Automated Shotcrete: A More Sustainable Construction Technology

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1 Introduction

The most common building material is concrete making it a major contributor to the ecological footprint of the construction sector, accounting for between 5 and 8% of global CO2 emissions (Anton et al. 2021, pp. 1–2). Global production of concrete totalled 4.4 billion tons in 2021, with output projected to reach 5.5 billion tons by 2050. Traditional concreting techniques rely on formwork, a mould or cast in which to pour concrete. Conventional formwork is often made using timber, but it is also possible to use other materials. Developing formwork is labour and material intense and accounts for between 35 and 60% of the total cost of concrete work (Bedarf et al. 2021, p. 3). It is also extremely wasteful, as most formwork is temporary and discarded after use, often having been used once only.

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Conservative practices together with technological challenges make construction one of the least digitised and least efficient industry sectors, with concrete construction still heavily reliant on manual processes (Anton et al. 2021, p. 2). Construction is accountable for 37% of CO2 emissions related to energy (UN Global Status Report for Buildings and Construction 2021, p. 15). Industry pressures including a desire to improve worker safety, productivity and efficiency, combined with market pressures caused by urbanisation, increasing labour shortages and the challenge of climate change, are driving the growing interest in advanced technologies such as shotcreting to challenge established practices (ABB Robotics 2022, p. 5). Extending and accelerating the application of shotcrete has the potential to reduce carbon emissions and increase the efficiency of concrete construction by reducing the quantity of used material, therefore supporting the construction industry in addressing UN Sustainable Development Goal 12.

2 3D Concrete Printing

Additive manufacturing (AM) processes offer potential efficiency through lower labour demands and reduced construction waste (Bedarf et al. 2021). AM also offers the potential for leaner and more sustainable structures to be developed, reducing waste by placing material only where it is needed to meet structural demands (Anton et al. 2021, p. 1). However, cement materials suitable for 3D printing can exhibit distinct mechanical properties compared with traditional concrete (Lu et al. 2019b, p. 478). Significant challenges to improve various characteristics of the material used for 3D printing including shape retentivity and extrudability remain unresolved (Nair et al. 2020). Other limitations of 3D printing with concrete (3DPC) are its inability to build overhangs and the vertical building rate. Mixtures must remain sufficiently soft to be extrudable and to mix with the layer deposited previously, the substrate, which needs to have cured sufficiently to support itself together with the weight of the most recently deposited material without significantly sagging (Wangler et al. 2016, p. 70). Achieving a high-quality surface finish and bonding weaknesses (cold joints) caused by the layering process are issues that limit current applications and require further investigation (Neudecker et al. 2016, p. 335).

Those limitations of 3D printing specifically when applied to concrete have motivated the investigation of alternative technologies and solutions with the aim of reducing the GHG impact of the construction industry.

3 Shotcrete

Shotcrete was developed (from early in the twentieth century) to address the needs of the tunnelling and mining industries. In contrast to conventional 3D printing, shotcrete is not extruded in a bead but combined with pressurised air and sprayed to create a 3D structure. Concrete is pumped through a tube to a nozzle through which it is sprayed under pressure (and thereby compressed) on to newly blasted surfaces to stabilise the excavation. 'Conveying, compacting and application of concrete material are performed in one operation, which is distinctive for this technique' (Lindemann et al. 2017, p. 4). Manual application of shotcrete is an arduous task with physical demands on the 'nozzle man' restricting productivity. The drive for improved productivity combined with the hazardous nature of tunnelling and mining automation of the shotcreting process has been an industry priority for many decades.

Shotcrete has the potential to be significantly more time and materially efficient than 3DCP, and therefore more sustainable, for both new construction and repair, thereby also delaying end-of-life impacts (Rispin et al. 2005). A brief history of the automation of shotcrete is detailed in (Rispin et al. 2005). Early innovations were restricted to nozzle-holding devices using cranes and lifts to move and direct the application of concrete. Specialised shotcrete manipulators began to appear in the 1980s offering greater accuracy and extension possibilities. Within a decade spraying manipulators became commonplace on all large construction projects where shotcrete was used (Rispin et al. 2005, p. 4).

