Design and development of a small-scale cement-based 3D printing robot extrusion nozzle

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Abstract. Additive manufacturing (AM), also known as three-dimensional (3D) printing, offers great potential to create complex structures layer by layer from computer-aided design (CAD) models. Despite advancements in printable concrete technology, controlling printing quality remains a challenge associated with both the geometric and materials design of the printer nozzle, especially for small-scale printing that may be required by small and medium-sized enterprises (SMEs). Therefore, this study explored the design and development of a robot nozzle system, optimised for a small-scale 3D printing of cement-based structures. Key design considerations included weight, nozzle diameter/shape, material compatibility, flow control, mixing mechanism, temperature resistance, cost-effectiveness, adaptability, safety, and ease of maintenance. Iterative designs were developed, focusing on stress concentration mitigation and material flow optimisation. The challenge of incorporating mixing mechanisms during nozzle designs was discussed, leading to the adoption of an on-demand accelerator spraying system. This method involved a micro-peristaltic pump connected to an accelerator tank, spraying accelerator onto the surface of the deposited material, as the robot moved along its programmed path. Evidently, both the nozzle design and the spraying approach improved the buildability and print quality of the extrusion-based 3D-printed cement-based structures.

1 Introduction

Additive manufacturing (AM), also known as three-dimensional (3D) printing, is the process of creating 3D objects from computer-aided design (CAD) models by depositing material layer by layer to achieve the final shape of an object or component [1]. A major issue involved in the adoption of AM is the size constraint of printed structures [2]. Previous studies have reported the design [3-5], extrudability, buildability and hardened properties of printable concrete in extrusion-based 3D printing technology. However, controlling the printing quality remains a challenge, as observed from inconsistent surfaces of printed buildings and unpredictable filament shaping [6]. Studies have attempted to improve the surface quality of filaments by using rectangular nozzles and trowels, but poor printing quality still remains a problem [5, 7]. Conversely, circular nozzles have the potential to print freeform patterns,

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resulting in complex geometries [6]. Therefore, controlling the printing quality of fresh concrete is vital for extrusion-based printing technology.

This research used a 6 axis Mitsubishi robotic arm programmed in MELFA-BASIC VI. The robot was utilised as a 3D-printer to extrude materials (fine sand and cement) or as an ancillary constructor and is preferred, due to its ability to perform several degrees of freedom during printing. After design iterations and testing, the proposed nozzle with its accelerator spraying approach 3D-printed cement-based structures with good buildability and print quality.

2 Design, materials and manufacture of robot extrusion nozzle

2.1 Design considerations

The design concept for the nozzle involved various requirements, such as weight, appropriate diameter and shape, material compatibility, flow control, mixing mechanism, temperature resistance, cost-effectiveness, adaptability, safety, ease of cleaning and maintenance. The design was optimised to accommodate the homogenous blending of materials (fine sand and cement) during small-scale 3D printing. It also prevented clogging or uneven extrusion and withstood high temperatures. It was adaptable to various printing conditions and adhered to safety standards.

The nozzle design was initiated using CAD which was then converted into a stereolithography (STL) document before being sent to the slicing software. Slicing converted the 3D model into a G-code that the 3D printer understood. After printing, post-processing was conducted to remove the support structure and blurred sharp edges. The nozzle was made from poly lactic acid (PLA), a biodegradable thermoplastic derived from renewable material; corn-starch. PLA is easy to print with and has higher stiffness when compared with other materials, such as nylon and acrylonitrile butadiene styrene (ABS). Some of the limitations of PLA concern its low heat and chemical resistance. Table 1 presents the properties of PLA material used.

Table 1. Properties of PLA material used.

Property	Density (g/m^3)	Elastic modulus (GPa)	Poisson's ratio	Specific heat capacity (J/(kg·K))	Thermal conductivity (W/(m·K))	Tensile strength (MPa)
Quantity	1.25	35.00	0.30	1200.00	0.12	65.00

2.2 Nozzle design

The first nozzle design for small and medium-sized enterprises (SMEs) was created to fit perfectly onto the robot system and had a material inlet branch pipe and an outlet pipe to ensure smooth flow of material, as shown in Figs 1(a) and 2(a). However, the design had a major flaw as the material inlet branch pipe was perpendicular to the material exit pipe, causing a high level of stress concentration on the outlet pipe. This was attributed to the sharp edges and the material hitting the walls of the outlet pipe before changing direction towards the exit pipe. This high level of stress concentration led to pre-mature cracks or fracture of the PLA nozzle over time. Fig. 1 compares the flow of material between sharp corners and filleted corners through simulation.

