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Short Communication

Adaptive-binder-aggregate mixing (ABAM): Concept for extrusion-based multi-material 3D concrete printing

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ABSTRACT

3D concrete printing (3DCP) enables layerwise fabrication with digital control, offering geometric freedom and material efficiency. However, conventional pump-based 3DCP is constrained by conflicting material requirements, namely sufficient workability for pumping and extrusion versus sufficient resistance to flow and early-age structural build-up for buildability after deposition. This paper introduces Adaptive-Binder-Aggregate Mixing (ABAM), a process concept that avoids long-distance pumping of an aggregate-rich printable cementitious composite (PCC), which can be critical for porous lightweight aggregates and can limit feasible aggregate size and volume fraction. Instead, a pumpable cementitious compound (CC) without aggregates is prepared in the stationary environment and conveyed to the end-effector, where aggregates are stored and incorporated near the nozzle to form the PCC shortly before deposition. The process enables functional material gradation by switching aggregate type during printing, allowing spatial property tailoring within a monolithic element. A prototype implementation is presented together with an initial feasibility demonstration.

1. Introduction

The construction sector is increasingly adopting automated additive construction methods, especially extrusion-based 3D concrete printing (3DCP). Similar to polymer and metal additive manufacturing, 3DCP enables layerwise fabrication with high geometric freedom and digital control of deposition. This can reduce formwork demand, material waste, and on-site labor while enabling geometries that are difficult to realize with conventional casting [1–5].

Multi-material printing is mature in polymer additive manufacturing, but it is not yet widely implemented in 3DCP due to the lack of specifically designed processes and systems [6]. Constraints due to the pumping process involved in conventional extrusion-based 3DCP systems hinder material gradation and limit the use of higher aggregate contents for improved sustainability.

This paper introduces Adaptive-Binder-Aggregate Mixing (ABAM), a process type for extrusion-based multi-material 3DCP in which a highly workable cementitious compound (CC) is prepared upstream and combined with aggregates near-nozzle in a controlled manner. The paper presents the ABAM process, its implementation in a simplified prototype, and an initial feasibility demonstration based on switching between mortar types. Material characterization data from a prior homogeneity study [7] is presented to contextualize the process behavior, while the present work focuses on process design and prototype feasibility under printing conditions.

2. Background

2.1. Processability requirements in extrusion-based 3DCP

State-of-the-art 3DCP processes face significant challenges in balancing two opposing material requirements: workability and buildability. Workability refers to the material's ability to be pumped and extruded smoothly during printing. It requires low yield stress and a

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viscosity range that permits these sub processes without excessive pressure while maintaining stability avoiding segregation [8].

Buildability, in contrast, is the ability of the deposited material to prevent the collapse of objects during printing. It depends on specific rheological properties and is limited by two main failure modes:

- **Plastic failure:** Occurs when stresses in the lower layers exceed the material's resistance to flow due to insufficient structuration rate leading to plastic deformation and loss of structural integrity [5,9].
- Buckling**:** Occurs when mechanical stresses from the weight of subsequently deposited layers exceed the wall's stability threshold, causing collapse due to geometric instability rather than rheological weakness [9,10].

To achieve high buildability, the material must have a sufficient yield stress and a rapid structuration rate after deposition. Larger aggregate sizes and higher aggregate volume fractions can improve buildability by increasing the stiffness and Young's modulus of the fresh material. This reduces the likelihood of buckling and enables higher vertical build rates, and thus higher productivity of the process [11]. These properties directly oppose those required for workability. An increase in aggregate size and volume fraction elevates internal friction and yield stress, thereby increasing pumping pressures. The mechanical stresses in progressive cavity pumps may damage fragile porous aggregates, which can alter the mixture's particle-size distribution and surface area and thereby cause increased variability in flowability during pumping and extrusion [5]. In addition, porous aggregates can absorb water during pumping, reducing workability and repeatability, compromising the intended material properties, especially for light-weight mortars [5,12,13]. The pumping process restricts aggregate type, content, and size and increases the processes sensitivity to segregation and blockages [5,6].

2.2. Sustainability

Key strategies to reduce the ecological and economic impact of cementitious materials include:

- **Increasing the Aggregate Volume Fraction**: In standard concrete, aggregates occupy roughly 75 % of the volume [14]. In published 3DCP studies, reported aggregate volume fractions are lower, typically in the range of 45 % [15] to 53 % [16].
- **Incorporating SCMs into the Binder**: SCMs can greatly minimize the carbon footprint of cementitious materials. However, they affect both the rheological behavior in the fresh state and the mechanical properties in the hardened state [17,18].
- **Structural Optimization**: Structural optimization improves material efficiency by concentrating material where load paths require it and reducing material in regions with lower mechanical demand, for example by using denser material in load-bearing zones and lower-density in non-structural zones [19].

The processability requirements in Section 2.1 constrain the achievable aggregate volume fraction and the extent of cement substitution by SCMs, which limits potential reductions in cement content and the associated environmental impact. Although 3DCP supports structural optimization by placing material primarily where it is structurally required, the elevated Portland cement clinker content often used to ensure robust printability remains a major environmental concern due to its carbon-intensive production [3].

Assessing the compatibility of these sustainability strategies with 3DCP is essential for future construction. Current extrusion-based 3DCP systems restrict the use of sustainable constituents, particularly open-pored or recycled aggregates in high contents, because of their sensitivity to consistency variations that increase the risk of segregation or blockages during pumping [5,6].

Improving and expanding 3DCP requires the coordinated optimization of process, system and material and motivates concepts that allow the in-line adjustment of fresh-state properties while enabling the printing of a variety of materials rather than relying on a single static mix design. In-line adjustments can be beneficial for maintaining print quality under changing environmental conditions, for example temperature or humidity variations that affect rheology and setting behavior [4].

3. State of the art

3.1. Extrusion-based 3DCP

Concrete extrusion is a widely used additive construction process for cementitious composites and is commonly classified as a subclass of additive manufacturing for cementitious materials [20–22]. A robotic arm, gantry, or boom systems control the nozzle path along which material is deposited in three-dimensional space [23]. Printable cementitious composite (PCC) is deposited in successive layers to fabricate components either on-site or off-site, combining disciplines from civil engineering, materials science, robotics, and computer-aided design [21].

With respect to how PCC is prepared and conditioned prior to deposition, current 3DCP implementations are commonly grouped into one-component (1K) (section 3.2), two-component (2K) (section 3.3) and near-nozzle mixing (NNM) processes types (section 3.4), while numerous variants with different system configurations and operational methods exist. The following sections provide an overview of the characteristic subprocesses to transform raw constituents into a self-supporting object for the three process types mentioned, adopting the terminology according to [24].