As demands for increased productivity grew, the need to quickly and accurately apply large volumes of shotcrete led to the development of remote controls, with radio remote quickly becoming the industry standard. Autonomous spray mobiles containing all the equipment needed to deliver quality shotcrete were tailored to meet the needs of specialist construction tasks (Rispin et al. 2005, p. 4). Computer-controlled multi-axis robots capable of scanning and spraying an area have become increasingly common since the start of the twenty-first century.

Automation has delivered significant productivity enhancements and offers the potential to create complex geometries, a significant advantage compared with 3DCP which is restricted to vertical builds. Hand-held nozzles can cover 7–9 cubic metres per hour, while mechanised spraying can cover more than double of the output up to 20 cubic metres per hour (Rispin et al. 2005, p. 5). Automation has delivered improvements in safety and reduced set-up times, requiring less people in the process.

Academic attention has recently focused on developing shotcrete as an alternative to conventional 3DCP, combining the benefits of shotcrete with AM processes, shotcrete-based 3D printing or SC3DP. Researchers at Technische Universität Braunschweig led the development of 'a robotically controlled additive manufacturing process that builds concrete components layer by layer through the controlled addition of compressed air' (Kloft et al. 2020a, p. 609). The concrete layer's height is inversely proportional to the speed of the robot-controlled nozzle, while width can be determined through adjusting the distance of the nozzle from the surface. Complex geometries including overhangs and the integration of built-in parts or reinforcement become achievable (Kloft et al. 2020, p. 2).

One of the main benefits of SC3DP is that interlayer bonding is improved using high air pressure which 'tears up' the concrete in the nozzle and creates a high contact surface area with the air stream facilitating the intermixing of additives (Kloft et al. 2020, p. 2). Layer interlocking and hence interlayer bond strength are enhanced by SC3DP compared with traditional additive manufacturing due to the high kinetic energy of the sprayed material, which reduces the prospect of cold joints forming. 'In general, SC3DP specimens show better mechanical performance than extrusion-based 3D printed materials and cast specimens of the same mixture design' because of improved interlaying bonding (Heidarnezhad and Zhang 2022, p. 7). Performance can be enhanced by precisely controlling layer thickness (Northcroft and Ziegler 2008).

3.1 Formwork

Developing traditional formwork is labour and material intense accounting for between 35 and 60% of the total concrete work cost (Bedarf et al. 2021, p. 3). It is also extremely wasteful, as most formwork is temporary and discarded after use, often having been used once only. Reducing or eliminating formwork saves not only the natural resources and labour required to build it but also the transport and disposal impacts, highlighting a significant sustainability advantage of shotcrete (Schokker 2010).

Work at Braunschweig has led to the development of techniques to SC3DP without conventional single-use formwork. A 2016 paper outlined their proposed experiments progressing from a flat wall with opposing formwork to creating complex curved walls (Neudecker et al. 2016, p. 336). Among the many challenges, the research team needed to develop simulation tools, an automated injection tool and a control system. Long-range scanners supplemented with a 3D laser triangulation scanner and a 3D vision system were used to monitor performance (Neudecker et al. 2016, p. 335). Although experiments were not complete at the time of publishing, the researchers identified 'a water-to-cementitious ratio of 0.4, with a pressure of 6.5 bar in the pneumatic cylinder of the pumping system' produced the best spray (Neudecker et al. 2016, p. 338). Pressure at the nozzle tip of 5.2 bars resulted in the highest-quality results with a rebound rate of just 8%.

The Block Research Group combined a reusable cable net with a fabric overlay to create formwork for an anticlastic mesh-reinforced sandwich shell roof (Block et al. 2017). This lightweight solution eliminated the need for both falsework and foundations for the formwork. An evolutionary design process was employed to identify the most optimal geometry for the roof, allowing the thickness of the shells to be reduced to between just 5 cm and 3 cm (Block Research Group 2018).

