

# The status quo of 3D concrete printing: are we there yet?

Rob Wolfs<sup>1+\*</sup>

<sup>1</sup> Eindhoven University of Technology, The Netherlands

+ Rob Wolfs was invited for submission of this letter as an awardee of the Gustavo Colonnetti Medal granted by RILEM in 2024

Received: 24 May 2024 / Accepted: 11 September 2024 / Published online: 13 September 2024

© The Author(s) 2024. This article is published with open access and licensed under a Creative Commons Attribution 4.0 International License.

## Abstract

The technology of 3D concrete printing has seen a rapid growth in industrial applications and academic activities over the past decade. 3D Printing is being advertised to address the urgent sustainability and productivity challenges in the field of construction, by reducing the total amount of concrete in buildings or structures, and by producing them in an automated, high-speed and robust manner. Today, however, 3D concrete printing does not yet live up to its full potential. In this contribution, the advancements in recent years are discussed, and the status quo of the technology is assessed from a productivity and sustainability perspective. Finally, recommendations for the next steps in the development towards a higher efficiency and reduced environmental impact are provided.

**Keywords:** Additive Manufacturing; Digital Fabrication; Quality Control; Structural Design.

## 1 Introduction

The technology of extrusion-based 3D concrete printing (3DCP), a member of the ‘digital fabrication with concrete’ (DFC) family [1], has seen rapid growth in recent years both from an industrial and academic perspective. The number of projects in practice is increasing quickly, [2–4], highlighted by press headlines and media coverage with ever more exciting (but often unsubstantiated) records in speed, cost reduction, project size, or novelty. In parallel, the research activities are growing in a similar, exponential fashion [5].

This attention and growth rate may be attributed to the sustainability and productivity advantages 3DCP promises to bring to construction [6,7], and their timeliness in an age where the call for a reduced environmental impact and increased construction efficiency is louder and more urgent than ever. 3D printing is an additive manufacturing technology, which, in comparison to conventional subtractive methods (e.g., milling, cutting), reduces generation of waste. Due to the layer wise nature of the printing process, material can be placed only where it is functionally required, and thus, optimized objects can be created with an overall reduced material consumption. 3DCP does not require any (traditional) formwork to be used, which, in particular for complex geometries, provides additional savings in material waste (and costs). From a productivity perspective, 3DCP is envisioned to improve construction efficiency due to its digital and automated nature, as less process steps may be required

(e.g., formwork placement and removal), and additional functionalities may be integrated in one go.

Given the rapid increase of attention in recent years and the clear and timely advantages that 3DCP promises, the question rises whether the full potential of this technology has been reached – in particular since these advantages do not come free, but introduce new complexity into concrete construction. To formulate an answer to this question, this paper will briefly reflect on the history and present state of this technology, then highlight the key (sometimes paradoxical) challenges regarding productivity and sustainability gains, and finally provide recommendations for the next steps in its development towards a higher efficiency and reduced environmental impact.

## 2 A brief history of 3DCP

The first recorded attempts to produce concrete structures in a layer wise, additive fashion, date back to as early as the 1930’s. Although technically not fully aligned with the definition of additive manufacturing [8], multiple patents filed by the ‘URSCHEL’ company (founded by William E. Urschel), describe and illustrate ‘machines for building walls’ by moulding concrete in strips or layers without any traditional formwork, using a rotating, telescopic arm [9–11], demonstrating a remarkable resemblance to the robotic 3D concrete printers of today. Notably, a video recording of this technique being used in the 30’s is available online [12]. In the subsequent decades, multiple similar patents were filed to

\*Corresponding author: Rob Wolfs, E-mail: [r.j.m.wolfs@tue.nl](mailto:r.j.m.wolfs@tue.nl)

construct concrete wall elements layer by layer without formwork [13–18]. All of these approaches present adaptations of rotating or telescopic arms, and as a result, the envisioned applications of these technologies concern cylindrical, spherical, or hemi-ellipsoidal structures. This clear relation between manufacturing technique and design still holds today, although the geometric freedom is much larger, due to the increased degrees of freedom of robotic systems.

The first digital and automated 3D concrete printing approaches appeared around the turn of the 21st century. Pegna presented ‘Solid Freeform Construction’, a particle-bed 3D printing technique based on the selective deposition and curing of cement, and demonstrated this concept by designing, slicing, and subsequently printing a house sized to the palm of a man’s hand [19,20]. Khoshnevis developed ‘Contour Crafting’ at the University of Southern California, an extrusion based 3D concrete printing method to additively shape the outer contours and (optionally) infill of wall structures using large gantry-system 3D printers [21–23], and produced some of the first iconic prototypes of large scale applications. Finally, Dini established the ‘D-Shape’ printing strategy, a binder jetting 3D printing system on a scale large enough to produce building or bridge parts, and demonstrated its freedom in design by printing various complex geometric objects [24]. These true pioneers moved beyond the largely manual or machinery approaches patented throughout the 20th century, and successfully adopted digital tools to design (CAD) and robotic systems to print (CAM) applications for the field of concrete construction. At the time, however, a widespread uptake of their technologies by the construction industry was limited, and academic activities remained small – with the exception of first significant research programs such as ‘Freeform Construction’ at Loughborough University [25–27].

The turning point occurred roughly ten years ago from the time of writing, when industrial activities started to increase exponentially all across the globe [5,28,29]. Now, the implementation of digital tools in construction had become more widely accepted compared to when Pegna, Khoshnevis, or Dini presented their disruptive techniques (although digitalization still occurs at a much slower pace than in other industries [30]). The need to change constructions’ productivity and environmental impact also became more clear. As a result, an increasing number of start-up companies began to develop 3DCP approaches to challenge the conventional practice in concrete construction, and, in parallel, well-established parties (engineering firms, material suppliers, contractors, or architectural firms) gradually incorporated digital fabrication and 3D printing in their portfolio. Today, the industrial activities include sales of 3D concrete printers which can fit on your desk or produce a multi-storey building – and everything in between –, offering off-the-shelf printable materials, or providing 3D concrete printing as a service. First structural applications of 3DCP (pedestrian or bicycle bridges, or small buildings) have appeared in practice [2,31–33], but since the quality control and thus code compliance is challenging, as will be discussed in the next section, the majority of applications are non-

structural. Here, safety requirements are lower, yet the advantages related to customization are equally present. Such examples include lost formwork applications, (urban) furniture, coral reefs, or stair cases.