3.2. Single component (1K) 3DCP Process

The 1K process is illustrated in Fig. 1.

The process chain begins with the proportioning of the raw constituents: cement, aggregates, supplementary cementitious materials (SCMs), chemical admixtures (CA), and water, according to a predefined material mix design. The solid fraction can be dosed as individual constituents or be provided as a premixed dry blend (dry mix).

The solid constituents are combined with water and CA and mixed in a primary mixer (PCC-mixing) to produce a PCC with rheological properties suitable for extrusion, showing both workability and buildability. Batch and continuous mixing are both used in 3DCP practice. A storage unit in the stationary environment is used to buffer the PCC, guaranteeing a continuous material supply to the transport system. Then the PCC is conveyed to the end-effector through a hose, often using progressive cavity pumps that also regulate the deposition rate. This configuration is commonly referred to as a direct-extrusion system. An optional near-nozzle buffer can provide short-term storage and low-shear agitation to reduce material build-up. If a buffer is used to decouple the transport to the end-effector from the deposition rate an additional extruder screw or pump after the buffer is used to control the materials flow rate. All process steps, including material design and end-effector design, affect the extruded strand's shape and properties [24].

3.3. Two-component (2K) 3DCP Process

The 2K process, illustrated in Fig. 2, follows the same initial steps of proportioning as the 1K system (cf. section 3.2), but differs when and where the PCC is formed.

The solid and liquid constituents are combined in the CC-mixing step to produce a highly workable CC. The formed material is pumpable but lacks buildability due to a low yield stress in favor of workability. The CC is then buffered to ensure a continuous supply for the transport from the stationary to the end-effector environment. The CC is transported and

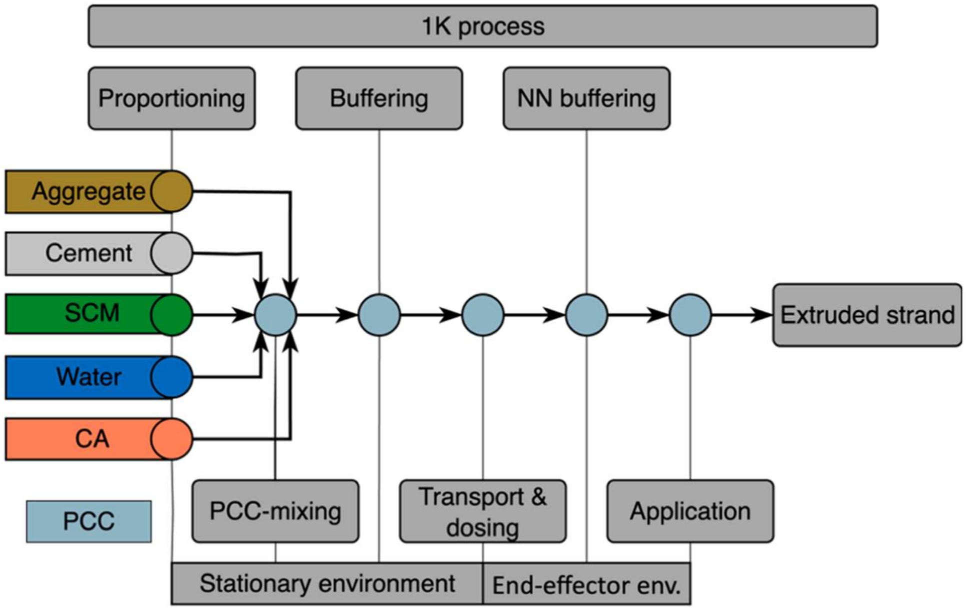

Fig. 1. Material flow in a 1K system, from raw constituents to extruded strand, with key steps: proportioning, PCC-mixing, buffering, transport & dosing, near-nozzle buffering, and application, including transitions from a stationary to an end-effector environment, following the framework in [24].

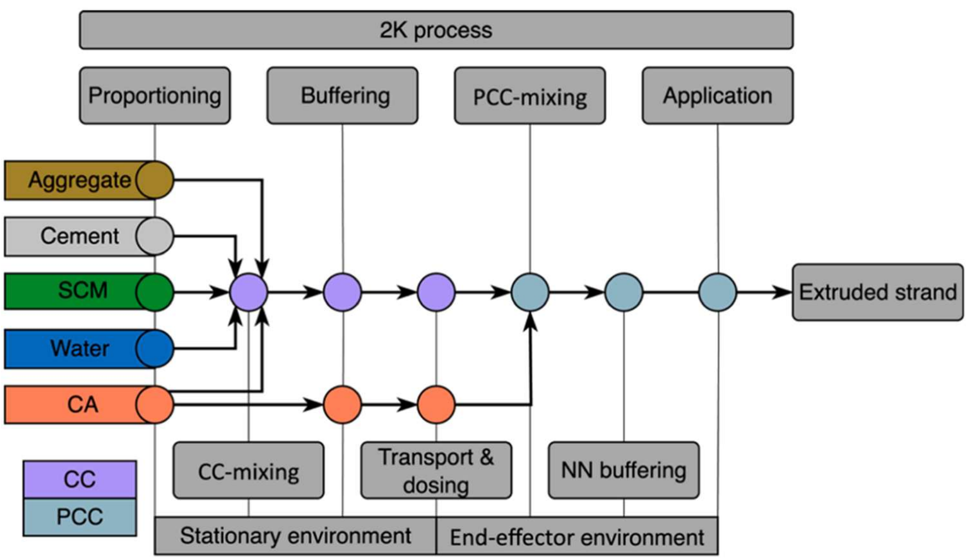

Fig. 2. Material flow in a 2K system, from raw constituents to extruded strand, with key steps: proportioning, CC-mixing, buffering, transport & dosing, PCC-mixing, near-nozzle buffering, and application, including transitions from a stationary to an end-effector environment, following the framework in [24].

dosed to the end-effector via progressive cavity pumps. At the end-effector, a CA, typically an accelerator or viscosity-modifying agent, is added to the CC as the second component (2K) in a secondary mixing process to form a printable material (PCC-mixing). CA is typically stored separately in the stationary environment and supplied to the end-effector through an independent dosing system. CA adjusts the CC's rheological properties shortly before deposition, increasing stiffness and structuration rate providing buildability and reducing workability after deposition. During application, the PCC is deposited through a nozzle to form the structure along a predefined path. In 2K systems, accurate CA dosing and reproducible secondary mixing (PCC-mixing) are critical to ensure consistent application.

3.4. Near-nozzle and quick-nozzle mixing (NNM/QNM)

The Near-nozzle mixing (NNM) process is shown in Fig. 3 where the PCC is formed at the end-effector by combining raw constituents in the end-effector environment shortly before application.