3.2 Reinforcing Agents

Combining the traditionally separate requirement of formwork and reinforcement into a single robotic fabrication process has potential to 'produce an additive and waste-free, material-efficient, and geometrically unconstrained method of fabricating complex non-standard concrete constructions' (Hack and Lauer 2014, p. 52). Hack and Laurer report on using acrylonitrile butadiene styrene (ABS) to print mesh mould formwork that can also act as a reinforcement for concrete structures. Concrete is sprayed and protrudes through the mesh mould with surfaces manually trowelled to smooth and level (Hack and Lauer 2014, p. 49). Using polymers developed for conventional 3D printers permitted 'precise control over the material's hardening behaviour. Pinpoint cooling during the extrusion process, for example, gives such a high level of control that free spatial extrusions become possible and, consequently, the "knitting" of structures freely in space' (Hack and Lauer 2014, p. 49). Moving to spatial extrusion, in contrast to layer deposition, significantly reduces fabrication time and can be deployed at a large scale. However, the mesh structure is not sufficiently strong to resist structural loads, limiting its application to non-structural components (Wu et al. 2022, p. 13). Hack and Lauer also highlight the potential for carbon, glass, bamboo or basalt to be co-extruded to develop constructions that can withstand high tensile forces. Hack then continued to experiment with the technique for his PhD dissertation, transitioning from polymer to structurally superior steel meshes suitable as a loadbearing construction system, which was used at the DFAB (NEST) house (see below) (Hack 2018).

Inspired by the ferrocement technique (developed in the 1940s) of manually throwing concrete against a dense, self-supporting reinforcement mesh, researchers at ETH Zurich investigated robotic spraying of glass fibre-reinforced concrete on a permeable reinforcement mesh made from carbon fibre (Taha et al. 2019). This approach allowed the researcher to move away from the limitation of only spraying horizontal layers (as with the work at Braunschweig). Square, 38 mm glass-fibre mesh was bent and stabilised into the desired shape. Glass fibre was mixed with the concrete in the nozzle of the spraying gun. Through experimentation the optimal fibre length (42.5 mm) in relation to mesh opening size was identified as crucial to ensure the material clogged the openings of the mesh and adhered to it, 'while also assuring that excess of material penetrating through the mesh during the fabrication was minimized' (Taha et al. 2019, p. 248). A double-curved structure with an average thickness of just 3 cm was successfully developed. The researchers conclude that their approach could be compatible with mesh mould in the application of surface finishing.

The DFAB (NEST) house was conceived as a multi-technology demonstrator of digital fabrication techniques (Fig. 1). A densely reinforced load-bearing concrete wall was built in situ at the house. The steel reinforcing mesh was constructed more densely than traditional steel rebar cages to prevent the concrete mix from flowing through the mesh. To build the mesh accurately, the fabricator sensed its position within the construction site and continuously monitored the shape of the mesh. A 12 m wall, 2.8 m high, requiring over 20,000 weld points was constructed using 6 mm steel rods over a period of 125 hours.[1] Undulations were incorporated into the design to stiffen the wall to compensate for its relative thinness.

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[1] A video of this project can be viewed at: https://www.youtube.com/watch?v=Fi3SyfQ3hnc.

Fig. 1 The in situ fabricator building the mesh mould at the NEST house. The mesh mould process unifies the reinforcement and formwork production into a single and robotically controlled on-site fabrication system. (Image courtesy: NCCR Digital Fabrication)

In 2019, Hack et al., inspired by lattice structures traditionally constructed using steel or aluminium, began to experiment with using reinforced concrete for geometrically complex spatial structures suitable for long-spanning, column-free construction (Hack et al. 2019). In this approach, the spatial structures were modularised into planar components (Fig. 2). Using identical, planar truss girders reduced material use and eliminated the need for formwork. Planar components were 3D printed using three layers of shotcrete reinforced with a (manually placed) carbon fibre grid. After milling the edges, the planar elements were cured and then assembled. It was noted that more sophisticated module typologies need to be developed ‘to allow for improved connectivity and multidirectional load transfer between neighbouring modules’ (Hack et al. 2019, p. 371).