Research activities have grown exponentially in parallel, where the majority of studies revolve around printable material development or characterization, while topics such as process control, reinforcement strategies, or (structural) design are underrepresented [5]. The active academic community is united in international research communities, aiming to provide a common scientific bases related to e.g., classification or testing procedures. This has, amongst others, resulted in a first state-of-the-art report of the now closed RILEM Technical Committee 276-DFC ‘Digital fabrication with cement-based materials’ [34], two significant interlaboratory studies on mechanical and durability properties of both fresh and hardened printable concrete, organized by the successive Technical Committees 303-PFC ‘Performance requirements and testing of fresh printable cement-based materials’ and 304-ADC ‘Assessment of Additively Manufactured Concrete Materials and Structures’, and first national standards in the US (ISO/ASTM 52939:2023 [35]) and China (T/CECS 786-2020 [36]).

Following the principle of the Gartner Hype Cycle [37] this rapid increase of activities is expected to slow down in time. The questions then rises whether 3DCP will be sufficiently matured to remain anchored in the construction industry, fulfilling its promises regarding increased productivity and sustainability gains. This will be evaluated in the following two sections.

### 3 Productivity – are we there yet?

To reach the envisioned productivity gains, 3D concrete printing will have to develop towards a ‘first-time-right’ manufacturing technology. This means being able to control the quality of both the printing process (maximizing production speed without errors/failure) and the printed product (reaching desired levels of e.g., safety, durability, geometric conformity, aesthetics). This is, however, not straightforward to achieve as 3DCP introduces added complexity compared to conventional concrete processing (casting in a formwork). As a result, most 3DCP applications are still a result of trial-and-error, which leads to additional material waste. A 3DCP process can be considered as multiple consecutive phases, each of which poses specific and potentially contradictory requirements on the material behaviour, process settings, and design considerations [38–40]. The material should initially be fluid to facilitate ease of pumping and extruding, after mixing [38–42]. Then, as soon as a single layer is extruded, the stiffness and strength of this material should be sufficiently high to maintain the desired layer geometry (i.e., carry its self-weight without excessive deformation) [38,39,43,44]. Since no supporting formwork is present, the strength and stiffness should then increase considerably, or the vertical growth rate must be limited, to avoid excessive deformation or even failure [45–49] as layers are added consecutively. In this stage, the bond between layers is also formed, which will define to a large extent the

mechanical and durability performance in the use phase. This poses an upper limit to the rate at which the material properties should evolve during printing or the toolpath length [26,50–54]. Finally, once the printing process is complete and the printed objects are to be used, the (structural) design considerations may deviate once more from common practice. The layered build-up of printed structures can lead to strength reductions in certain loading orientations, and the customized or optimized (thin) objects can behave differently from their conventional, monolithic counterparts.

Characterizing this material behaviour across the critical time- and length scales of the entire 3DCP process is not self-evident, as the material gradually transitions from a fluid towards a solid. A ‘slump test’ to establish proper workability, and a ‘compression test’ on a hardened cube or cylinder to establish the 28-day strength, may no longer suffice [55]. This revision of well-established concrete testing procedures in the light of digital fabrication poses new challenges, and is consequently an active topic in the academic community. Characterizing the fresh, early-age properties requires testing procedures which are able to capture the relevant range of strength and stiffness properties (going beyond rheology tests, yet considerably lower than hardened concrete) [56], which can be executed rapidly, and comprise handling and measurement procedures with minimal unintentional destructuration. Examples include tests coming from soil mechanics or hardened concrete, adapted to fresh concrete, such as uniaxial unconfined compression tests, direct shear tests, or triaxial compression tests [45,56–60]. These are, however, tests of a destructive, off-line nature. This implies that the test should be repeated multiple times to capture material evolution as well as process variations, and the tested material cannot be (re-)used for printing. Given the digital nature of 3DCP, a strong potential resides in the development towards on-line or in-line methods for quality control [55,61,62]. These tests either make use of the printing process itself (e.g., gravity-driven tests, including the formation of droplets or ‘slugs’ [43,63–67], or performing printing trials [48]), or are based on various types of sensors (e.g., pressure, power consumption, acoustic, thermal) which are correlated with the relevant properties [57,68–72]. These approaches typically provide high frequency measurements, and are therefore very suitable to capture material evolution or process variations, and, in the case of non-destructive tests, do not lead to any material waste.

Similarly, for hardened material properties, establishing the mechanical or durability performance using well established testing protocols for samples cast in a mould may be insufficient. The build-up of layers and thus presences of ‘interfaces’ can lead to reduced performance compared to cast, monolithic samples [73]. The extent of this reduction depends however on various material and process parameters, as well as the orientation in which the layers are subjected to loading or the environment [26,50–54]. This too will require the established (destructive) test protocols to be updated for 3DCP. Similarly to fresh concrete testing, the development towards non-destructive in-line measurements

could reduce the large number of destructive tests required. For instance, monitoring key state parameters such as surface roughness, moisture content, and thermal history, and correlating these properties to the bond strength, appears a promising alternative to large destructive experimental programs [74,75].

Once the fresh and hardened material properties can be characterized using suitable test methods, the properties can be used as input for analytical or numerical models of the various phases of 3DCP. These digital representations of the manufacturing process can be used, for instance, to analyse the layer geometry [76–81], predict the potential occurrence of failure during printing [45,46,81–83], or to systematically evaluate the influence of material, process or design choices. For industrial applications, these models can be utilized to generate process design graphs or establish efficient operation windows [46–48,84,85].

While the majority of material testing and quality assessment takes place on the level of the material or a couple of layers only, moving to structural applications of 3DCP requires quality control on full object scale. This bridge between scale levels (e.g., establishing potential size effects) is still to be defined. In its absence, the performance of such objects is currently demonstrated by means of large-scale, destructive testing [4,31,32,86]. While this is a suitable solution on short term to prove compliance with building codes and facilitate permitting, on the long run, this time- and material-consuming approach will hinder productivity gains of 3DCP significantly.