Depending on the process variant, constituents can be supplied as fully separated streams as intended in the theoretical concept (e.g., aggregates, cement, SCMs, water, and CA) or as partially premixed feeds (e.g., a prehomogenised dry mix combined with water and CA) often used in research as simplification measures [6]. The theoretical concept of NNM represents the process with the highest possible material flexibility and in-line material control due to shortest possible material residence times and the ability to control every raw constituent individually.

QNM is a variant of NNM aiming for high process efficiency through high-shear mixing, aiming for the shortest possible residence-times of a dry mix buffered in the end-effector environment [6,25–28]. NNM and their variants require transport, dosing, and synchronization of the selected raw material streams, together with a primary near-nozzle

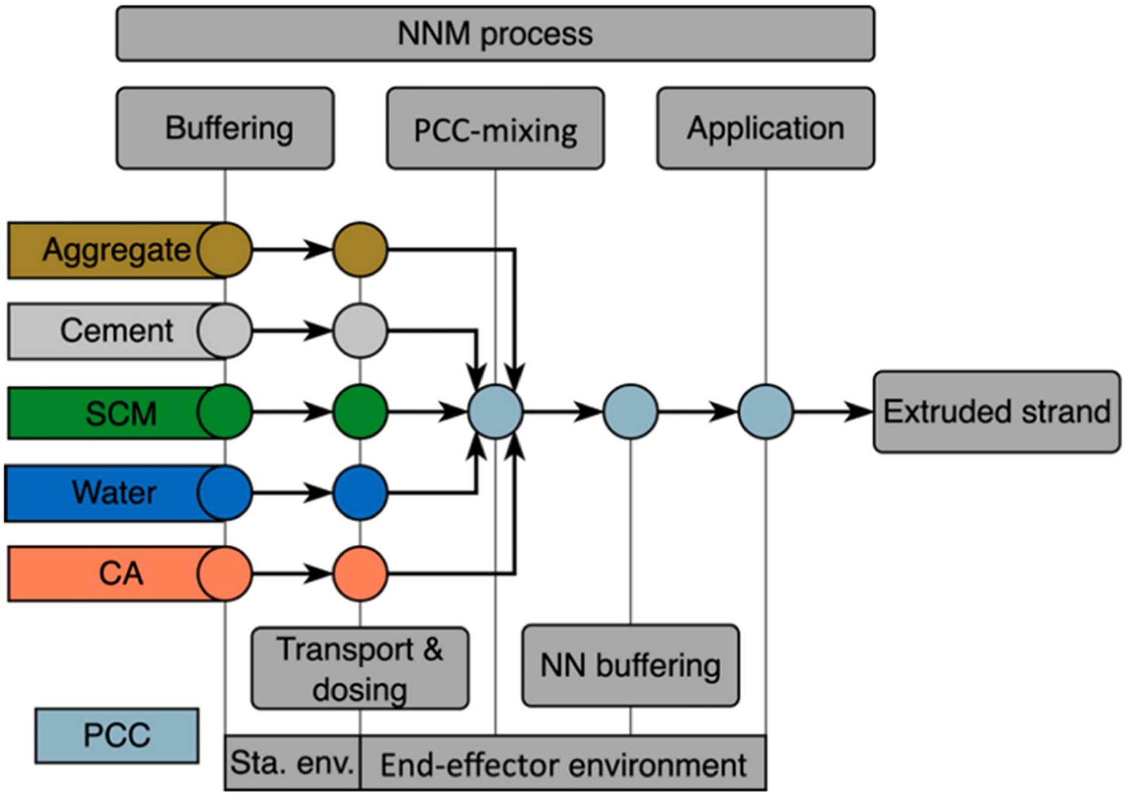

Fig. 3. Overview of a near-nozzle mixing system with separate supplies for water, CA, cementitious powder, and aggregates. Key steps include buffering, transport and dosing, PCC-mixing, near-nozzle buffering, and application, including transitions from a stationary to an end-effector environment, in adherence to the framework in [24].

PCC-mixing process.

3.5. Design requirements for multi-material 3DCP systems from limitations of state-of-the-art processes

Pump-based 1K and 2K extrusion systems are constrained by the need to transport cementitious material through hoses and a pump. This limits feasible aggregate size and volume fraction and increases sensitivity to segregation and blockage, particularly when pumping pressures rise. For porous lightweight aggregates, pumping pressure effects and the mechanical action of progressive cavity pumps can alter aggregate integrity, which can increase density and alter fresh-state properties such as consistency as well as hardened properties [5]. For aggregates with porous structure the partly unpredictable change in consistency can lead to higher pumping pressures increasing the risk of blockage additionally [5,6].

The 2K process adds a second component (CA) at the end-effector to increase stiffness and structuration rate shortly before deposition. Pumping a highly workable material (CC) instead of PCC shows promising results with a more controllable material flow, consistent pumping pressures and higher build-rates. However, 2K processes still requires the pumping of an cementitious material containing aggregates, where the achievable aggregate volume fraction remains limited. Furthermore, this process type demands a separate storage and dosing of CA and introduces a secondary mixing process near-nozzle, increasing process complexity. The 2k process demands reproducible and accurate dosing and secondary mixing to avoid insufficient activation or premature stiffening. The higher vertical build-rate due to CA enhances the productivity, but primarily for small- to midscale use-cases. Large-scale objects with high layer times such as houses can only be realized in modules due to the maximum layer-time to prevent cold-joints causing significant challenges for process control.

Near-nozzle and quick-nozzle mixing (NNM/QNM) avoid the pumping of PCC and CC by forming a PCC in a primary mixing process at the end-effector. This significantly enhances the possible maximum aggregate content, but shifts key process functions to the dynamic end-effector environment. NNM requires the transport and highly accurate dosing of multiple raw material streams as well as the integration of a compact yet energy intensive primary mixing process on the end-effector. End-effector integration of these sub-processes impose constraints on the possible mixer volume due to weight limitations of kinematics. Achieving full material control via gravimetric dosing at the end-effector is challenging because end-effector accelerations, vibrations, and the dynamics of primary mixing degrade weighing accuracy. Gravimetric dosing in the stationary environment with pneumatic conveying to the end-effector is also constrained because segregation during transport can compromise the intended sieve line of dry constituents. In the case of QNM the high mixing intensity poses a risk for fragile aggregates keeping the material variety limited.

From these limitations, the following design requirements for a multi-material 3DCP process can be derived:

- (R1) Enable full in-line material adjustment during printing.
- (R2) Avoid pumping of aggregate-rich PCC for high material variety (Lightweight- and recycled aggregates).
- (R3) Minimize the number of conveyed raw material streams in and/or into the end-effector environment.
- (R4) Minimize the introduced energy into the material on the end-effector.
- (R5) Preserve fragile aggregates by limiting mechanically- and pressure-induced damage.