In 2020, Kloft and Hack successfully produced a fully reinforced, double-curved concrete wall over 5 square meters and 18cms thick using a 6-axes Stäubli robot (Hack and Kloft 2020). In this process horizontal and vertical (10 mm B500B steel) rebars were positioned manually as the structure was printed (Fig. 3 and described in more detail in (Kloft et al. 2020b)). A second three-centimetre layer of concrete was applied embedding the reinforcements, while creating a foundation for the surface finishing, using a trowelling process (a 3-axes Omag milling application) (Hack and Kloft 2020, p. 1130).

Mike Xie, from RMIT in Melbourne, led a project to construct a 4.2 m wall using fibre reinforced ultra-high-performance concrete sprayed over 80 moulds, 3D

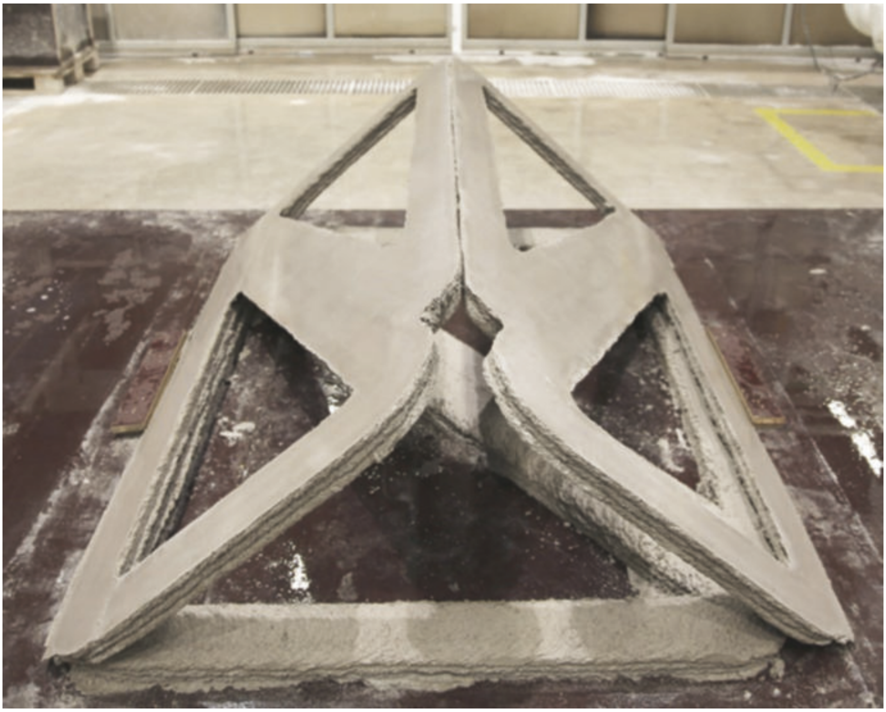

Fig. 2 Assembled prototype element demonstrating proof of concept for a project at Technische Universität Braunschweig. (Image courtesy of Norman Hack)

printed from PETG (Fig. 4). After printing and assembly moulds were sprayed with concrete in layers. The demoulded polished concrete components were transported for on-site assembly (Centre for Innovative Structures and Materials 2021; Dingwen 2022).

The German government-financed Carbon Concrete Composite project is approaching completion of the construction of The Cube, a building made, in part, from precast panels with sections shotcreted onto a carbon fibre mesh. The carbon fibre reinforcement allowed double-curved geometry walls just 4 cm thick to be built without the need for conventional formwork. It is claimed that the construction will have four times the strength of a regular reinforced concrete building and contain 70% less embodied carbon (the use of clinker has been avoided). The use of flexible (rust proof) carbon reinforcement mesh has allowed for new geometric forms to be explored in the design of the building. The 220 square meter building on the grounds of the Technische Universität Dresden has a predicted lifespan nearly three time the standard 70–80 years for concrete buildings reinforced conventionally (Cousins 2021; Fearson 2021). The Cube showcases the potential for shotcrete to create longer-lasting buildings, a significant sustainability advantage compared with traditional construction techniques as end-of-life impacts are delayed.

