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The role of early age structural build-up in digital fabrication with concrete

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ABSTRACT

The advent of digital fabrication for concrete calls for advancing our understanding of the entanglement of processing technology, rheology, admixture use and hydration control, in addition to developing novel measurement and control techniques. We provide an overview of recently proposed building processes, defining the type and range of yield stress evolution that they require for successful building. In doing so, we explain which mechanisms are at stake and how their consequences can be measured.

Controlling the structural build-up of concrete with the precision required by digital processes will be at the heart of future progress. For this, chemically controlling cement hydration of concrete is essential and we provide an overview of admixtures, focusing on "set on demand" solutions, concluding that activators should be added as closely to the delivery point as possible. Advantages and limitations are discussed and showcased using recent successes in process scaling and material and process control.

1. Introduction

Digitalisation is reaching out to revolutionise a host of industries, among them the construction industry and concrete technology. No longer limited to the rapid prototyping of small scale models, additive manufacturing is now being realized in construction scale applications [1,2]. Digitalisation in concrete technology comes with the promise of integration of design, planning and construction processes as well as increased automation and rationalisation of building processes [3], savings on labour costs and formwork and increased workspace safety [4,5]. Additionally, the use of robots can compensate for the increased difficulty in precisely materialising the non-standard complex geometries that architects can design and plan with their panoply of digital design tools [6]. The extension of what we can imagine, design and plan has opened up a highly innovative playground for new and rethought building processes with new challenges for concrete processing and early age mechanics.

In this new age, concrete pumping will be the backbone of automation in construction. High-resolution geometrical features and low precisely controlled process rates will limit the maximum aggregate size, by limiting the cross-sections of pumping systems and extruders. Concrete compositions will thus have higher proportions of matrix material and the limited aggregate size will reduce the aggregate packing fraction further [7]. Optimising material use, eliminating formworks or integrating additional functionality into building elements can however offset the induced additional material costs [8].

Faced with automation, the need for precise placing, and limitations of traditional formworks, the paradigms "Harder, Better, Faster, Stronger" formerly at the heart of technological development and linked primarily to hardened concrete properties are now complemented by the new paradigms of precision, control, resilience and compliance, linked overwhelmingly to processing and fresh concrete properties.

This means that the efforts in bringing the up-and-coming building processes, as described in the following section 2.1, into practical use will revolve around *precisely controlling* concrete processing, flow behaviour, placing, activation and hardening, ensuring *resilience* of the building processes and of the material against deterioration and *complying* with building codes (especially incorporation of reinforcement) [9], process boundaries and economical considerations.

This paper provides an overview of recently proposed building processes, their requirements of yield stress evolution, how such evolutions can be measured and which physico-chemical mechanisms are underlying them. In addition the paper shows levers to modify yield stress evolution and discusses practical consequences for the design of these digital building processes.

2. Types of material evolution in digital fabrication

2.1. Building processes in digital fabrication

The technologies associated with digital fabrication, of which a

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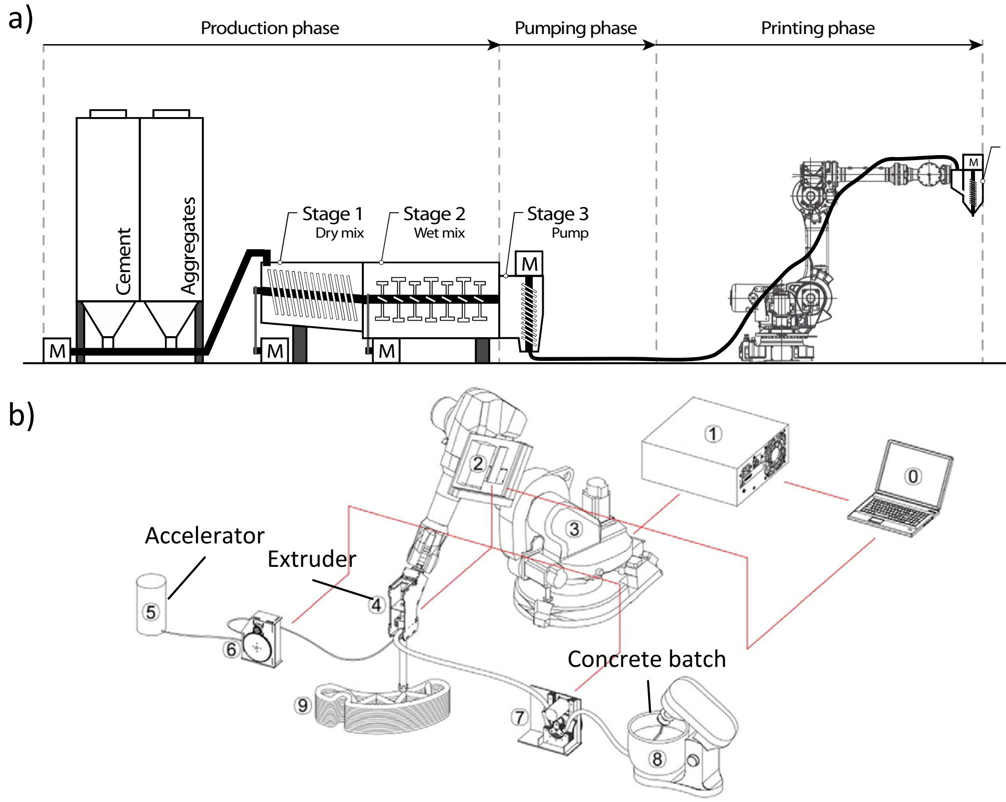