4. Adaptive-binder-aggregate mixing (ABAM)

4.1. Motivation

To address the design requirements derived in section 3.5, ABAM is presented as an alternative process type in which an pumpable CC than in 2k processes is prepared in the stationary environment and combined with aggregates near-nozzle to form a PCC.

Section 4.2.1 introduces the theoretical concept of the ABAM process type, section 4.2.2 positions ABAM relative to 1K, 2K and NNM/QNM approaches and section 4.2.3 describes the simplified ABAM process variant for initial feasibility assessment. Section 4.3 describes the prototype system used for this study. Section 4.4 defines the operating envelope used for the demonstration and evaluation presented in section 5.

4.2. Adaptive-binder-aggregate mixing (ABAM)

4.2.1. Theoretical process concept

In the theoretical concept of the ABAM process, cement, SCMs, water, and CA are continously proportioned into a continuous primary mixer in the stationary environment to produce a binder without aggregates as a highly workable CC (see Fig. 4).

After mixing the CC is buffered, to minimize aging effects and ensure continuous supply to the dosing system for the transport from stationary- to end-effector environment. At the end-effector, the PCC is formed by combining the CC with continuously dosed aggregates near the nozzle shortly before extrusion. In the conceptual design, continuous aggregate dosing is required to achieve high dosing accuracy and to achieve full material gradation during printing.

4.2.2. Positioning relative to 1K/2K and NNM/QNM

ABAM follows the concept of both 2k and NNM process types to form a PCC near-nozzle. In comparison to NNM it shifts primary mixing of the CC upstream into the stationary environment, as successfully implemented in 2k processes. This eliminates the necessity of a highly accurate powder dosing in the end-effector environment. Powders should be dosed gravimetrically, which is difficult to realize in a dynamic environment such as the end-effector [29]. ABAM enables gravimetric dosing for all raw constituents except aggregates in the more controllable stationary environment. Relative to the theoretical concept of NNM with multiple raw material streams, ABAM reduces the number of separately conveyed powder and liquid streams to the dynamic end-effector environment consolidating them in CC, providing a more controllable and accurate process.

In contrast to 2k processes the conversion from CC to PCC is not achieved by introducing CA but by introducing aggregates into the CC. The increase in buildability is not achieved due to chemical activation but due to the aggregate content, which in 2k processes is limited as a result of the pumping process.

ABAM retains the potential of NNM but enables the variation of aggregates including light-weight aggregates that are not affected by pumping nor an energy intensive primary mixing process, since they are introduced at the latest possible time into a near-nozzle secondary mixing process.

Material gradation can be achieved by controlling the volume fraction of different aggregate types and / or the tailoring of binder composition.

4.2.3. Simplified ABAM process and first system prototype

To demonstrate the feasibility of ABAM three (3) central measures have been realized to demonstrate multi-material printing.

(i) High-intensity primary mixing of CC in the stationary environment.
(ii) Aggregate incorporation near-nozzle using low-intensity mixing to minimize damage to fragile aggregate types.
(iii) Alteration of aggregates type for multi-material printing.

To reduce system complexity for this initial feasibility study, the following simplifications were implemented:

- Aggregates were stored in a hopper on the end-effector and supplied via volumetric dosing as successfully demonstrated in QNM for the feasibility of NNM with more delicate powders.
- The CC was produced batch-wise and buffered, so the CC composition was not altered during printing. Instead, the solely the aggregates were exchanged during printing to showcase multi-material printing, since these largely define the mortar type. This simplification was mandatory since inline paste production with full binder adjustability was not fully studied during the time of this study.

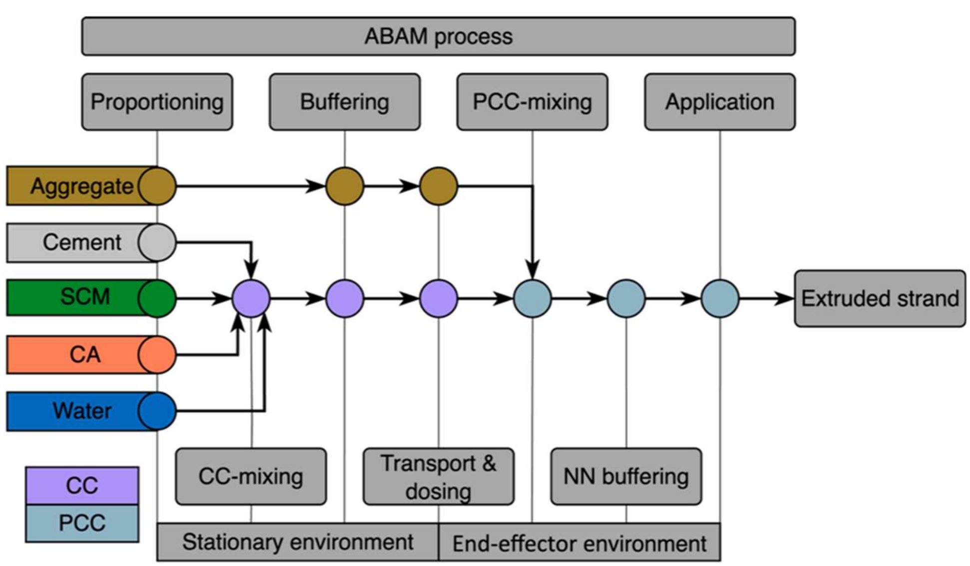

Fig. 4. Material flow in a general ABAM system from raw constituents to extrusion. Key steps include proportioning, CC mixing, separate buffering of CC and aggregates, transport and dosing, PCC mixing by aggregate addition near the nozzle, optional near-nozzle buffering, and application.

4.3. System prototype

4.3.1. Primary mixing equipment (stationary environment)

A PFT MULTIMIX 140 plus batch mixer was used for CC-mixing. After primary mixing, the binder was transferred into a buffer equipped with an agitator to mitigate segregation and structural build-up, as well as ensuring a continuous material supply. A peristaltic pump (VERDERFLEX DURA 15) transferred the CC from the buffer unit in the stationary environment to the secondary mixing process (PCC-Mixing) at the end-effector.

4.3.2. End-effector for secondary mixing (end-effector environment)

Initially designed for primary mixing of dry mortar with water, a D10 (m-tec) (Fig. 5) was used as a system base for the volumetric dosing of buffered aggregates in the hopper (Pos. 1) with a volume of approximately 50 l as well as the secondary mixing process to form the PCC at the end-effector. Through heavy modifications, the base system was adopted as follows to enable the simplified ABAM process described in section 4.2.3

The original water-dosing system and electrical components (Pos. 2) as well as the end cap (Pos. 3) were removed from the base system. The water dosing system was not suitable for CC containing solid particles resulting in a much higher viscosity. Furthermore, the cleaning of the complex piping was not expected to be feasible. The original three-phase motor was replaced with a servo motor to enable continuous process feedback and documentation for future trails (Pos. 4). A flap (Pos. 5) was integrated below the buffer (Pos. 1), enabling the switch of materials during the process by draining and refilling with different aggregate types. During this switch, the coupled shaft between the mixing and dosing was turned off (Pos. 4). The mixing shaft's geometry (Pos. 6) was designed to avoid dead zones and provide a repeatable continuous material flow into the extrusion section via vertical interface (Pos. 7).

