

Exploring Aerial Additive Manufacturing with Cementitious Materials using Autonomous Drones

R.J. Ball and B. Dams

Department of Architecture and Civil Engineering, University of Bath, Bath, UK
Centre for Integrated Materials, Processes & Structures (IMPS), University of Bath, Bath, UK

P. Shepherd

Department of Architecture and Civil Engineering, University of Bath, Bath, UK
Centre for Digital, Manufacturing & Design (dMaDe), University of Bath, Bath, UK

B. Chen

Department of Architecture and Civil Engineering, University of Bath, Bath, UK
School of Mechanical Engineering, Beijing Institute of Technology, Beijing, China

ABSTRACT

Aerial additive manufacturing (AAM) represents a novel approach to construction by enabling untethered autonomous unmanned aerial vehicles (UAVs, or drones) to deposit cementitious materials in mid-flight, overcoming geometric and accessibility limitations associated with ground-based additive manufacturing. This study presents research to investigate the structural viability of cementitious mixes tailored for aerial extrusion, focusing on rheological optimisation, mechanical performance, and deposition feasibility. Pseudoplastic behaviour was achieved through the use of hydrocolloids, enabling low viscosity under shear for extrusion while rapidly stiffening post-deposition to maintain layer geometry. Fibre reinforcement and inorganic fullerene tungsten disulphide (IF-WS₂) nanoparticles were incorporated to enhance flexural strength, interlayer cohesion, and impact resistance. Laboratory trials using a miniaturised UAV-mounted extrusion system demonstrated successful deposition of multiple layers with positional accuracy within ± 10 mm. Results indicate that carefully balanced mix compositions allow structural layering, yielding compressive strengths above 25 MPa and improved toughness. The study highlights the potential of AAM for applications in confined, elevated, or hard-to-access environments, while emphasising current limitations including UAV payload, flight stability, and extrusion synchronisation. Overall, this work provides proof-of-concept evidence that autonomous aerial deposition of cementitious materials is feasible, opening avenues for future research into multi-agent cooperative building, material optimisation, and automated construction in challenging conditions.

Keywords: aerial additive manufacturing, rheology, UAV.

1. INTRODUCTION

Additive manufacturing (AM) has become increasingly prominent within the construction sector, offering the potential for automation, reduced material waste, and greater architectural freedom. Most large-scale initiatives to date have relied on ground-based platforms such as gantries or robotic arms (Dams *et al.*, 2025). While these approaches have produced impressive demonstrators, they are fundamentally constrained by their size, reach, and lack of mobility, which makes construction in confined or elevated environments particularly challenging.

Exploring aerial additive manufacturing (AAM) with autonomous drones offers a potential alternative by shifting deposition from stationary equipment to untethered UAVs (Zhang *et al.*, 2022; Dams *et al.*, 2024a). By enabling material placement during flight, drones remove many of the geometric constraints imposed by ground-based systems. Recent studies have begun to explore this approach demonstrating that cementitious mortars can be deposited using robotic arms to simulate flight (Dams *et al.*, 2023a). Additionally, the rheological

properties of pseudoplastic mortars have been tailored for printing (Dams *et al.*, 2023b; Dams *et al.*, 2024a), and multi-drone cooperative building missions have been demonstrated in principle (Zhang *et al.*, 2022).

Despite this progress, integrating autonomous aerial platforms with structural cementitious materials remains at a very early stage. Success depends on miniaturising extrusion systems to a weight suitable for UAVs, tailoring fresh-state rheology so that materials can be extruded under shear but stiffen rapidly after deposition, and ensuring that the hardened properties are sufficient to form coherent structures.

Laboratory demonstrations show untethered autonomous drones depositing cement-based materials in mid-flight, producing layered structures under controlled conditions. The study focuses on developing cementitious mixes, characterising their rheological behaviour, and exploring aerial deposition feasibility. The general concept of the system is illustrated in **Figure 1**.