#### 4 Sustainability – are we there yet?

3D Printing is often advertised to be a ‘sustainable’ manufacturing technology, as the total amount of material can be reduced due to the nature of the process. The environmental impact a printed object is, however, not a function of material consumption only. Using the first order approach proposed in [87], the environmental impact can be expressed as (1):

$$\text{Environmental Impact of } \begin{matrix} \text{(3D Printed) Concrete} \\ \text{per Year of Service} \end{matrix} \propto \frac{\text{Embedded CO}_2 \times \text{Total Volume}}{\text{Unit Volume} \times \text{Service Life}} \quad (1)$$

The right-hand side of this relation contains three main components which contribute to the final environmental impact: 1) the embodied CO<sub>2</sub> of the material used, 2) the total amount of material consumed, and 3) the expected life of the product. The majority of 3D printable material compositions is characterized by relatively large cement contents and an absence of large aggregate sizes (and thus, they could be formally classified as ‘mortars’ rather than ‘concrete’). As a result, the impact of printable concrete per unit volume is still (too) high, in particular compared to conventional mixtures designed for casting in a formwork, and must be addressed by reducing (or replacing) the cement content, including larger aggregates, and potentially incorporating recycled materials [87–92].

While this ‘material’ component receives by far the most attention [5], an equally large contribution can be made in the

field of (structural) design. The total amount of material in structures can be considerably reduced by creating more efficient structural layouts, for instance by size, shape, or even topology optimization [93–96]. These structural optimization approaches generally result in complex geometries which are difficult (costly) to produce by conventional formwork systems, yet much more feasible to 3D print. This requires the development of design tools which integrate the constraints and possibilities of the manufacturing method, as well as the mechanical behaviour of concrete (e.g., asymmetric behaviour in compression and tension) [93]. In the absence or limited availability of such tools and methodologies, most of the structural applications in practice do not yet make full use of the design freedom offered by 3DCP. For instance, the majority of 3D printed concrete houses show a close resemblance to the structural designs based on conventional construction using formwork, where in certain cases the printed concrete is used exclusively as a lost formwork. First examples of 3DCP informed structural designs are appearing in practice as well, making use of geometric freedom to increase strength or stiffness (e.g., curvature or local stiffening ribs), or by creating compression-dominated structures [31–33,97,98].

In addition to the reduction of total material usage, increasing the lifespan of the printed objects can also lower the total impact per service year. In today's practice, however, most printed projects are largely monolithic structures, printed in 'one go' on-site. This limits their reuse or repair, principles of a circular economy which will extend the total lifespan. Developing 'dry' connections for 3DCP structures is therefore a promising yet hardly explored road. The geometric freedom offered by digital fabrication can be applied on this scale level as well, for instance to create sinusoidal or tooth-like demountable connections with sufficient structural capacity [99,100].

Regardless the level of circularity reached, the service life and thus environmental impact is also dependent on the durability performance of the printed objects. The absence of formwork at early ages, the high cement contents, the presence of interfaces, and a structural thickness in the order of magnitude of merely the 'cover' of conventional concrete structures, make this a challenging feat and, as discussed in the previous section, a topic of ongoing research related to quality control [73].

Finally, to use 3D printed concrete in efficient structural applications, the topic of reinforcement must inevitably be addressed. In recent years, various reinforcing solutions have been developed, each of which having their own characteristics, classified in recent contributions [101–103]. A single, 'one-size-fits-all' solution for 3DCP, similar to rebar or reinforcement meshes, might not be available (yet), which may be attributed to some of the incompatible features of 3DCP and reinforcement. 3D Printing with thin layers to create complex geometries requires the integration of 'flexible' reinforcement solutions, yet sufficient structural capacity (i.e., tensile strength or ductility) might require much larger steel cross sections which do not necessarily provide the same freedom in geometry (straight rebars and meshes).

Continuity of reinforcement throughout the object is moreover desirable, but this interferes with the layer wise manufacturing process. Bridging layers is challenging as the material of each layer is likely to have a different age, whereas pre-placing the reinforcement can limit the geometric freedom of the printing process. Finally, the topic of concrete cover and reinforcement durability must be revisited, as the structural mass (and thus the cover) of a printed structure is much smaller compared to conventional concrete structures.

## 5 What's next?

Inspired by pioneers and early adopters of 3D concrete printing in the early 21st century, the technology has seen a rapid development in the last decade. Research activities are still growing exponentially, and 3DCP projects appear almost on a daily basis in practice. In most cases, they are still the result of trial-and-error, or have been designed using conventional methodologies or standards, and as such, do not make full use of the advantages which 3D printing offers. To reach these promises of an increased construction productivity and reduced environmental impact, the following targets have been formulated.

Productivity gains requires first-time-right manufacturing and thus, quality control of both the printing process and printed product. The developments so far have been showing successful approaches of quality assessment for 3DCP, where standardized approaches are appearing. Standardization will harmonize the findings across research groups or industrial parties, and reduce the total amount of tests required, not only on small scale, but in particular also regarding the large-scale structural tests currently performed on most real-life applications.

The associated test methods typically concern destructive, off-line testing, whereas a shift towards non-destructive on-line or in-line methods has a high potential in an automated, digital process, and moreover, might be a prerequisite to move from assessment to quality control. In this shift towards high-frequency non-destructive measurements, the amount of data collected increases considerably compared to isolated 'slump' or 'compression' tests. This requires the development of quality control procedures which are able to incorporate such comprehensive amount of information. Moreover, such decision-making should be able to bridge across time- and length-scales as the target material behaviour and key process features are very different between mixing, pumping, extruding, printing, and the use phase. In this light, there can be a role for data-driven (e.g., artificial intelligence based) approaches for the field of concrete technology, in addition to well established model-driven solutions.

To reduce the environmental impact of concrete construction through 3DCP, printable material compositions will require further developments towards lower footprint solutions, by including coarse aggregates, alternative binders, or recycled materials, and by expanding the materials' functionality. Significant research efforts are targeting this topic globally. More emphasis should be put on the impact that can be made through efficient structural design, by developing 3DCP informed design methodologies to reduce the total volume

(structural optimization) and enable re-usability (inclusion of dry connections, principles of modularity and circular economy). In the end, the total environmental impact is a combination of these three components.

