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Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing

R.J.M. Wolfs*, F.P. Bos, T.A.M. Salet

Department of the Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands

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A B S T R A C T

A numerical model was developed to analyse the mechanical behaviour of fresh, 3D printed concrete, in the range of 0 to 90 min after material deposition. The model was based on a time-dependent Mohr-Coulomb failure criterion and linear stress-strain behaviour up to failure. An experimental program, consisting of unconfined uniaxial compression tests and direct shear tests, was set-up and performed to obtain the required material properties. The material tests showed that the Young's modulus and cohesion linearly increase with fresh concrete age, as do the compressive and shear strength. The Poisson's ratio and angle of internal friction, on the other hand, remain constant. Subsequently, the model was validated by comparison to printing experiments. Modelling of the printed samples reproduced the experimental results qualitatively, but the quantitative agreement with the print experiments could be improved. However, the deviations can well be explained and the type of failure-deformation mode was predicted accurately.

1. Introduction

For some decades now, the construction industry has gradually moved towards a digitalization of processes. In the design phase, architects work in a digital environment, and engineers have adopted numerical tools for structural analyses. Data exchange using Building Information Models (BIM), which allow automated design evaluation, has become standard in many practices. Consequently, automation in the construction phase is becoming more common, as illustrated by e.g. advanced prefab and precast industries. More recently, explorations have started into new, additive manufacturing techniques for the construction industry. Many construction materials can be used with various 3D printing methods to manufacture objects ranging in scale from connection elements, to components, to complete buildings. Although 3D print techniques for e.g. ceramics, steel, polymers, foams, glass, or concrete are still in different stages of Technology Readiness Level, their potential in terms of design optimization and customization is becoming increasingly clear [1–5].

3D Concrete printing is one of the areas which is rapidly developing, as illustrated by the high frequency in which new projects are being presented by a growing number of private enterprises and research institutes worldwide [6–9]. These projects still have a case study character: they showcase the possibilities of what could be printed. However, a fundamental understanding of the particularities of the print process and its relation to the properties of the printed product has yet to be developed.

An obvious path of research for 3D concrete printing focuses on the final, hardened printed product, including the interface strength between layers, which is expected to deteriorate for larger interval times between layers [10]. Le et al. [11] discuss a reduction in bond strength between layers as the printing time gap increases, whereas Duballet et al. [12] report a toolpath dependent failure mode in printed specimens.

However, there is an additional, new phase that needs to be addressed: the mechanical behaviour during the 3D printing process. While printing, layers of concrete are deposited on top of each other without the presence of formwork to confine and stabilize the material. The fresh concrete should therefore be sufficiently strong, stiff, and stable to carry its self-weight and the weight of the layers above it, and limit deformations.

First experiences with 3D concrete printing by the authors [5,13] and other research institutes [14,15] have shown that both the printability (i.e. the structural integrity of the object during printing) and the post-print properties (e.g. interface strength) are highly dependent on print process parameters, such as time, temperature, kinematics etc. This has resulted in premature object failures during printing as well as variations in quality of the printed product.

The process-product dependency is also known from 3D printing processes used in other industries. For instance, Dunbar et al. [16] identify a number of build failures that can occur in laser powder bed fusion (LPBF) due to residual thermal stresses, including layer

* Corresponding author.
E-mail address: r.j.m.wolfs@tue.nl (R.J.M. Wolfs).

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delamination, post-build distortions, and more. To be able to accurately predict print product quality (during and after printing) and avoid failures (in other words: obtain a robust print process), extensive finite element-based methods have been developed to model the printing process, including transient behaviour such as time dependencies.

For 3D concrete printing, however, such a virtual production tool has hitherto been non-existent. For low-cost/crude-quality applications, the necessity of such a tool could be debated. But when aiming to compete with existing high-quality manufacturing methods generally associated with prefabricated concrete, it is indispensable. Therefore, this study presents an experimentally validated modelling method of the 3D concrete printing process to assess the printability, based on perhaps the primary process-product dependency: the time-dependent development of mechanical properties of fresh concrete during printing.

Experimental results [17,18] and an analytical framework on fresh printed concrete [19] provide a starting point. However, these concern a purely strength-based failure criterion, whereas in-print failures are also often initiated by loss of stability, as observed in a range of (largely unpublished) printing experiments. Besides, layers may not be stacked exactly on top of each other, either on purpose (cantilevering objects), or due to imperfections/vibrations in the printing process. The printing process itself is not necessarily a constant one, as stops may occur or the printing strategy may change from layer to layer. Additionally, concerning multi material printing or filling the printed structure with a secondary material while printing, stresses may occur not exclusively in vertical direction. In these cases the critical layer is no longer the one with the highest loading, i.e. the initial layer, and an analytical strength-based criterion no longer holds. Any approach should thus be based on the development of both the mechanical properties (including stiffness), and the 3D geometry of the printed object over time.