The extrusion section shown in detail in Fig. 6 was designed around the base system.

The extruder was designed modularly, ensuring high flexibility for research. The extruder base, including the base plate (Pos. 8), bearing sleeve (Pos. 9), and motor-shaft coupling (Pos. 10), was permanently installed onto the mixing section by screws to ensure easy adaptability. The extrusion motor (Pos. 11) and laser-distance sensor (Pos. 12) were mounted by a quick-release mechanism enabling a quick detachment of electrical components for cleaning. The extruder compartment was mounted by simple clamps and are thus also easily removable. The extruder compartment is an assembly of the main conical housing (Pos. 13) and the buffer-enhancing housing (Pos. 14) for flexible buffer volumes. The mixing shaft contains the main shaft (Pos. 15) and the screw shaft (Pos. 16), which must be extended by the buffer shaft module (Pos. 17) in the case of using the buffer-enhancing module (Pos. 14) for larger buffer volumes. The laser-distance sensor (Pos. 12) enhances process control by regulating material flow from the mixing section, preventing overflow or shortfalls through continuous feedback of the extrusion section fill level. The end-effector assembly has an approximate mass of 100 kg and was mounted onto a six-axis KUKA KR

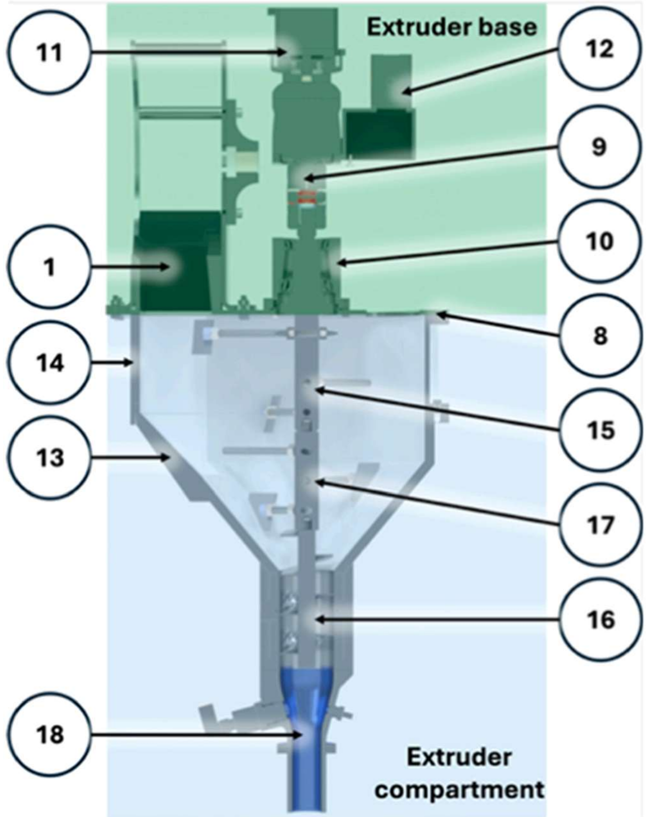

Fig. 6. Cross-section of the extrusion section with interface (7), base plate (8), bearing sleeve (9), motor-shaft coupling (10), extrusion motor (11), laser-distance sensor (12), main conical housing (13), buffer-enhancing housing (14), main shaft (15), screw shaft (16), buffer shaft module (17), nozzle with pressure- and temperature sensor (18).

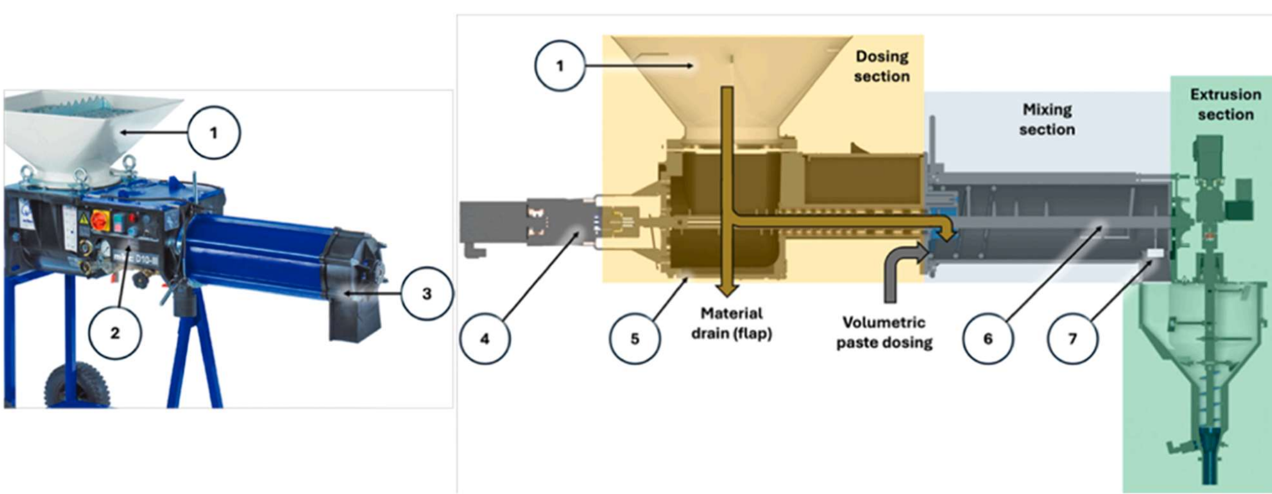

Fig. 5. (Left) m-Tec D10 with hopper for DryMix / aggregates as base system (1), electrical and water dosing installation (2) and end cap (3); (Right) cross section of first system prototype with hopper (1), servo motor (4), flap (5), coupled volumetric dosing and mixing shaft (6), mixing- and extrusion section interface (7).

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4.4. Operating envelope

This section summarizes the operating settings and boundary conditions used to run the ABAM system. The prototype is operated in open-loop mode, meaning that dosing and actuation are commanded by fixed setpoints without closed-loop regulation.

