ARTICLE IN PRESS

Cement and Concrete Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Vision of 3D printing with concrete — Technical, economic and environmental potentials

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ABSTRACT

A vision is presented on 3D printing with concrete, considering technical, economic and environmental aspects. Although several showcases of 3D printed concrete structures are available worldwide, many challenges remain at the technical and processing level. Currently available high-performance cement-based materials cannot be directly 3D printed, because of inadequate rheological and stiffening properties. Active rheology control (ARC) and active stiffening control (ASC) will provide new ways of extending the material palette for 3D printing applications. From an economic point of view, digitally manufactured concrete (DFC) will induce changes in the stakeholders as well as in the cost structure. Although it is currently too ambitious to quantitatively present the cost structure, DFC presents many potential opportunities to increase cost-effectiveness of construction processes. The environmental impact of 3D printing with concrete has to be seen in relation to the shape complexity of the structure. Implementing structural optimization as well as functional hybridization as design strategies allows the use of material only where is structurally or functionally needed. This design optimization increases shape complexity, but also reduces material use in DFC. As a result, it is expected that for structures with the same functionality, DFC will environmentally perform better over the entire service life in comparison with conventionally produced concrete structures.

1. Introduction

3D printing is getting an exponentially increasing attention nowadays. In some industries, additive manufacturing and rapid prototyping are a daily reality already. In other industries, including construction industry, some showcase examples are available (e.g. Smart Dynamic Concrete, XTree, TotalKustom, WinSun), but daily practice still seems far away. This comes from the fact that construction industry is risk adverse and conservative in its practice but also because there are some technical, economic and social challenges that need to be overcome to unlock and trigger all opportunities from 3D printing in building sector. Gibson et al. [1] introduce the concepts and challenges for extrusion-based 3D manufacturing. For successful 3D printing, high-quality final properties have to be targeted, further considering that the material needs to successfully go through a "liquid" stage (fresh material flowing towards and in the print head) and a "solidification" process (transition to a rigid material supporting self-weight and subsequently added layers).

Considering the specific rheological properties of self-compacting concrete (SCC) [2], automated casting operations become more and more realistic. The development of SCC has led to the introduction of fundamental rheological research in concrete science, as illustrated by Roussel [3]. As stated by Shah in his recent '*future research needs*' paper [4], "*… research in the rheology of SCC is a key to increasing SCC versatility in construction and utility in various construction types*". This research goes beyond basic rheological parameters such as viscosity and yield stress, and needs to include complex behaviour such as thixotropy "*… because of its benefits, such as […] timely green strength and shape stability in slip-form construction …*". Several approaches for 3D printing of concrete exist (e.g. contour crafting [5], D-shape [6], smart dynamic casting [7]), with the most popular and promising ones considering extrusion-based processing, producing elements or layers that have to be self-supporting.

In a first stage, the material needs to be fluid, in order to be easily pumped towards the printing unit, and in order to properly compact and fully fill the print volume during the time the concrete is still supported by the print head. However, as soon as the print head is no longer supporting the material, the concrete should be stiff enough. Significant yield stress is needed, in combination with adequate thixotropic behaviour. Well-chosen additions (e.g. clay powders) and admixtures can help to achieve the desired level of thixotropic behaviour, without impairing the high fluidity of fresh concrete while in motion [8]. As soon as the printed concrete is in its final position, the yield stress temporarily provides enough stiffness to ensure shape stability of

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https://doi.org/10.1016/j.cemconres.2018.06.001
Received 6 November 2017; Received in revised form 4 June 2018; Accepted 6 June 2018
0008-8846/

Please cite this article as: De Schutter, G., Cement and Concrete Research (2018), https://doi.org/10.1016/j.cemconres.2018.06.001

an individual layer, while the thixotropy should ensure the shape stability of collective layers following in the process of additive manufacturing. However, with increasing number of printed layers, further and speedier increase in stiffness and strength is needed to ensure the shape and buckling stability of the growing structural element. Therefore, the hydration process should proceed soon enough in order to provide a load-bearing internal skeleton of solid hydration products [9,10]. The printed volume should not be prone to shrinkage cracking (plastic shrinkage is of a particular relevance here, since there is no formwork to protect the freshly placed concrete against desiccation). The final result should reach required mechanical properties (including bond to previous layers) and durability performance. The entire 3D printing process should be technically sound and cost-effective, and should be in line with modern environmental considerations. It is noteworthy that the rate of printing defines the economic potentials and should be harmoniously controlled, balancing both early strength and ability to avoid cold-joints.