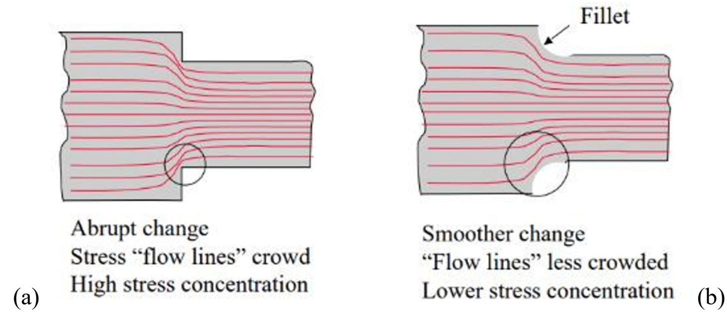


Fig. 1. Comparison between filleted corner stress and sharp corner [8].

Stress concentration is a crucial problem in structural engineering because it causes structural failure if not predicted, evaluated and reduced correctly. It occurs when there are sudden changes in product geometry, cross-section variations, shape discontinuities, as well as straight and sharp edges. Stress concentration is mostly severe when the changes are abrupt and pronounced. Therefore, it is important to avoid sudden 90^o changes to the flow of material and design parts using the smoothest possible geometry. For instance, a simple fillet can be used to reduce the value of the stress concentration factor (SCF) [8].

The second nozzle design had an inlet pipe fixed at a 45^o (Fig. 2b), which reduced the stress concentration, but not to the desired level. The third design (Fig. 2c) had a curved pipe as the material inlet, which greatly reduced the stress concentration on the outlet pipe.

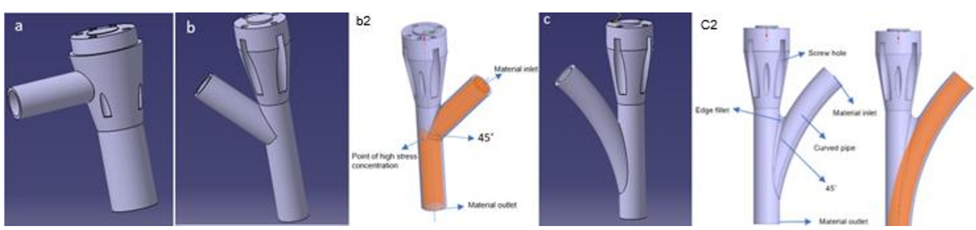


Fig. 2. (a) First nozzle design at 90^o, (b) second design at 45^o and b2 illustrates material flow at 45^o and (c) third design with fillet edge to reduce stress and c2 depicts optimum material flow.

3 Results and discussion

The process of 3D-printing of cement involved turning on the cement pump and using clean water to flush the system before feeding the prepared cement mixture into the hopper. The cement pump pushed the mixture to the robot extrusion nozzle, which controlled the flow and deposition of the cement material. To prevent potential voids or blockage, the system was allowed to extrude the cement-based material before printing began. The 6-axis robot-assisted system used a Cartesian coordinate method to create the desired structure layer by layer under a precise control. The quality of the 3D-printed material depended on various factors, including print speed, pump speed and layer height. To improve quality of the structure, the nozzle movement was synchronised with the extrusion process.

During the 3D-printing process, fracture of the PLA nozzle occurred, due to the pumping pressure, force from the cement and weight of the cement pipe on the extrusion nozzle and the rotation of the robot, as shown in Figs 3(a) and (b). The nozzle was re-manufactured using the adventurer 4 flashforge 3D printer using aluminium as subsequently elucidated.