Aggregate incorporation and CC homogenization at the end-effector are performed at 100 rpm of the mixing motor (Fig. 5 Pos. 4). The extruder screw is operated at a speed of 70 rpm (Fig. 6 Pos. 11). The nozzle diameter is 30 mm. The PCC volumetric output at the nozzle is 2.4 L/min, with an aggregate-to-paste ratio of 3:2 by volume. Deposition is performed at a robot travel speed of approximately 60 mm/s. The typical layer time is approximately 60 s. The corresponding productivity, based on the nozzle output, is 0.144 m^3/h.

After each trial, cleaning is performed manually. The mixing chamber, extruder, and nozzle components are disassembled as needed. Residual material is removed mechanically, and components were rinsed and brushed before reassembly.

5. Feasibility demonstration

This section evaluates the simplified ABAM process. Sections 5.1-5.3 document process execution and the capabilities of the prototype described in section 4.2.3, operated within the envelope defined in section 4.4. Material characterization data used to interpret the results were obtained in a prior study [7] under identical parameters and are summarized in section 5.1.

5.1. Material parameters (context from prior work)

ABAM process stability was previously assessed in a homogeneity study conducted over a 2 h printing session [7]. Three mortar types were investigated: natural sand mortar (NSM), recycled aggregate mortar (RAM), and lightweight mortar (LWM). Table 1 summarizes key fresh- and hardened-state parameters as mean values with given coefficients of variation (CV).

The fresh-state yield stress ranged from 0.377 kPa (LWM) to 1.244 kPa (RAM), which exceeds typical literature ranges reported for extrusion-based 3DCP (0.05–0.76 kPa) [30]. All mortars were produced at an aggregate volume fraction of 60 %, which is above the range commonly reported for pump-based 1K systems (45 - 53 %) [15,16]. The three mortars represent distinct functional targets: NSM provides high compressive strength (66.4 MPa) for load-bearing applications, RAM provides comparable strength (64.4 MPa) with aggregate substitution for improved resource efficiency, and LWM provides low density (1.13 kg/dm^3 hardened) and low thermal conductivity (0.38 W/mK) for insulation-oriented regions [7]. Across all three mortars, the coefficients of variation indicate repeatable processing and consistent material properties under the applied operating conditions.

Table 1
Fresh and hardened material parameters for LWM, NSM, and RAM reported as mean (coefficient of variation, CV). Data taken from the prior homogeneity study [7].

Parameter	LWM	NSM	RAM	Unit
Slump flow mortar	157.5 (5.09 %)	170 (3.34 %)	162 (4.08 %)	mm
Yield stress	377 (1.46 %)	492 (3.57 %)	1244 (10.95 %)	Pa
Density (fresh)	1.17 (1.21 %)	2.1 (0.95 %)	1.8 (0.56 %)	kg/dm^3
Compressive strength	21.8 (11.54 %)	66.4 (5.92 %)	64.4 (3.88 %)	MPa
Density (hardened)	1.13 (2.83 %)	2.13 (1.41 %)	2 (1.00 %)	kg/dm^3
Thermal conductivity	0.38 (2.64 %)	1.86 (2.15 %)	1.4 (6.43 %)	W/(mK)

5.2. Aggregate integrity

Fig. 7 provides a qualitative comparison of porous lightweight aggregate integrity between a conventional 1K process including a pumping process with a progressive cavity pump (Fig. 7, left) and the ABAM process without the pumping of the material containing aggregates (Fig. 7, right).

Both specimens used the same porous lightweight aggregate types and the same packing-density-optimized sieve line (composed of four size fractions) as defined in [5]. For the ABAM process, no “pre-pump” state exists by design, and an equivalent before/after pumping density comparison is therefore not possible. As a quantitative proxy for the expected density scale, the hardened bulk density of the LWM measured in the prior homogeneity study is 1.13 kg/dm^3 [7]. The corresponding fresh density can be estimated from the mixture design (mass–volume balance) as approximately 1.10 kg/dm^3. By contrast, [5] reports a density increase in the order of +25 % associated with the destruction and infiltration (with binder) of the porous aggregates through the pumping process. The much larger density change reported under pumping conditions is consistent with increased aggregate crushing and pore collapse, while the ABAM specimen does not show damage of this magnitude in the qualitative comparison. The low intensity mixing and extruding of the material did not introduce severe aggregate destruction nor the infiltration with binder causing density increases.

5.3. Gradation demonstration

The ABAM prototype enables material gradation by changing the aggregate stream during printing while keeping the CC constant. Thus, a graded demonstrator was successfully produced by switching the aggregate type from natural sand for NSM (see Fig. 8; bottom) to lightweight expanded-glass aggregates for LWM (see Fig. 8; top) during the process. For a better visual distinction, red pigments were added and premixed into the aggregates prior to printing. Based on visual inspection of the color transition along the printed path, the aggregate switch produced an transition length of approximately 14 m. The transition length is attributed to the material volume in the mixer and the residence time of the material inside the end-effector.

6. Limitations and future research

The ABAM process demonstrated in this work represents a first feasibility study and therefor shows several optimization potentials for future applications.

At present, the CC is produced in batches. Using multiple batches for large-scale application requires the coordination between mixing and extruder speeds due to gradual changes in CC properties as a consequence of material aging. A continuous in-line CC mixer with individual raw constituent dosing, combined with continuous and independent aggregate dosing, are mandatory to realize the still theoretical ABAM concept (section 4.2.1). This would enable full material control through the simultaneous adaptation of paste and aggregate composition during printing.

The automated supply of aggregates to the end effector was simplified by buffering and switching the material inside the buffer through draining and refilling. Thus, only one aggregate sieve line can be handled. Industrial application will require either the storage of multiple aggregate types on the end-effector or a robust aggregate dosing system from the stationary environment, minimizing segregation.

In the current prototype, process control is open loop. CC and aggregate mass flows are set based on prior system calibration. Since robust in-line sensors for key fresh-state properties (e.g., density and consistency) are not yet established for routine use in extrusion-based 3DCP, closed-loop control based directly on rheological state is not

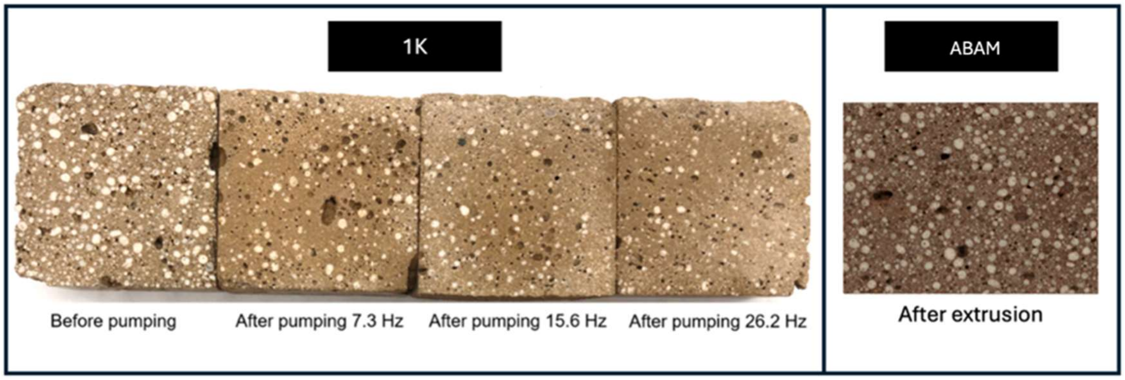

Fig. 7. Cross-section views of Lightweight Mortar (LWM). Left: Processed with a 1K system using an progressive cavity pump, showing crushed porous aggregates due to high mechanical stress through rising pump speed [5]. Right: Processed with the ABAM system, showing intact porous aggregates preserved by the low shear mixing process. Both specimens had similar aggregate sieving lines from 0-2 mm.