Fig. 3 Threading unbent vertical reinforcement into the shotcrete core structure. (Image courtesy Norman Hack)

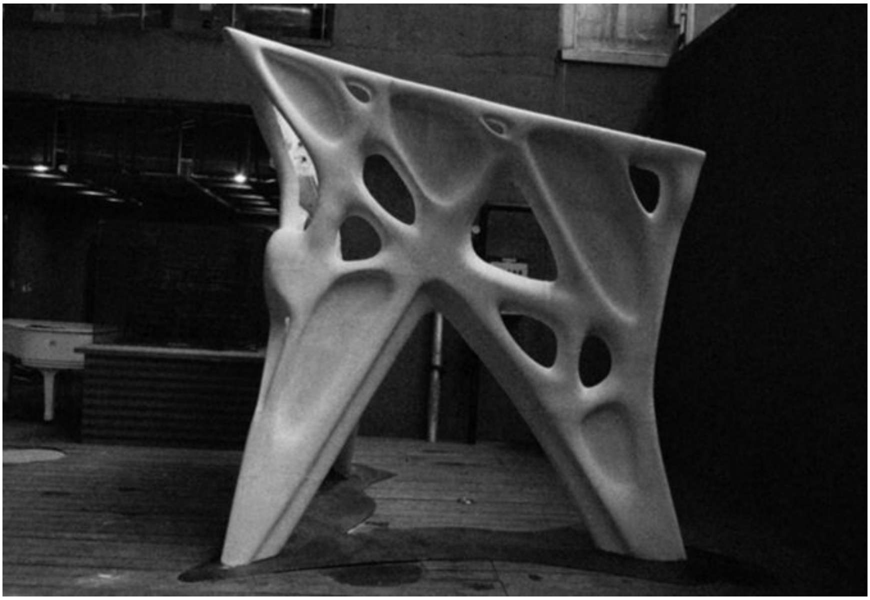

Fig. 4 Intelligent form. (Image courtesy: Dingwen ‘Nic’ Bao, Xin Yan, Yi Min ‘Mike’ Xie, Wei Qiu and Jianan Peng)

Additionally, shotcrete can be used to economically repair or rehabilitate structures, extending their lives and delaying potential impacts caused by demolition and reconstruction.

3.3 Control Systems

The accuracy and consistency of the sprayed results is determined by the sophistication of the control system which determines the location and quantity of material and calculated the desired compaction. Adaptive control algorithms can be used to incorporate feedback from sensors monitoring material distribution in real time. The ability to precisely control the thickness of a section to match its structural requirements eliminates wasted material, one of the main sustainability advantages of shotcrete. Traditional processes such as trowelling and milling can be used to improve surface finish (Hack and Kloft 2020, p. 1129).

Synchronising the measuring system with the robot-held nozzle to obtain consistent results within acceptable tolerances remains a significant challenge. Irregular environmental characteristics and fluctuations in the composition of the concrete mix can result in 'vast deviation between designated and printed geometry' (Lachmayer et al. 2023). A 2018 state-of-the-art review of in situ measurement technologies identified laser triangulation as more accurate and reliable compared with 2D camera-based monitoring (Lindemann et al. 2019). Informed by this review, the authors concluded that model-based offline planning alone was insufficient to deliver the accuracy required and implemented a series of monitoring and control initiatives using a Beckhoff control system.

Layer width and height were controlled by two algorithms developed to compensate for material displacements causing geometric inaccuracies. By controlling the velocity of deposition and the distance from the nozzle to the surface, the required layer height and width could be achieved, although the authors note that control of the layer width measurement is indirect, which they planned to address by direct measurement to deliver closed-loop control of layer width (Lindemann et al. 2019, p. 294). This project resulted in SC3DP constructing a wall with complex concrete geometries, featuring a significant overhang and integrated reinforcement for the first time (Lindemann et al. 2019, p. 296).

Researchers at Cambridge University developed trajectory planning algorithms to produce doubly curved ribbed concrete shells using the C# plug-in for Grasshopper's 3D visual programming environment (Nuh et al. 2022). Two prototypes were produced using this process: a 4.5 m nine-segment shell and a deep ribbed thin shell. The authors note that the benefit of the Grasshopper plug-in is that 'it can be applied to any robotic assembly system with a concrete sprayer attached'.