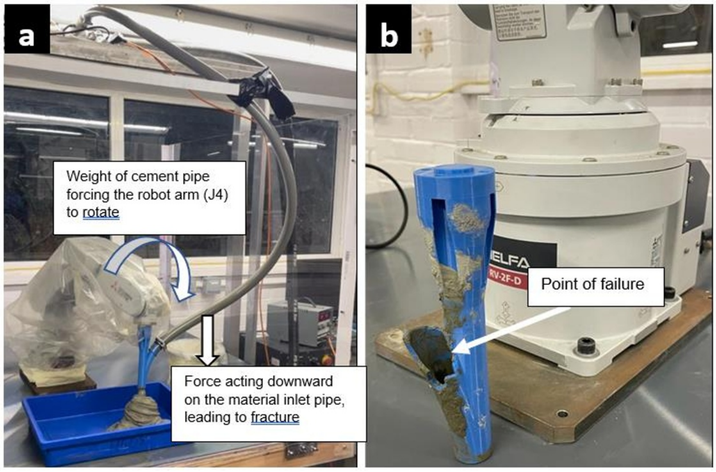


Fig. 3. (a) Force acting downward on nozzle inlet and (b) a fractured PLA nozzle.

3.1 Optimisation of 3D printing robot nozzle

The fourth improved nozzle was designed and manufactured in-house at the University of Hertfordshire machine shop. Aluminium was selected, due to the plastic failure of the PLA nozzle. Aluminium is a lightweight, workable, corrosion-resistant and recyclable material. The nozzle has an outlet thickness, inner and outer diameters of 4, 20 and 22 mm, respectively. The inlet pipe was welded at 30^o to prevent stress concentration. The nozzle has a shorter length of 120 mm to avoid overloading of the robot arm, which has a maximum load capacity of 3 kg, but it was rated at 2 kg. The inlet pipe had a threaded groove to improve the connection between the cement pipe and the nozzle inlet. Fig. 4 shows the nozzle connected to the robot part.

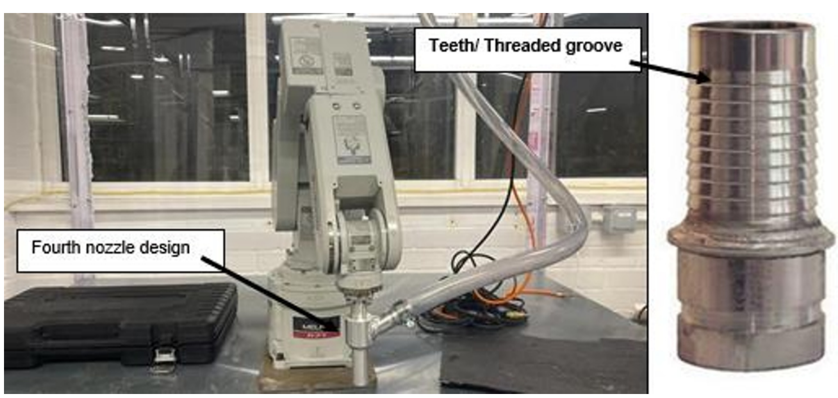


Fig. 4. Aluminium extrusion nozzle design with threaded grove.

Furthermore, the hardened properties of cement-based structures are crucial for the success of 3D-printed structures. To improve the print quality and buildability of the cement-based material, it was important to implement an inlet into the nozzle for unimpeded flow of the accelerator. Hence, an auger (Figs 5a and b) was integrated into the 3D printing nozzle system to effectively rotate and uniformly mix the cement with sand and accelerator, and maintain a consistent mixture during the printing process. This design aimed to optimise the combination of materials for enhanced quality and structural integrity of printed structures.