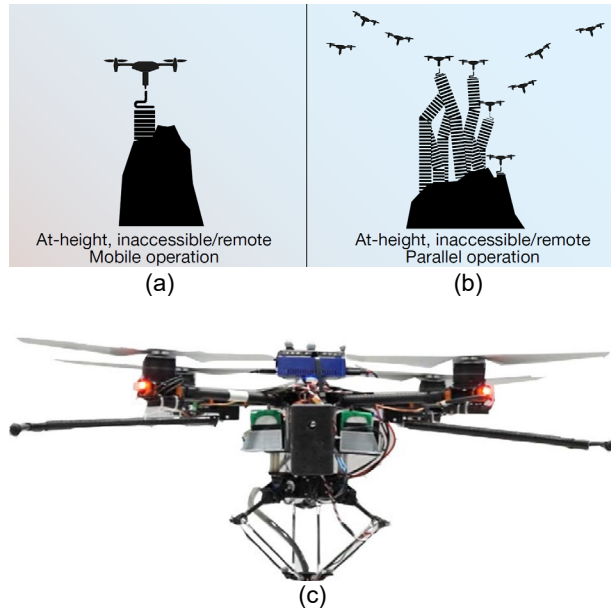


Fig. 1. A flying, untethered Unmanned Aerial Vehicle (also known as a 'drone') 3D printing multiple layers in (a) single and (b) parallel operation. (c) Drone with delta arm to manipulate printing nozzle (Zhang *et al.*, 2022).

2. MATERIALS AND METHODS

A quadcopter UAV was modified to carry a miniaturised extrusion device designed to be lightweight while still able to exert sufficient extrusion pressure. The deposition system drew power from the UAV battery supply and was integrated into the flight control software so that material extrusion could be synchronised with drone movement. Similar devices have been tested previously on robotic arms as proxies for aerial systems (Dams *et al.*, 2023a), and in multi-robot frameworks designed to coordinate deposition in three-dimensional space (Zhang *et al.*, 2022).

The cementitious mixes were specifically developed for aerial application, drawing on earlier advances in pseudoplastic mortars (Dams *et al.*, 2023b; Dams *et al.*, 2024a), fibre-reinforced quaternary systems (Dams *et al.*, 2023b), and nanoparticle-enhanced composites (Chen *et al.*, 2023). Rheology was modified through the addition of hydroxymethyl ethyl cellulose and xanthan gum, which created the desired pseudoplastic behaviour by reducing viscosity under shear and facilitating rapid recovery after deposition. Flow characteristics were improved by using smooth-particle sand and fly ash. Polypropylene and polyvinyl alcohol fibres were incorporated to enhance flexural strength and interlayer cohesion, although their inclusion inevitably reduced workability. To address toughness, inorganic fullerene tungsten disulphide (IF-WS₂) nanoparticles were added at a dosage of 1 wt%, following evidence of their positive effects on cementitious matrices (Chen *et al.*, 2023).

Rheological behaviour was characterised using flow tests to determine yield stress and changes in viscosity, and oscillatory tests to determine the phase angle and complex modulus, in line with methods applied in previous AAM studies (Dams *et al.*, 2023b; Dams *et al.*, 2024a). Hardened samples were tested for compressive and

flexural strength, allowing the impact of fibres and nanoparticles to be evaluated. The trade-off between workability and buildability, and the proposed constituents for aerially extrudable cementitious materials, are summarised in **Figure 2**. The figure highlights how certain additives improve flowability while maintaining structural coherence after deposition. Deposition trials were then conducted with the UAV extruding material along predefined paths, enabling the stacking of layers to be observed. Build height, deformation, and interlayer stability were monitored, while high-speed cameras were used to assess positional accuracy (Dams *et al.*, 2024b).

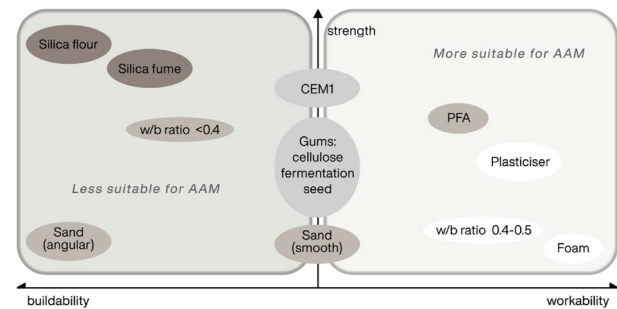


Fig. 2. Trade-off between workability and buildability, the constituents used in AM applications and additional constituents proposed for AAM structurally viable cementitious material, with a focus upon workability being of primary importance for a miniaturised deposition process (Dams *et al.*, 2025).

3. RESULTS

The rheological tests confirmed that the cellulose- and xanthan-modified mortars achieved the desired pseudoplastic response. Under shear, viscosity was sufficiently reduced to enable extrusion through the lightweight nozzle, while after deposition the material recovered stiffness rapidly enough to maintain its shape. Yield stresses in the range of 1.1–1.3 kPa were measured, broadly consistent with earlier findings for pseudoplastic mortars (Dams *et al.*, 2023b). Phase angle values within a two-hour open time remained below 5°, suggesting a balance of elastic and viscous contributions appropriate for stable layer stacking (Dams *et al.*, 2024a).