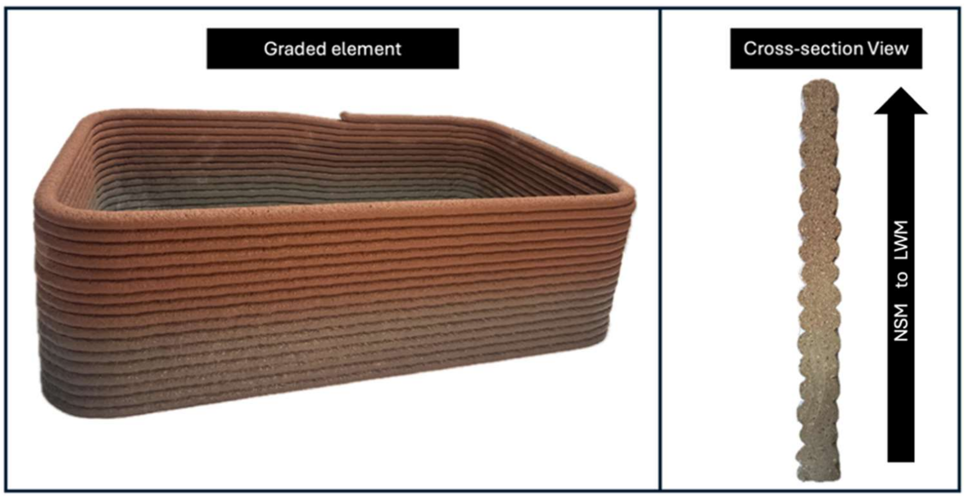

Fig. 8. (Left) shows a structure with a graded material composition, featuring a Natural Sand Mortar (NSM) base and a Lightweight Mortar (LWM) top, demonstrating the Adaptive-Binder-Aggregate Mixing (ABAM) system's ability to change materials during the printing process. (Right) A cross-sectional view of the same structure highlights the continuous transition between the two materials. The LWM is distinguished by its red pigments. The overall dimensions of the structure are 110 cm x 70 cm, with each layer measuring 30 mm in width and 20 mm in height.

implemented in the present prototype. In principle, indirect measurements such as filament geometry and material temperature could be integrated and may provide correlated control variables for process monitoring. However, such surrogate signals are not expected to fully compensate for intrinsic material variability through process parameter adjustment alone. The integration and validation of suitable sensing and control strategies therefore remain subject to future research.

A further limitation is the mass and geometry of the end-effector. The prototype, including mixer, buffer, and aggregate dosing units, has a total mass on the order of 100 kg. This restricts the choice of kinematic systems, reduces the available working envelope for a given robot payload class, and limits achievable printing speeds due to inertial effects. Interdisciplinary end-effector optimization is required to reduce mass and length and to refine mixer geometry while maintaining sufficient residence time and minimizing aggregate damage and retained material volume.

These limitations are mainly related to the systems maturity rather than to the underlying process principle. Addressing the identified challenges are expected to significantly enhance the practical potential of ABAM in industrial application for utilizing the advantages of multi-material printing.

7. Conclusion

This study presents ABAM as a process type for extrusion-based 3DCP in which a highly workable CC is prepared in a stationary environment and converted into a PCC by near-nozzle aggregate incorporation.

By avoiding long-distance pumping of aggregate-rich PCC, ABAM can reduce pumping-related constraints on aggregate size and maximum volume fraction and enables the property retaining printing of porous lightweight aggregates that are sensitive to pressure and mechanical loading in progressive cavity pumps. Compared to conventional 2K systems, ABAM achieves near-nozzle conversion by aggregate incorporation rather than chemical activation, reducing the reliance on accelerators while requiring aggregate storage, dosing, and mixing at the end-effector.

The feasibility study successfully demonstrated multi-material printing, exemplified by transitions between NSM and LWM to obtain locally different strength and thermal conductivity. Through further research the specifically designed ABAM system for multi-material printing shows stable process execution of ABAM within the investigated operating envelope and exhibits great potentials for future automated construction.

Outlook

Ongoing development of the ABAM system targets improved process flexibility, reliability, and scalability toward industrial application. The next iteration will implement two separately controlled aggregate hoppers and an in-line paste mixer for continuous CC production with individual gravimetric dosing of raw constituents, enabling controlled transitions without the batch-mixing constraints related to material aging. Fresh-state control will be expanded from aggregate-to-paste ratio adjustments to controlled dosing of superplasticizers and other CA, enabling rheological fine-tuning while maintaining base mix proportions for binder systems matched to the selected aggregate types. Closed-loop monitoring and control, including in-line estimation of fresh-state properties and material tracking, are being investigated to improve repeatability under variable boundary conditions. In parallel, continuous, segregation-resistant aggregate supply concepts are under development to reduce end-effector mass and improve controllability. Quantification of the transition zone associated with material switching, including transition length and the evolution of individual material parameters, is also under investigation.

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CRediT authorship contribution statement

Christian Maximilian Hechtl: Writing – original draft, Conceptualization. **Maximilian Dahlenburg:** Writing – review & editing, Conceptualization. **Freek Bos:** Writing – review & editing, Supervision. **Thomas Kränkel:** Writing – review & editing, Supervision. **Christoph Gehlen:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] G. Cruz, J.R.C. Dizon, N. Farzadnia, H. Zhou, M. Margarito, J.A. Garcia, et al., Performance, applications, and sustainability of 3D-printed cement and other geomaterials, MRS. Commun. 13 (2023) 385–399, https://doi.org/10.1557/s43579-023-00358-x.

[2] T. Wangler, N. Roussel, F.P. Bos, T.A.M. Salet, RJ. Flatt, Digital concrete: a review, Cem. Concr. Res. 123 (2019) 105780, https://doi.org/10.1016/j.cemconres.2019.105780.