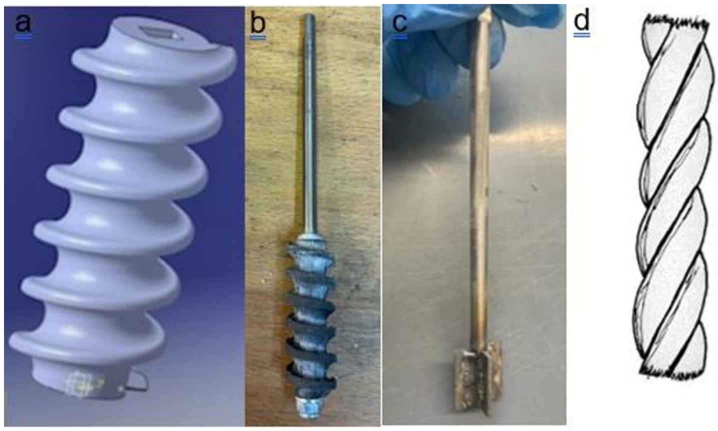


Fig. 5. An auger (a) in CAD, (b) after manufacture, and (c) propeller-like mixer, d) shape of the extruded filament.

The incorporation of an auger within the 3D printing nozzle for material mixing faced a setback, due to backpressure caused by the slow speed of the auger. This led to cement obstructing the free flow of the accelerator into the system and impeded the mixing process, rendering the system ineffective for the designed purpose. As a result, the system was unable to print. Consequently, further optimisation was conducted involving the replacement of the auger with a propeller-like mixer (Fig. 5c) inside the 3D printing nozzle. The rationale behind this was to ensure proper mixing of the cement-based material and accelerator. The auger was made from aluminium material, due to the corrosive nature of the accelerator on metal. The initial improvement achieved a more consistent print, but this modification proved insufficient. Similar to the auger design, the propeller-like mixer turned at a slow speed to produce backpressure, causing the cement to escape through the proposed accelerator inlet. In addition, the deposited material was divided into four distinct partitions (Fig 5d), due to the shape of the propeller-like mixer, presenting an additional complication in the material flow. Fig. 5(d) shows the shape of the extruded filaments after extrusion.

To ensure smooth flow of the cement-based material through the robot nozzle, the propeller-like mixer and motor were removed after troubleshooting. A novel aluminium device with an accelerator inlet diameter of 3 mm at a 45^{o} was integrated into the robot printing system to prevent cement from flowing backward and ensure a steady flow of the accelerator, as shown in Fig. 6. However, this solution introduced two new challenges; increase in accelerator pumping pressure could make the material too viscous, compromising its buildability and surface finish, and a slow pump speed increased the risk of cement blocking the small accelerator inlet.

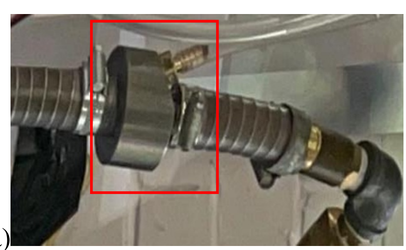
(a)  (b) 

Fig. 6. (a) Aluminium device for in-flow of accelerator (in red) and (b) better 3D-printed structure.

The mechanism (Fig. 6a) was eliminated, and a new method, known as on-demand accelerator spraying was implemented. To achieve this, a micro peristaltic pump was attached to the accelerator tank via the inlet pipe, and the outlet pipe was connected to the robot extrusion nozzle. This new approach ensured that the accelerator sprayed the surface of the freshly deposited material to enhance buildability, as the robot followed its programmed path. Afterwards, a compression device was attached to the robot nozzle by reducing the extrusion outlet diameter from 20 to 18 mm. This enabled the filament to be more compact and adhere properly. Consequently, this further enhanced the extrudability, buildability and print quality of 3D-printed cement-based structure (Fig. 6b). The relevant properties obtained from the 3D-printed structures were compared with that of the traditional cast structures. The comparative results are under preparation for another or further publications.

4 Conclusions

This study investigated into the importance of optimised nozzle geometric and material design towards achieving high-quality and reliable 3D-printed cement-based structures. Through iterative design and troubleshooting, an optimised aluminium nozzle design with an adopted on-demand accelerator spraying system emerged as a promising technique to enhance extrudability, buildability and print quality of 3D-printed cement-based structures. While challenges, such as back pressure and material backward flow remain with addition of accelerator internally, the study underscored the need for continued research and innovation to address these issues and unlock the full potential of extrusion-based 3D printing in construction applications in SMEs. With further advancements, this is a promising technology for revolutionisation of the construction industry by enabling cost-effective, customisable and sustainable building solutions.

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