Mechanical testing indicated that compressive strengths above 25 MPa were achievable, demonstrating that the lightweight deposition system did not require compromises in structural performance. Flexural tests highlighted the benefits of fibre reinforcement in delaying crack formation and increasing ductility, but they also revealed reductions in flowability and extrusion regularity at higher fibre dosages (Dams *et al.*, 2023b). The incorporation of IF-WS₂ nanoparticles enhanced compressive strength by around 15% and significantly improved impact resistance, findings consistent with the exceptional performance reported in nanoparticle-modified cement (Chen *et al.*, 2023).

Deposition trials showed that the UAV could successfully extrude multiple layers in flight. Layer heights of several centimetres were achieved before collapse or lateral spreading occurred. The best-performing mixes exhibited rapid viscosity recovery without excessively stiffening, allowing consistent extrusion. Positional accuracy was

within ± 10 mm, close to values achieved in earlier aerial deposition of polyurethane foams (Dams *et al.*, 2024b). The positive effect of various additives on the buildability of cementitious mixes is illustrated in **Figure 3**.

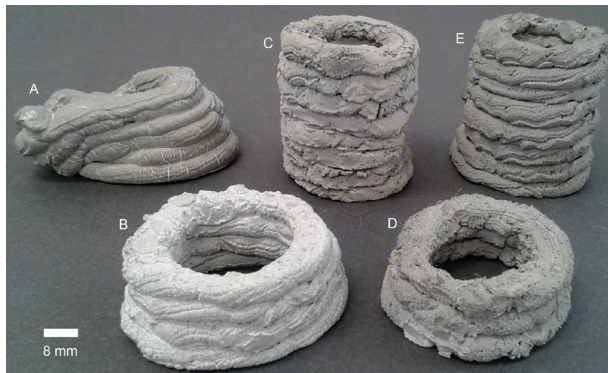


Fig. 3. The 50 mm diameter circular layers of the extruded mixes: A (cement paste), B (the introduction of fine aggregate), C (polyol resin), D (polypropylene fibres) and E (LimeX70) (Dams *et al.*, 2023a).

4. DISCUSSION

The findings demonstrate that rheological optimisation is the key enabler of aerial additive manufacturing. The use of hydrocolloids was effective in generating pseudoplastic mixes capable of transitioning between flow and solidity in the timescales required for autonomous drone deposition (Dams *et al.*, 2023b; Dams *et al.*, 2024a). Fibres enhanced structural performance but compromised extrusion regularity, underlining the need for balance between reinforcement and workability. The hybrid strategy combining a modest fibre content with nanoparticle reinforcement proved particularly effective, as it delivered improvements in toughness without excessively reducing extrudability (Chen *et al.*, 2023).

Deposition trials highlight both the promise and the limitations of autonomous systems. UAVs can deposit cementitious layers under controlled conditions, confirming feasibility, but persistent limitations in payload, flight stability, and extrusion synchronisation restricted build height, led to accuracy deviations of around 4 mm, and occasionally caused deposition irregularities (Dams *et al.*, 2024b). These findings emphasise that this work should be regarded as an exploratory proof-of-concept rather than a demonstration of a construction-ready system.

5. APPLICATIONS AND LIMITATIONS

While AAM with autonomous drones has been suggested as a potential method for constructing complex or hard-to-access structures (Zhang *et al.*, 2022; Dams *et al.*, 2025), the present study demonstrates feasibility only under laboratory conditions. Significant technical challenges remain, including UAV payload capacity, flight endurance, trajectory control, and extrusion synchronisation. Therefore, AAM should be viewed as a complementary technique to ground-based systems, applicable in niche

scenarios where access or safety risks limit conventional methods rather than as a replacement technology.

6. CONCLUSIONS

This study provides exploratory evidence that untethered autonomous UAVs can perform additive manufacturing with cementitious materials. Pseudoplastic mixes incorporating hydroxymethyl ethyl cellulose and xanthan gum achieved the rheological properties required for aerial extrusion (Dams *et al.*, 2024a). The addition of fibres and WS₂ nanoparticles enhanced compressive and flexural strength, with compressive strengths exceeding 25 MPa and a marked improvement in toughness (Dams *et al.*, 2023b; Chen *et al.*, 2023). Laboratory deposition trials demonstrated that UAVs could deposit multiple layers in flight with positional accuracy of around 10 mm, consistent with prior aerial deposition studies (Dams *et al.*, 2024b). While the work confirms feasibility, it also highlights significant limitations that restrict immediate application.

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