Developing and validating a modelling method for 3D concrete printing presents four major challenges. First, a suitable material failure model has to be selected. Conventional experiments and analyses on fresh concrete generally focus on concrete in a dynamic state, in relation to e.g. pumpability or filling of formworks. These theories do not hold for fresh 3D printed concrete, which is in a static state after extrusion. Therefore a model was adopted for the state of the material directly after printing, i.e. in between a Bingham fluid and a proper solid. Secondly, specific experimental methods, based on geotechnical test methods of soils, had to be devised to determine the relevant material properties. Once the tests had been carried out, a FE-model was developed as a third step, using the commercially available Abaqus FE-code. It was used to model the material tests and evaluate the results, which proved to be in very close agreement with the experimental results. Finally, a 3D concrete print was modelled with the developed method and validated by comparing the results to actual prints of the same design. This involved development of custom optical measuring methods to track the object behaviour during printing and allow for comparison to the FE-results. Although the quantitative agreement could be improved, the qualitative similarity between the experimental and numerical results already is striking.

2. Modelling parameters for 3D printed concrete

3D concrete printing generally requires a low- to zero-slump material to maintain shape and position after deposition. In this research, a custom designed printable concrete mix was applied as described by [5], containing Portland cement (CEM I 52.5 R), siliceous aggregate with a maximum particle size of 1 mm, limestone filler, additives, rheology modifiers and a small amount of polypropylene (PP) fibers. Fig. 1 shows a close up of the concrete during printing.

The shape stability is also an essential property for other concrete construction processes in which the material is loaded in the dormant period, like slip forming [20,21]. The 'green strength' which allows fresh concrete to carry its own weight immediately after mixing or compacting, is attributed to a combined inter particle friction, and cohesion [22]. This mechanical behaviour is similar to that of soils, and as such a Mohr-Coulomb yield criterion is proposed by [23–26], and likewise adopted in the present study, albeit in an expanded form to include time dependent development of the material properties, as given in Eq. 1:

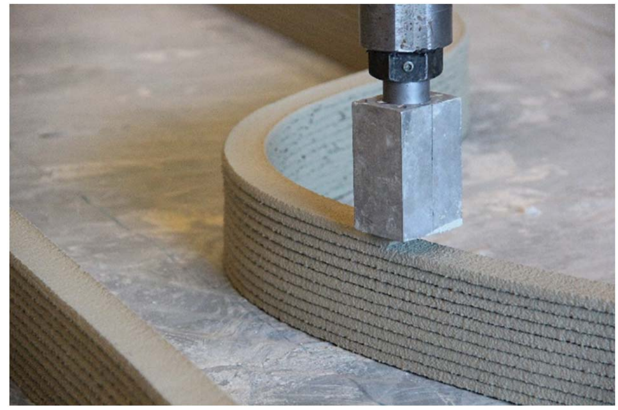

Fig. 1. Close-up of concrete filament during printing: a low- to zero-slump material is required to maintain shape and position after deposition.

$$\tau_y = C(t) + \sigma_n \cdot \tan(\varphi(t)) \tag{1}$$

where C is the cohesion between particles bonded by cement, and φ is the angle of internal friction caused by the frictional resistance and interlocking between internal particles, both of which may be time dependent. The shear yield stress and acting normal stress are given by τ_y and σ_n, respectively.

Two competing time dependent processes during printing determine structural failure of a printed object: the increasing strength and stiffness caused by thixotropic build-up of the concrete [27,28] needs to keep up with the gradually increasing load as more layers are deposited on each other. The latter effect can be incorporated in the numerical model by stepwise load increments, whereas the former is accounted for by updating the yield criterion over time. Experimental findings presented by [29–31] have shown the thixotropic build-up causes the Mohr-Coulomb parameters to evolve significantly within the time frame of a typical printing process. Consequently, the parameters $C(t)$ and $\varphi(t)$ have been established experimentally in this study through direct shear tests on specimens of different age.

However, since print object failures are often stability-driven, the stress-strain relation before failure also was established to determine the stiffness, taken as the tangent Young's modulus $E(t)$, and Poisson ratio $\nu(t)$. These parameters are both needed to model the object response before yielding. As the direct shear test is unsuitable to obtain these due to the non-uniform stress distribution in the sample, an unconfined compression test was adopted. Both experiments are discussed in the next section.

A print object is considered failed when the yield stress is reached at any point in the object, as it will likely coincide with extensive deformations, progressive collapse, and cracking. Therefore, complex post-yield phenomena like viscous behaviour and dilatancy effects have not been established experimentally. Rather, a dilatancy angle ψ has been assumed merely in order to avoid abortion of the numerical analysis when the yield stress is (locally) exceeded, as discussed further in Section 3.3.3.

3. Experimental program

An experimental program is designed to define the Mohr-Coulomb parameters, and strength and stiffness development of fresh 3D printed concrete. Similar to [17,29,32,33] the authors adopted geotechnical