3.4 Material Mixtures

Developing suitable cementitious materials specifically for SC3DP is another area of enquiry (Lu et al. 2019a, p. 1074). Incorporating supplementary cementitious materials such as fly ash or recycled aggregate into the concrete mix avoids landfill, highlighting another sustainability advantage of SC3DP. Material must be specifically developed to ensure it is suitable to be pumped through the hose and propelled through the nozzle. Coarse aggregates have not been used to date. Pumping performance can be improved if the mixture has low plastic viscosity and low dynamic yield, both of which can be manipulated by incorporating additives (Heidarnezhad and Zhang 2022, p. 6). Of particular note Yun et al. report that adding up to 4.5% of silica fumes by weight improved pumpability by lowering viscosity (Yun et al. 2015). Yun also notes shootability is improved with higher yield stress and increased viscosity resulting in improved build-up thickness while reducing rebound rates. Neudecker et al. recommend a water to cement ratio of 0.4 applied with a pressure of 6.5 bar to achieve the best shootability performance (Neudecker et al. 2016, p. 338). Researchers at Zurich found that the addition of steel fibres led to significant improvements in ductility and strength (Pfändler et al. 2019).

To reduce the density of concrete and to improve the accuracy of spraying, researchers at the Singapore Centre for 3D Printing experimented with adding an air-entraining agent (AEA) and incorporating lightweight aggregate (fly ash cenosphere – FAC) in the mixture (Lu et al. 2019a). Adding AEA reduces yield stress, improving pumpability (Lu et al. 2019a). Experiments showed that the introduction of FAC and AEA lowered the spread diameter and slump values of freshly sprayed cement, suggesting the material could better retain its shape, but negatively impacted its pumpability (Lu et al. 2019a, p. 1075). A mixture containing 100% FAC aggregate and 0.1 grams/litre of AEA presented the lowest plastic viscosity and dynamic yield stress requiring the lowest calculated pumping pressure, achieving the best performance in delivery and deposition.

Computer-controlled dosage of accelerator creates a more uniform shotcrete quality. Adding accelerator and silica fume to shotcrete means it hardens more quickly, achieving high static yield stress more quickly (Heidarnezhad and Zhang 2022, p. 7). Material with 6% accelerator had a deformation modulus about 14 times higher than the material without accelerator (Dressler et al. 2020, p. 16). However, increasing the accelerator dosage can reduce interlayer bonding, potentially compensated by increasing the air volume flow (Lachmayer et al. 2023, p. 13).

3.4.1 Functionally Graded Concrete

Functionally graded concrete is produced by adding a gas-releasing foaming agent, such as aluminium powder, to react with alkaline hydration products or by mixing wet foams with cement paste. The later approach enables different density levels to be achieved, from 200 to 1900 kg/m^3, compared with ~2500 kg/m^3 for standard concrete. The ability to vary density creates the opportunity to develop monomaterial manufacturing processes that address demand for varying the mechanical properties of elements within a structure. Functionally graded materials offer the potential for improvements in material usage, strength and functionality while reducing weight when compared with their homogenous equivalents (Keating 2011, p. 1). Researchers at MIT produced a graded cylinder beam weighing 9% less than a solid cylindrical beam of the same dimensions capable of supporting the same load, illustrating the sustainability benefits of this approach (Keating 2011, p. 5). Functionally graded concrete can contribute to improved material efficiency in construction. In addition, 'foam concrete has lower thermal conductivity (~0.065 Wm^{-1} K^{-1} at ~250 kg/m^3) compared to regular concrete (~0.5 Wm^{-1} K^{-1})', decreasing the need for insulation, yet another sustainability benefit (Bedarf et al. 2021, pp. 7, 10). The internal composition of structural components can be aligned with their 'specific structural and thermal performance requirements' (Herrmann et al. 2018, p. 54).