The development of systematic approaches to evaluate the environmental consequences and productivity gains of material, design, and process choices in an integral manner will therefore enable valid claims regarding the sustainability and economic potential of 3D concrete printing.

A multitude of reinforcement solutions is currently under development in research environments. In practice, however, most load-bearing 3D printed structures are loaded in compression only (either because of their geometry or by applying pre-stressing), or the printed material is used as a (non-structural) lost formwork. Industrial-level reinforcement solutions are required, if the 3DCP technology is to be used for a variety of efficient structural applications.

### Competing interest

The author declares that there are no competing interests that are relevant to the content of this article.

### Authorship statement (CRediT)

**Rob Wolfs:** Conceptualization; Writing – original draft

### References

- [1] R.A. Buswell, W.R.L. Da Silva, F.P. Bos, H.R. Schipper, D. Lowke, N. Hack, H. Kloft, V. Mechtcherine, T. Wangler, N. Roussel, A process classification framework for defining and describing Digital Fabrication with Concrete, *Cement and Concrete Research* 134 (2020) 106068. <https://doi.org/10.1016/j.cemconres.2020.106068>
- [2] F.P. Bos, C. Menna, M. Pradena, E. Kreiger, W.R.L. Da Silva, A.U. Rehman, D. Weger, R.J.M. Wolfs, Y. Zhang, L. Ferrara, V. Mechtcherine, The realities of additively manufactured concrete structures in practice, *Cement and Concrete Research* 156 (2022) <https://doi.org/10.1016/j.cemconres.2022.106746>
- [3] J. Xiao, G. Ji, Y. Zhang, G. Ma, V. Mechtcherine, J. Pan, L. Wang, T. Ding, Z. Duan, S. Du, Large-scale 3D printing concrete technology: Current status and future opportunities, *Cement and Concrete Composites* 122 (2021) 104115. <https://doi.org/10.1016/j.cemconcomp.2021.104115>
- [4] M. Kreiger, E. Kreiger, S. Mansour, S. Monkman, M.A. Delavar, P. Sideris, C. Roberts, M. Friedell, S. Platt, S. Jones, Additive construction in practice - Realities of acceptance criteria, *Cement and Concrete Research* 186 (2024) 107652. <https://doi.org/10.1016/j.cemconres.2024.107652>
- [5] G. Ma, R. Buswell, W.R. Leal Da Silva, L. Wang, J. Xu, S.Z. Jones, Technology readiness: A global snapshot of 3D concrete printing and the frontiers for development, *Cement and Concrete Research* 156 (2022) 106774. <https://doi.org/10.1016/j.cemconres.2022.106774>
- [6] F. Bos, R. Wolfs, Z. Ahmed, T. Salet, Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing, *Virtual and Physical Prototyping* 11 (2016) 209-225. <https://doi.org/10.1080/17452759.2016.1209867>
- [7] C. Menna, J. Mata-Falcón, F.P. Bos, G. Vantghem, L. Ferrara, D. Asprone, T. Salet, W. Kaufmann, Opportunities and challenges for structural engineering of digitally fabricated concrete, *Cement and Concrete Research* 133 (2020) 106079. <https://doi.org/10.1016/j.cemconres.2020.106079>
- [8] ASTM, F2792-12a: Standard Terminology for Additive Manufacturing Technologies, (n.d.).
- [9] W.E. Urschel, Eskimo house building form, US1995692A, 1935.
- [10] W.E. Urschel, Molding and depositing machine for solidifiable plastic materials, US2314468A, 1943.
- [11] W.E. Urschel, Machine for building walls, US2339892A, 1944.
- [12] Urschel Wall Building Machine, 2017. <https://www.youtube.com/watch?v=QXgwnJTVsSE>
- [13] E. Shuter, Concrete wall machine, US2532246A, 1950.
- [14] J.R. Urschel, Machine for building walls of hardenable plastic material, US2607100A, 1952.
- [15] J.B. Winn, Monolithic wall forming apparatus, US3034732A, 1962.
- [16] F.J. Lowes, Apparatus for the preparation of elliptical structures, US3376602A, 1968.
- [17] W.B. Goldsworthy, E.E. Hardesty, On-site wall structure formation, US3966533A, 1976.
- [18] P.T. Maddock, Machine for building a dome or sphere, US4734021A, 1988.
- [19] J. Pegna, Application of Cementitious Bulk Materials to Site Processed Freeform Construction, in: 1995.
- [20] J. Pegna, Exploratory investigation of solid freeform construction, *Automation in Construction* 5 (1997) 427-437. [https://doi.org/10.1016/S0926-5805\(96\)00166-5](https://doi.org/10.1016/S0926-5805(96)00166-5)
- [21] B. Khoshnevis, Automated construction by contour crafting-related robotics and information technologies, *Automation in Construction* 13 (2004) 5-19. <https://doi.org/10.1016/j.autcon.2003.08.012>
- [22] B. Khoshnevis, D. Hwang, K.T. Yao, Z. Yeh, Mega-scale fabrication by Contour Crafting, *IJISE* 1 (2006) 301. <https://doi.org/10.1504/IJISE.2006.009791>
- [23] J. Zhang, B. Khoshnevis, Optimal machine operation planning for construction by Contour Crafting, *Automation in Construction* 29 (2013) 50-67. <https://doi.org/10.1016/j.autcon.2012.08.006>
- [24] D. Lowke, E. Dini, A. Perrot, D. Weger, C. Gehlen, B. Dillenburger, Particle-bed 3D printing in concrete construction - Possibilities and challenges, *Cement and Concrete Research* 112 (2018) 50-65. <https://doi.org/10.1016/j.cemconres.2018.05.018>
- [25] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, A.G.F. Gibb, T. Thorpe, Mix design and fresh properties for high-performance printing concrete, *Mater Struct* 45 (2012) 1221-1232. <https://doi.org/10.1617/s11527-012-9828-z>
- [26] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, R. Law, A.G.F. Gibb, T. Thorpe, Hardened properties of high-performance printing concrete, *Cement and Concrete Research* 42 (2012) 558-566. <https://doi.org/10.1016/j.cemconres.2011.12.003>
- [27] S. Lim, R.A. Buswell, T.T. Le, S.A. Austin, A.G.F. Gibb, T. Thorpe, Developments in construction-scale additive manufacturing processes, *Automation in Construction* 21 (2012) 262-268. <https://doi.org/10.1016/j.autcon.2011.06.010>
- [28] X. Wang, W. Li, Y. Guo, A. Kashani, K. Wang, L. Ferrara, I. Agudelo, Concrete 3D printing technology for sustainable construction: A review on raw material, concrete type and performance, *Developments in the Built Environment* 17 (2024) 100378. <https://doi.org/10.1016/j.dibe.2024.100378>
- [29] R.A. Buswell, W.R. Leal De Silva, S.Z. Jones, J. Dirrenberger, 3D printing using concrete extrusion: A roadmap for research, *Cement and Concrete Research* 112 (2018) 37-49. <https://doi.org/10.1016/j.cemconres.2018.05.006>
- [30] European Construction Sector Observatory, Digitalisation in the construction sector - Analytical Report, (2021).
- [31] R. Wolfs, D. Bos, T. Salet, Lessons learned of project Milestone: The first 3D printed concrete house in the Netherlands, *Materials Today: Proceedings* (2023) S2214785323035770. <https://doi.org/10.1016/j.matpr.2023.06.183>
- [32] Z. Ahmed, R. Wolfs, F. Bos, T. Salet, A Framework for Large-Scale Structural Applications of 3D Printed Concrete: the Case of a 29 m Bridge in the Netherlands, *Open Conf Proc* 1 (2022) 5-19. <https://doi.org/10.52825/ocp.v1i.74>
- [33] S. Bhooshan, V. Bhooshan, A. Dell'Endice, J. Chu, P. Singer, J. Megens, T. Van Mele, P. Block, The Striatum bridge: Computational design and robotic fabrication of an unreinforced, 3D-concrete-printed, masonry arch bridge, *Archit. Struct. Constr.* 2 (2022) 521-543. <https://doi.org/10.1007/s44150-022-00051-y>
- [34] N. Roussel, D. Lowke, eds., Digital Fabrication with Cement-Based Materials: State-of-the-Art Report of the RILEM TC 276-DFC, Springer International Publishing, Cham, 2022. <https://doi.org/10.1007/978-3-030-90535-4>
- [35] ISO/ASTM 52939: Additive Manufacturing For Construction - Qualification Principles - Structural And Infrastructure Elements, (2023).
- [36] T/CECS 786-2020: Technical specification for concrete 3D printing, (2020).
- [37] J. Fenn, A. Linden, Understanding Gartner's Hype Cycles, (2003).