This paper presents a vision for future concrete 3D printing industries. The vision includes challenging scientific and technical ideas to better control the transient phases of flowing and stiffening of the printed material, in view of obtaining targeted high-level final quality. The presented vision further includes the interesting economic potential and process aspects, as well as an appealing view on environmental benefits. The contents of the paper is based on emerging scientific results and studies, hoping to reveal a glimpse of what could be a future-proof 3D printing approach in concrete industries.

2. Technical challenges

2.1. Material choice

A major current obstacle in view of advanced 3D printing in construction industries is the very limited material palette currently available in practice. Many current showcases are not based on high-quality materials required to reach a reasonable service live in natural or industrial exposure conditions. They are rather narrowly based on the technological issue of being able to add layers on top of each other without premature collapse. When checking material performance in some showcases in more detail, striking insufficient performance can sometimes be noticed, e.g. related to shrinkage cracking as shown in Fig. 1 for the situation of an early showcase of 3D printed mortar structural element with an excessive degree of shrinkage cracking. It is currently well understood that shrinkage cracking has to be well controlled by a combination of appropriate mix design and efficient curing measures. Current printing operations normally avoid significant shrinkage cracking as shown in Figure 1. Nevertheless, the issue of

Fig. 1. Excessive shrinkage cracking in an early showcase 3D printing mortar element, as an example of 'bad practice'.
(Courtesy G. De Schutter.)

appropriate curing of 3D printed elements or structures, in absence of formwork from the beginning, remains a technical challenge requiring further optimization.

The current focus on material properties (mechanical, durability) is still limited, although several groups recently initiated major research steps in this respect. The challenge still seems to be the transformation of available high-quality cementitious materials, specifically also concrete materials complying with valid structural concrete codes, to printable materials, so that we can move from formwork-based technologies to more automated additive manufacturing approaches. Fundamental approaches are followed to modify the mix design e.g. in view of modifying the particle clustering and structural build-up at micrometer level [11]. Intense work on admixture development to get the desired material performance has been done recently [10]. The detailed control of rheological properties allow to develop a structural buildup of the building element when material is combined with the right technical set up to support and adapt itself to material evolution [9]. Although these developments are promising and have already been implemented on the field, they are quite sensitive to the physico-chemical composition of the mix. A change in the cement type, or aggregate nature might require a new adaptation of the concrete mix design and admixture type. This hinders the scale up possibilities as it is not straightforward to transfer knowledge and development. However, a more robust approach is to actively control rheology and stiffening in real time during production.

2.2. Active control of rheology and stiffening

The problem while placing concrete is that the rheological properties cannot be actively adjusted during the casting process. Based on mix design and mixing procedure, the concrete will show its particular rheological behaviour, only further influenced by environmental conditions and duration of the casting process.

A fundamentally new way will be to actively control rheology and stiffening of the fresh cementitious material, as currently studied in the ERC Advanced Grant 'SmartCast' project [12]. The main objective of 'SmartCast' is to develop concrete with actively controllable rheology and stiffening, in order to automate and optimize concrete casting operations. The principle of Active Stiffening Control (ASC) and Active Rheology Control (ARC) can already be demonstrated with available materials. The following initial results illustrate the concepts using magnetic particles and magnetic fields. A responsive paste ingredient might contribute to the paste stiffness by aligning itself with the magnetic field lines, forming a more rigid or entangled structure. In case of magnetic particles, a rigid network structure is expected to contribute to the shear resistance of the paste, making this particle-field combination a prime method to arrest paste flow.

The feasibility of this method depends on the relation between the applied magnetic field strength and the dosage of magnetic particles. It is unclear how the dosage affects the immediate rheological response to the field and whether there are any lasting effects due to earlier magnetization periods. To that end, two pastes were prepared of CEM I 42.5 N (W/C 0,35) with and without an additional 5% (of cement weight) of magnetic particles (FeO). The pastes were both exposed to the same series of subsequent magnetic field strengths (i.e. 0 T, 0.34 T, 0.76 T, 0 T) without leaving the rheometer. The equipment used was a rotational rheometer (MCR 301, Anton Paar, Graz, Austria) combined with its magnetic rheological cell (MRD 70/1 T). In the cell, a typical parallel plate (20 mm diameter) measurement can be performed while the strength of a vertical magnetic field can be varied. A gap width of 1mm was maintained between the plates and the temperature was kept constant at 20 °C. Drying of the cement paste was prevented by sealing the exposed side of the paste with a lightweight silicon oil (10 mPas). The tests started when pastes were at the age of 15 min after mixing.

In Fig. 2 the storage modulus is shown for the cement pastes with and without 5% of magnetic particles. The magnetic field strengths