) metrics; (iii) evaluating the feasibility of fabricating these complex geometries using 3D printed formwork; and (iv) demonstrating material-efficient, low-carbon structural design at the building-block scale.

3. Proposed Methodology

A. Generative Design Framework

The core of the proposed work is a generative model based on parametric implicit surface equations. This will enable the creation of diverse microstructures, from established TPMS families (Gyroid, Schwarz Primitive, etc.) to novel, gradient-density hybrids, by adjusting parameters like relative density, cell size, and wall thickness. This approach is intended to facilitate both the reconstruction of known topologies and the discovery of new, high-performance designs.

B. AI-Powered Multi-Objective Optimisation

To navigate the vast design space, a Bayesian optimisation loop will be implemented [5]. This process will be guided by a Gaussian Process regression surrogate model trained on data from finite element simulations [4]. The optimisation function will aim to concurrently minimise material volume and predicted chloride diffusivity while maximising compressive stiffness. Constraints for printability and structural stability will be incorporated to ensure manufacturability.

C. Performance Estimation

Mechanical performance, including compressive strength and effective stiffness, will be estimated using finite element analysis on homogenised representative volume elements, with surrogate models trained to predict these properties across the design space. Durability, specifically resistance to chloride ingress, will be approximated via tortuosity-based diffusion modelling, which aims to quantify how effectively a given microstructure extends the diffusion path length.

4. Expected Results

Preliminary computational studies on established TPMS geometries indicate the potential for significant performance improvements over conventional solid or hollow sections. Indicative simulations (Table 1) suggest that optimised microstructures can achieve substantial material reductions (~25-30%) while maintaining high stiffness and increasing the effective diffusion path length by up to 1.5x. It is anticipated that the generative framework will discover novel geometries that push these Pareto frontiers further. The controlled internal curvature is expected to not only delay chloride ingress but also improve stress redistribution, thereby enhancing overall durability.

Table 1: *Indicative simulation results for selected TPMS geometry types (preliminary, subject to revision).*

Structure Type	Volume Reduction	Predicted Stiffness Ratio	Diffusion Path Increase
Gyroid Column	~26%	0.92	~1.45×
Schwarz Primitive Panel	~25%	0.95	~1.38×
Diamond Beam	~30%	0.89	~1.52×

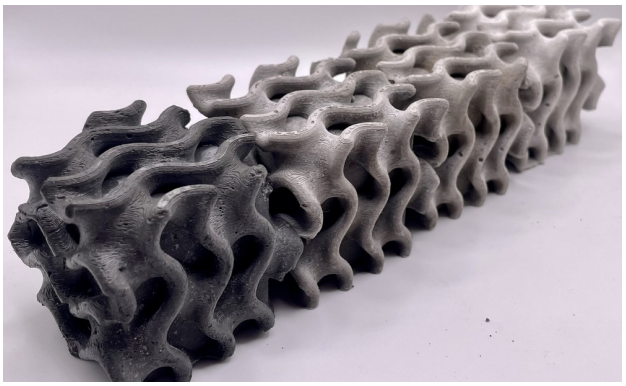

Fig. 2: Gyroid-geometry cementitious building blocks fabricated using 3D printed formworks. The specimens represent a 70% relative density compared to a 100% infill 5 cm cube reference, and incorporate varying proportions of carbon black in the cementitious mix, illustrating the material and geometric design space targeted by the proposed framework.

5. Indicative Design Tool

To support the proposed framework, an interactive AI-assisted design interface is being conceptualised (Fig. 3). The envisioned tool would allow users to adjust geometric

parameters in real time, visualise candidate microstructures, and review surrogate-predicted mechanical and durability properties alongside an optimisation progress tracker. This is presented as an indicative concept of the tool to be developed, not a completed system.

Fig. 3: Indicative concept of the AI-assisted generative design tool to be developed. The interface is envisioned to allow real-time geometry generation, parameter adjustment, and surrogate-predicted property review.

6. Significance

This research endeavours to shift the paradigm in construction material design from a focus on bulk properties to one of engineered internal microstructures. By integrating parametric geometry, surrogate modelling, and multi-objective optimisation, the proposed AI-assisted framework seeks to establish a scalable and computationally efficient workflow for creating bespoke, high-performance cementitious materials. This provides a practical pathway toward data-driven, closed-loop material design, enabling the development of durable, material-efficient, and low-carbon solutions for the construction industry, with applications ranging from building components to specialised infrastructure.

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