- [38] N. Roussel, Rheological requirements for printable concretes, *Cement and Concrete Research* 112 (2018) 76-85. <https://doi.org/10.1016/j.cemconres.2018.04.005>
- [39] V. Mechtcherine, F.P. Bos, A. Perrot, W.R.L. Da Silva, V.N. Nerella, S. Fataei, R.J.M. Wolfs, M. Sonebi, N. Roussel, Extrusion-based additive manufacturing with cement-based materials - Production steps, processes, and their underlying physics: A review, *Cement and Concrete Research* 132 (2020) 106037. <https://doi.org/10.1016/j.cemconres.2020.106037>
- [40] T. Wangler, R. Pileggi, S. Gürel, R.J. Flatt, A chemical process engineering look at digital concrete processes: critical step design, inline mixing, and scaleup, *Cement and Concrete Research* 155 (2022) 106782. <https://doi.org/10.1016/j.cemconres.2022.106782>
- [41] M. Choi, N. Roussel, Y. Kim, J. Kim, Lubrication layer properties during concrete pumping, *Cement and Concrete Research* 45 (2013) 69-78. <https://doi.org/10.1016/j.cemconres.2012.11.001>
- [42] S. Fataei, E. Secrieru, V. Mechtcherine, N. Roussel, A first-order physical model for the prediction of shear-induced particle migration and lubricating layer formation during concrete pumping, *Cement and Concrete Research* 147 (2021) 106530. <https://doi.org/10.1016/j.cemconres.2021.106530>
- [43] A. Geffraut, H. Bessaies-Bey, N. Roussel, P. Coussot, Printing by yield stress fluid shaping, *Additive Manufacturing* 75 (2023) 103752. <https://doi.org/10.1016/j.addma.2023.103752>
- [44] P. Carneau, R. Mesnil, O. Baverel, N. Roussel, Layer pressing in concrete extrusion-based 3D-printing: Experiments and analysis, *Cement and Concrete Research* 155 (2022) 106741. <https://doi.org/10.1016/j.cemconres.2022.106741>
- [45] R.J.M. Wolfs, F.P. Bos, T.A.M. Salet, Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing, *Cement and Concrete Research* 106 (2018) 103-116. <https://doi.org/10.1016/j.cemconres.2018.02.001>
- [46] A.S.J. Suiker, Mechanical performance of wall structures in 3D printing processes: Theory, design tools and experiments, *International Journal of Mechanical Sciences* 137 (2018) 145-170. <https://doi.org/10.1016/j.ijmecsci.2018.01.010>
- [47] R.J.M. Wolfs, A.S.J. Suiker, Structural failure during extrusion-based 3D printing processes, *Int J Adv Manuf Technol* 104 (2019) 565-584. <https://doi.org/10.1007/s00170-019-03844-6>
- [48] A.S.J. Suiker, R.J.M. Wolfs, S.M. Lucas, T.A.M. Salet, Elastic buckling and plastic collapse during 3D concrete printing, *Cement and Concrete Research* 135 (2020) 106016. <https://doi.org/10.1016/j.cemconres.2020.106016>
- [49] L. Reiter, T. Wangler, N. Roussel, R.J. Flatt, The role of early age structural build-up in digital fabrication with concrete, *Cement and Concrete Research* 112 (2018) 86-95. <https://doi.org/10.1016/j.cemconres.2018.05.011>
- [50] R.J.M. Wolfs, F.P. Bos, T.A.M. Salet, Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion, *Cement and Concrete Research* 119 (2019) 132-140. <https://doi.org/10.1016/j.cemconres.2019.02.017>
- [51] J. Kruger, G. Van Zijl, A compendious review on lack-of-fusion in digital concrete fabrication, *Additive Manufacturing* 37 (2021) 101654. <https://doi.org/10.1016/j.addma.2020.101654>
- [52] V. Mechtcherine, K. Van Tittelboom, A. Kazemian, E. Kreiger, B. Nematollahi, V.N. Nerella, M. Santhanam, G. De Schutter, G. Van Zijl, D. Lowke, E. Ivaniuk, M. Taubert, F. Bos, A roadmap for quality control of hardening and hardened printed concrete, *Cement and Concrete Research* 157 (2022) 106800. <https://doi.org/10.1016/j.cemconres.2022.106800>
- [53] I. Dressler, N. Freund, D. Lowke, The Effect of Accelerator Dosage on Fresh Concrete Properties and on Interlayer Strength in Shotcrete 3D Printing, *Materials* 13 (2020) 374. <https://doi.org/10.3390/ma13020374>
- [54] H. Kloft, H.-W. Krauss, N. Hack, E. Herrmann, S. Neudecker, P.A. Varady, D. Lowke, Influence of process parameters on the interlayer bond strength of concrete elements additive manufactured by Shotcrete 3D Printing (SC3DP), *Cement and Concrete Research* 134 (2020) 106078. <https://doi.org/10.1016/j.cemconres.2020.106078>
- [55] R. Wolfs, D. Bos, J.-F. Caron, M. Gerke, R. Mesnil, R. Buswell, N. Ducoulombier, N. Hack, E. Keita, P. Kinnell, K. Mawas, V. Mechtcherine, L. Miranda, D. Sokolov, J. Versteeg, N. Roussel, On-line and in-line quality assessment across all scale levels of 3D concrete printing, *Cement and Concrete Research* 185 (2024) 107646. <https://doi.org/10.1016/j.cemconres.2024.107646>