[3] editorA. Perrot (Ed.), 3D Printing of Concrete: State of the Art and Challenges of the Digital Construction Revolution, 1st ed., Wiley, 2019 https://doi.org/10.1002/9781119610755.

[4] V. Mechtcherine, F.P. Bos, A. Perrot, W.R.L. Da Silva, V.N. Nerella, S. Fataei, et al., Extrusion-based additive manufacturing with cement-based materials – Production steps, processes, and their underlying physics: a review, Cem. Concr. Res. 132 (2020) 106037, https://doi.org/10.1016/j.cemconres.2020.106037.

[5] CII. Matthäus, Performance Under Pressure: Effect Of Pumping Pressure On Additive Manufacturing Of Lightweight Aggregate Concrete, Doctoral Dissertation, Technical University of Munich, 2022.

[6] F. Craveiro, S. Nazarian, H. Bartolo, P.J. Bartolo, J. Pinto Duarte, An automated system for 3D printing functionally graded concrete-based materials, Addit. Manuf. 33 (2020) 101146, https://doi.org/10.1016/j.addma.2020.101146.

[7] Hechtl MC, Kränkl T, Gehlen C. Near-nozzle mixing for additive manufacturing of cementitious mortar: a homogeneity study 2023.

[8] A.K. Al-Tamimi, H.H. Alqamish, A. Khaldoune, H. Alhaidary, K. Shirvanimoghaddam, Framework of 3D concrete printing potential and challenges, Buildings 13 (2023) 827, https://doi.org/10.3390/buildings13030827.

[9] A.S.J. Suiker, R.J.M. Wolfs, S.M. Lucas, TAM. Salet, Elastic buckling and plastic collapse during 3D concrete printing, Cem. Concr. Res. 135 (2020) 106016, https://doi.org/10.1016/j.cemconres.2020.106016.

[10] R.J.M. Wolfs, F.P. Bos, TAM. Salet, Early age mechanical behaviour of 3D printed concrete: numerical modelling and experimental testing, Cem. Concr. Res. 106 (2018) 103–116, https://doi.org/10.1016/j.cemconres.2018.02.001.

[11] W. Si, M. Khan, C. McNally, A comprehensive review of rheological dynamics and process parameters in 3D concrete printing, J. Compos. Sci. 9 (2025) 299, https://doi.org/10.3390/jcs9060299.

[12] G. Girskas, M. Kligys, 3D concrete printing review: equipment, materials, mix design, and properties, Buildings 15 (2025) 2049, https://doi.org/10.3390/buildings15122049.

[13] M.K. Mohan, A.V. Rahul, K. Van Tittelboom, G. De Schutter, Evaluating the influence of aggregate content on pumpability of 3D printable concrete, in: F. P. Bos, S.S. Lucas, R.J.M. Wolfs, T.A.M. Salet (Eds.), Second RILEM International Conference on Concrete and Digital Fabrication, Cham 28, Springer International Publishing, 2020, pp. 333–341, https://doi.org/10.1007/978-3-030-49916-7_34.

[14] A.M. Neville, JJ. Brooks, Concrete technology, 2. ed, Harlow: Prentice Hall, 2010.

[15] Cho S, Kruger PJ, Zeranka S. 3D printing concrete technology and mechanics from industrial aspect 2020.

[16] Henke K. Leichtbeton-3D-druck: additive fertigung von multifunktionalen, monolithischen wandelementen durch extrusion von leichtbeton 2021.

[17] K.A. Knight, P.R. Cunningham, SA. Miller, Optimizing supplementary cementitious material replacement to minimize the environmental impacts of concrete, Cem. Concr. Compos. 139 (2023) 105049, https://doi.org/10.1016/j.cemconcomp.2023.105049.

[18] G. Habert, N. Roussel, Study of two concrete mix-design strategies to reach carbon mitigation objectives, Cem. Concr. Compos. 31 (2009) 397–402, https://doi.org/10.1016/j.cemconcomp.2009.04.001.

[19] K-MM Tam, CT. Mueller, Additive manufacturing along principal stress lines, 3D. Print. Addit. Manuf. 4 (2017) 63–81, https://doi.org/10.1089/3dp.2017.0001.

[20] P. Shakor, S. Nejadi, G. Paul, A study into the effect of different nozzles shapes and fibre-reinforcement in 3D printed mortar, Materials 12 (2019) 1708, https://doi.org/10.3390/ma12101708.

[21] R.A. Buswell, W.R.L. Da Silva, F.P. Bos, H.R. Schipper, D. Lowke, N. Hack, et al., A process classification framework for defining and describing digital fabrication with concrete, Cem. Concr. Res. 134 (2020) 106068, https://doi.org/10.1016/j.cemconres.2020.106068.

[22] F. Heidarnezhad, Q. Zhang, Shotcrete based 3D concrete printing: state of art, challenges, and opportunities, Constr. Build. Mater. 323 (2022) 126545, https://doi.org/10.1016/j.conbuildmat.2022.126545.

[23] GH. Ahmed, A review of "3D concrete printing": Materials and process characterization, economic considerations and environmental sustainability, J. Build. Eng. 66 (2023) 105863.

[24] T. Wangler, R. Pileggi, S. Gürel, RJ. Flatt, A chemical process engineering look at digital concrete processes: critical step design, inline mixing, and scaleup, Cem. Concr. Res. 155 (2022) 106782, https://doi.org/10.1016/j.cemconres.2022.106782.

[25] N. Zhang, M. Xia, J. Sanjayan, Short-duration near-nozzle mixing for 3D concrete printing, Cem. Concr. Res. 151 (2022) 106616, https://doi.org/10.1016/j.cemconres.2021.106616.

[26] N. Zhang, J. Sanjayan, Surfactants to enable quick nozzle mixing in 3D concrete printing, Cem. Concr. Compos. 142 (2023) 105226, https://doi.org/10.1016/j.cemconcomp.2023.105226.

[27] N. Zhang, J. Sanjayan, Quick nozzle mixing technology for 3D printing foam concrete, J. Build. Eng. 83 (2024) 108445, https://doi.org/10.1016/j.jobe.2024.108445.

[28] N. Zhang, J. Sanjayan, Pumping-less 3D concrete printing using quick nozzle mixing, Autom. Constr. 166 (2024) 105609, https://doi.org/10.1016/j.autcon.2024.105609.

[29] DIN EN 206:2021-06, Beton_- festlegung, eigenschaften, herstellung und konformität; Deutsche fassung EN_206:2013+A2:2021 n.d. https://doi.org/10.31030/3198971.

[30] A.U. Rehman, J-H. Kim, 3D concrete printing: a systematic review of rheology, mix designs, mechanical, microstructural, and durability characteristics, Materials 14 (2021) 3800, https://doi.org/10.3390/ma14143800.