The researchers at Universität Stuttgart combined two concrete mixes using two pumps and spray nozzles, continuously varying the quantities of mixtures: mixture one is a high-density fine-aggregate concrete, and mixture two has a lower density with a higher porosity. Significantly the two concretes were not mixed before spraying but applied at the same time through two separate nozzles. Topology optimisation algorithms were refined to achieve optimal material distribution. The pumps' volumetric flow control allows for seamless gradation across a wide spectrum of characteristics, ranging 'from low to high strength, heavy to ultra-lightweight, and low to high heat insulation properties' (Herrmann and Sobek 2017, p. 57). Experimental tests revealed that the bulk density of the specimen decreased progressively over its height, and this change was reflected in the mean compressive strength. Steel-reinforced beams with a mass reduction of 34% were successfully produced using functionally graded components (Herrmann and Sobek 2017, p. 62).

4 Future Research

Many topics require further investigation before SC3DP reaches the level of maturity required to achieve widespread deployment by the construction industry. Effectively guiding the development and deployment of in situ robotic fabrication processes presents a complex challenge that spans multiple disciplines and domains, requiring interdisciplinary collaboration and expertise (Buchli et al. 2018). Solutions require the intense collaboration of architects, materials scientists, roboticists, civil engineers and mechanical engineers, among others. Areas of research required are summarised by Heidarnezhand and Shang under three headings: (1) Establishing the correlation between the operational process parameters, material properties and the resulting printed layer geometry is crucial to enhance printing precision. We note that while it has been proven that laser triangulation is superior to 2D cameras to monitor performance, investigation of other measuring techniques is needed. (2)

Examine combining shotcrete with 3D extrusion printing, to help overcome the shortcomings of both technologies (e.g. 3D printing formwork to be over sprayed by shotcrete). (3) Innovate to develop superior printing mixtures, particularly with the addition of fibres, potentially as a replacement for reinforcement (Heidarnezhad and Zhang 2022, p. 9). Alternative reinforcement agents including plastics, carbon, glass and hemp require further experimentation. The effects of combining these reinforcement agents with other additives and accelerators remain an area ripe for further inquiry (Ivanova et al. 2022). Continued investigation into reinforcement structures that are more efficient than traditional steel rebar is needed. Offering faster build times and more efficient use of resources shotcreting is a more sustainable construction technology, but more research is required to quantify these environmental benefits. In particular, Saade et al. note a lack of comparable life cycle assessment studies (Saade et al. 2020).

Research priorities include varying the nozzle geometry to obtain more precision, as the layer geometry is determined by a variety of additional factors including pumping speed, air pressure and stand-off distance. Increasing the nozzle diameter decreases the spray velocity and results in lower compaction rates (Burak et al. 2018). Rebound rates are affected by nozzle positioning and speed, mix proportion, additives and rheological properties. Clear relationships between viscosity and yield stress and their impact on rebound rates have not yet been identified (Yun et al. 2015). Rebound not only wastes resources but also negatively impacts placement of material and potentially mechanical properties. Investigations to reduce rebound or compensate for its effects are needed. In their review of reinforcement technologies, Wu et al. emphasise the need for further development of design standards specific to printed concrete, as well as the establishment of code recognitions and/or guidelines that can verify equivalency to reinforced concrete through comprehensive testing (Wu et al. 2022, p. 21). They also call for standard testing procedures for safety-related performance to be established. SC3DP produces a rough textured surface, and more efficient, fully automated post-processes need to be developed to refine finished products.

Finally, the opportunity to continuously vary the density of the mixture (functionally graded concrete) during construction, investigated by researchers at MIT and Stuttgart, offers the possibility of achieving significant material and energy efficiencies and suggests a rich area for further investigation. The Stuttgart experiment used two nozzles to mix concrete materials at the point of application. Alternatively, more accurate methods to combine and deliver functionally graded concrete on demand require further experimentation. SC3DP functionally graded concrete creates the potential to deliver significant GHG reductions for both the concrete and construction industries through optimising structural designs, minimising the use of materials and significantly reducing waste while improving the sustainability profile of the construction industry and helping it meet the UN Sustainable Development Goal 12.

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