- [56] R. Nicolas, B. Richard, D. Nicolas, I. Irina, K.J. Temitope, L. Dirk, M. Viktor, M. Romain, P. Arnaud, P. Ursula, R. Lex, S. Dietmar, W. Timothy, W. Rob, Z. Wenqiang, Assessing the fresh properties of printable cement-based materials: High potential tests for quality control, *Cement and Concrete Research* 158 (2022) 106836. <https://doi.org/10.1016/j.cemconres.2022.106836>
- [57] R.J.M. Wolfs, F.P. Bos, T.A.M. Salet, Correlation between destructive compression tests and non-destructive ultrasonic measurements on early age 3D printed concrete, *Construction and Building Materials* 181 (2018) 447-454. <https://doi.org/10.1016/j.conbuildmat.2018.06.060>
- [58] R.J.M. Wolfs, F.P. Bos, T.A.M. Salet, Triaxial compression testing on early age concrete for numerical analysis of 3D concrete printing, *Cement and Concrete Composites* 104 (2019) 103344. <https://doi.org/10.1016/j.cemconcomp.2019.103344>
- [59] L.K. Mettler, F.K. Wittel, R.J. Flatt, H.J. Herrmann, Evolution of strength and failure of SCC during early hydration, *Cement and Concrete Research* 89 (2016) 288-296. <https://doi.org/10.1016/j.cemconres.2016.09.004>
- [60] A. Perrot, D. Rangeard, A. Pierre, Structural built-up of cement-based materials used for 3D-printing extrusion techniques, *Mater Struct* 49 (2016) 1213-1220. <https://doi.org/10.1617/s11527-015-0571-0>
- [61] D. Bos, R. Wolfs, A quality control framework for digital fabrication with concrete, *RILEM Tech Lett* 8 (2023) 106-112. <https://doi.org/10.21809/rilemtechlett.2023.181>
- [62] A.L. Bowler, S. Bakalis, N.J. Watson, A review of in-line and on-line measurement techniques to monitor industrial mixing processes, *Chemical Engineering Research and Design* 153 (2020) 463-495. <https://doi.org/10.1016/j.cherd.2019.10.045>
- [63] N. Ducoulombier, R. Mesnil, P. Carneau, L. Demont, H. Bessaies-Bey, J.-F. Caron, N. Roussel, The "Slugs-test" for extrusion-based additive manufacturing: Protocol, analysis and practical limits, *Cement and Concrete Composites* 121 (2021) 104074. <https://doi.org/10.1016/j.cemconcomp.2021.104074>
- [64] D. Bos, R. Wolfs, Automated Visual Inspection of Near Nozzle Droplet Formation for Quality Control of Additive Manufacturing, in: R. Buswell, A. Blanco, S. Cavalaro, P. Kinnell (Eds.), *Third RILEM International Conference on Concrete and Digital Fabrication*, Springer International Publishing, Cham, 2022: pp. 453-459. [https://doi.org/10.1007/978-3-031-06116-5\\_67](https://doi.org/10.1007/978-3-031-06116-5_67)
- [65] J.T. Kolawole, D. De-Becker, J. Xu, J. Dobrzanski, S. Cavalaro, S. Austin, N. Roussel, R. Buswell, Selected Test Methods for Assessing Fresh and Plastic-State 3D Concrete Printing Materials, in: R. Buswell, A. Blanco, S. Cavalaro, P. Kinnell (Eds.), *Third RILEM International Conference on Concrete and Digital Fabrication*, Springer International Publishing, Cham, 2022: pp. 460-466. [https://doi.org/10.1007/978-3-031-06116-5\\_68](https://doi.org/10.1007/978-3-031-06116-5_68)
- [66] D. Bos, S. Lucas, J. Blaakmeer, T. Salet, R. Wolfs, Development of the On-Line Gravity-Induced Compression Test: "The Inverse Slugs Test," in: D. Lowke, N. Freund, D. Böhrer, F. Herding (Eds.), *Fourth RILEM International Conference on Concrete and Digital Fabrication*, Springer Nature Switzerland, Cham, 2024: pp. 166-173. [https://doi.org/10.1007/978-3-031-70031-6\\_20](https://doi.org/10.1007/978-3-031-70031-6_20)
- [67] Y. Jacquet, V. Picandet, D. Rangeard, A. Perrot, Gravity induced flow to characterize rheological properties of printable cement-based materials, *RILEM Tech Lett* 5 (2020) 150-156. <https://doi.org/10.21809/rilemtechlett.2020.128>
- [68] D. Chopin, B. Cazacliu, F.D. Larrard, R. Schell, Monitoring of concrete homogenisation with the power consumption curve, *Mater Struct* 40 (2007) 897-907. <https://doi.org/10.1617/s11527-006-9187-8>
- [69] B. Cazacliu, N. Roquet, Concrete mixing kinetics by means of power measurement, *Cement and Concrete Research* 39 (2009) 182-194. <https://doi.org/10.1016/j.cemconres.2008.12.005>
- [70] V.N. Nerella, M. Näther, A. Iqbal, M. Butler, V. Mechtcherine, In-line quantification of extrudability of cementitious materials for digital construction, *Cement and Concrete Composites* 95 (2019) 260-270. <https://doi.org/10.1016/j.cemconcomp.2018.09.015>
- [71] J. Wiklund, M. Rahman, U. Hakansson, In-line rheometry of micro cement based grouts. a promising new industrial application of the

- ultrasound based UVP+PD method, *Appl. Rheol.* 22 (2012). <https://doi.org/10.3933/APPLRHEOL-22-42783>.
- [72] M. Rahman, U. Håkansson, J. Wiklund, In-line rheological measurements of cement grouts: Effects of water/cement ratio and hydration, *Tunnelling and Underground Space Technology* 45 (2015) 34-42. <https://doi.org/10.1016/j.tust.2014.09.003>
- [73] K. Van Tittelboom, M.K. Mohan, B. Šavija, E. Keita, G. Ma, H. Du, J. Kruger, L. Caneda-Martinez, L. Wang, M. Bekaert, T. Wangler, Z. Wang, V. Mechtcherine, N. Roussel, On the micro- and meso-structure and durability of 3D printed concrete elements, *Cement and Concrete Research* 185 (2024) 107649. <https://doi.org/10.1016/j.cemconres.2024.107649>
- [74] J. Versteede, R. Wolfs, T. Salet, A Data-Driven Approach to Additive Manufacturing with Concrete: Enhancing In-line Sensory Data by Utilizing Domain Knowledge, Part I - Geometry (In preparation), (n.d.).
- [75] J. Versteede, R. Wolfs, T. Salet, A Data-Driven Approach to Additive Manufacturing with Concrete: Enhancing In-line Sensory Data by Utilizing Domain Knowledge, Part II - Moisture and Heat (In preparation), (n.d.).
- [76] R. Comminal, M.P. Serdeczny, D.B. Pedersen, J. Spangenberg, Motion planning and numerical simulation of material deposition at corners in extrusion additive manufacturing, *Additive Manufacturing* 29 (2019) 100753. <https://doi.org/10.1016/j.addma.2019.06.005>
- [77] R.J.M. Wolfs, T.A.M. Salet, N. Roussel, Filament geometry control in extrusion-based additive manufacturing of concrete: The good, the bad and the ugly, *Cement and Concrete Research* 150 (2021) 106615. <https://doi.org/10.1016/j.cemconres.2021.106615>
- [78] M.T. Mollah, R. Comminal, M.P. Serdeczny, B. Šeta, J. Spangenberg, Computational analysis of yield stress buildup and stability of deposited layers in material extrusion additive manufacturing, *Additive Manufacturing* 71 (2023) 103605. <https://doi.org/10.1016/j.addma.2023.103605>
- [79] M.T. Mollah, R. Comminal, M.P. Serdeczny, D.B. Pedersen, J. Spangenberg, Stability and deformations of deposited layers in material extrusion additive manufacturing, *Additive Manufacturing* 46 (2021) 102193. <https://doi.org/10.1016/j.addma.2021.102193>
- [80] G. Rizzieri, L. Ferrara, M. Cremonesi, Numerical simulation of the extrusion and layer deposition processes in 3D concrete printing with the Particle Finite Element Method, *Comput Mech* (2023). <https://doi.org/10.1007/s00466-023-02367-y>
- [81] N. Roussel, J. Spangenberg, J. Wallevik, R. Wolfs, Numerical simulations of concrete processing: From standard formative casting to additive manufacturing, *Cement and Concrete Research* 135 (2020) 106075. <https://doi.org/10.1016/j.cemconres.2020.106075>
- [82] A. Perrot, A. Pierre, V.N. Nerella, R.J.M. Wolfs, E. Keita, S.A.O. Nair, N. Neithalath, N. Roussel, V. Mechtcherine, From analytical methods to numerical simulations: A process engineering toolbox for 3D concrete printing, *Cement and Concrete Composites* 122 (2021) 104164. <https://doi.org/10.1016/j.cemconcomp.2021.104164>
- [83] J. Kruger, S. Zeranka, G. Van Zijl, 3D concrete printing: A lower bound analytical model for buildability performance quantification, *Automation in Construction* 106 (2019) 102904. <https://doi.org/10.1016/j.autcon.2019.102904>
- [84] J. Kruger, S. Cho, S. Zeranka, C. Viljoen, G. Van Zijl, 3D concrete printer parameter optimisation for high rate digital construction avoiding plastic collapse, *Composites Part B: Engineering* 183 (2020) 107660. <https://doi.org/10.1016/j.compositesb.2019.107660>
- [85] A.S.J. Suiker, Effect of accelerated curing and layer deformations on structural failure during extrusion-based 3D printing, *Cement and Concrete Research* 151 (2022) 106586. <https://doi.org/10.1016/j.cemconres.2021.106586>
- [86] F. Bos, R. Wolfs, Z. Ahmed, T. Salet, Large Scale Testing of Digitally Fabricated Concrete (DFC) Elements, in: T. Wangler, R.J. Flatt (Eds.), *First RILEM International Conference on Concrete and Digital Fabrication - Digital Concrete 2018*, Springer International Publishing, Cham, 2019: pp. 129-147. [https://doi.org/10.1007/978-3-319-99519-9\\_12](https://doi.org/10.1007/978-3-319-99519-9_12)
- [87] R.J. Flatt, T. Wangler, On sustainability and digital fabrication with concrete, *Cement and Concrete Research* 158 (2022) 106837. <https://doi.org/10.1016/j.cemconres.2022.106837>
- [88] S. Bhattacherjee, A.S. Basavaraj, A.V. Rahul, M. Santhanam, R. Gettu, B. Panda, E. Schlangen, Y. Chen, O. Copuroglu, G. Ma, L. Wang, M.A. Basit Beigh, V. Mechtcherine, Sustainable materials for 3D concrete printing, *Cement and Concrete Composites* 122 (2021) 104156. <https://doi.org/10.1016/j.cemconcomp.2021.104156>
- [89] M.K. Mohan, A.V. Rahul, G. De Schutter, K. Van Tittelboom, Extrusion-based concrete 3D printing from a material perspective: A state-of-the-art review, *Cement and Concrete Composites* 115 (2021) 103855. <https://doi.org/10.1016/j.cemconcomp.2020.103855>
- [90] G. Bai, L. Wang, G. Ma, J. Sanjayan, M. Bai, 3D printing eco-friendly concrete containing under-utilised and waste solids as aggregates, *Cement and Concrete Composites* 120 (2021) 104037. <https://doi.org/10.1016/j.cemconcomp.2021.104037>
- [91] O. Şahin, H. İlcan, A.T. Ateşli, A. Kul, G. Yıldırım, M. Şahmaran, Construction and demolition waste-based geopolymers suited for use in 3-dimensional additive manufacturing, *Cement and Concrete Composites* 121 (2021) 104088. <https://doi.org/10.1016/j.cemconcomp.2021.104088>
- [92] A. Perrot, Y. Jacquet, J.F. Caron, R. Mesnil, N. Ducoilombier, V. De Bono, J. Sanjayan, S. Ramakrishnan, H. Kloft, J. Gossler, S. Muthukrishnan, V. Mechtcherine, T. Wangler, J.L. Provis, K. Dörfler, E. Krakovska, N. Roussel, E. Keita, Snapshot on 3D printing with alternative binders and materials: Earth, geopolymers, gypsum and low carbon concrete, *Cement and Concrete Research* 185 (2024) 107651. <https://doi.org/10.1016/j.cemconres.2024.107651>
- [93] M. Bayat, O. Zinovieva, F. Ferrari, C. Ayas, M. Langelaar, J. Spangenberg, R. Salajeghe, K. Poullos, S. Mohanty, O. Sigmund, J. Hattel, Holistic computational design within additive manufacturing through topology optimization combined with multiphysics multi-scale materials and process modelling, *Progress in Materials Science* 138 (2023) 101129. <https://doi.org/10.1016/j.pmatsci.2023.101129>
- [94] M. Bi, P. Tran, L. Xia, G. Ma, Y.M. Xie, Topology optimization for 3D concrete printing with various manufacturing constraints, *Additive Manufacturing* 57 (2022) 102982. <https://doi.org/10.1016/j.addma.2022.102982>
- [95] G. Vantghem, W. De Corte, E. Shakour, O. Amir, 3D printing of a post-tensioned concrete girder designed by topology optimization, *Automation in Construction* 112 (2020) 103084. <https://doi.org/10.1016/j.autcon.2020.103084>
- [96] L. Gebhard, J. Mata-Falcón, R. Ammann, N. Preßmair, B. Kromoser, C. Menna, A. Baghdadi, H. Kloft, M. Gabriel, M. Walch, W. Kaufmann, Enhancing structural efficiency with digital concrete - Principles, opportunities and case studies, *Cement and Concrete Research* 185 (2024) 107645. <https://doi.org/10.1016/j.cemconres.2024.107645>
- [97] L. Breseghello, H. Hajikarimian, R. Naboni, 3DLightSlab. Design to 3D concrete printing workflow for stress-driven ribbed slabs, *Journal of Building Engineering* 91 (2024) 109573. <https://doi.org/10.1016/j.jobe.2024.109573>
- [98] D. Lowke, A. Anton, R. Buswell, S.E. Jenny, R.J. Flatt, E.L. Fritschi, N. Hack, I. Mai, M. Popescu, H. Kloft, Digital fabrication with concrete beyond horizontal planar layers, *Cement and Concrete Research* 186 (2024) 107663. <https://doi.org/10.1016/j.cemconres.2024.107663>
- [99] P. Bischof, J. Mata-Falcón, J. Burger, L. Gebhard, W. Kaufmann, Experimental exploration of digitally fabricated connections for structural concrete, *Engineering Structures* 285 (2023) 115994. <https://doi.org/10.1016/j.engstruct.2023.115994>
- [100] J.-P. Lanwer, H. Weigel, A. Baghdadi, M. Empelmann, H. Kloft, Jointing Principles in AMC-Part 1: Design and Preparation of Dry Joints, *Applied Sciences* 12 (2022) 4138. <https://doi.org/10.3390/app12094138>
- [101] D. Asprone, C. Menna, F.P. Bos, T.A.M. Salet, J. Mata-Falcón, W. Kaufmann, Rethinking reinforcement for digital fabrication with concrete, *Cement and Concrete Research* 112 (2018) 111-121. <https://doi.org/10.1016/j.cemconres.2018.05.020>
- [102] V. Mechtcherine, R. Buswell, H. Kloft, F.P. Bos, N. Hack, R. Wolfs, J. Sanjayan, B. Nematollahi, E. Ivaniuk, T. Neef, Integrating reinforcement in digital fabrication with concrete: A review and classification framework, *Cement and Concrete Composites* 119 (2021) 103964. <https://doi.org/10.1016/j.cemconcomp.2021.103964>

- 
- [103] H. Kloft, M. Empelmann, N. Hack, E. Herrmann, D. Lowke, Reinforcement strategies for 3d concrete printing, *Civil Engineering Design 2* (2020) 131-139.  
<https://doi.org/10.1002/cend.202000022>