Fig. 1. Setups to control concrete hardening for layered extrusion.
a) Setup in which hardening is controlled by continuous concrete preparation and pumping, controlling the age at the extruder. Reproduced from [85], with permission.
b) Setup in which hardening is controlled by continuously pumping concrete from a batch and an accelerator into an extruder tool, in which they are mixed before exiting the nozzle. Reproduced from [14] with permission.

summary can be found in [10] pose particular new challenges for control of rheology [7]. Some of these new technologies, in particular 3d-printing by layered extrusion, slipforming and form filling in weak formworks, additionally require the concrete to quickly become self-supporting upon placing (at rest), in order to keep the shape stability or limit formwork pressure.

In the case of layered extrusion (also known by the names Contour Crafting, 3d concrete printing or cementitious ink printing), layers of concrete, mortar or cement paste are extruded and placed by means of an actuated gantry or robotic arm [3,11–14]. The concrete is required to stay in place instantaneously upon extrusion and to build enough strength to sustain the subsequently placed layers on top of it. Setups featuring methods to control hardening rates are illustrated in Fig. 1.

In the case of slipforming (also called Smart Dynamic Casting when digitally controlled), a self-compacting concrete is cast into an actuated formwork that is lifted during filling [15]. Upon placing, the concrete should spread evenly inside the formwork, without segregating, bleeding or layering. Then, the placed concrete must gain strength and be strong enough to support the mass above it by the time it is released from the upward moving formwork [16]. A setup featuring a method to control hardening rates for slipforming is illustrated in Fig. 2.

The only physical differences in terms of concrete processing characteristics are that, in layered extrusion, the concrete is at rest from the time of extrusion and self-supporting immediately, while, in slipforming, it is at rest from the time of casting and self-supporting when exiting the formwork. In terms of technological process characteristics however, layered extrusion is a pressure driven extrusion process, while slipforming is a gravity driven one, with respective major benefits to freedom of shape for layered extrusion and the possibility to insert reinforcement through the open top of the formwork for slipforming.

When it comes to filling formworks, recent developments indicate the interest to fill concrete or grout into formworks produced with other additive manufacturing techniques such as binder jetting [7,17], fused deposition modelling [18] or concrete with textiles [19]. This provides a means to integrate reinforcement, eliminate possible layering issues and ultimately obtain a concrete element more similar mechanically and durability-wise to one built with non-digital processes, thus facilitating acceptance with respect to existing building codes. When these formworks are weak, the pressure exerted on the formwork by the cast concrete can break them. One possibility to solve this challenge is to limit the formwork pressure by slowly casting a thixotropic concrete [20].

2.2. *Macroscopic buildup requirements*

In all of the above applications and as illustrated in Fig. 3, the concrete yield stress/strength should evolve faster than the hydrostatic pressure of subsequently placed concrete. In layered extrusion and slipforming one would generally target constant vertical building rates. Thus, the yield stress should at least evolve linearly over time throughout the timescale of construction, with a similar evolution for every layer with respect to the time of placing (unless the contour length changes significantly with height). This requirement is elaborated below first for layered extrusion and then slipforming.

In layered extrusion the yield stress for a single layer at the time of extrusion should be at least in the range of 150 Pa, sufficient to self-support a typical layer height of 1 cm and prevent flow off. For every layer placed on top, the yield stress should increase at least according to the additional weight, in order to prevent flow out of the lower layers [7,10,21]. If the yield stress of the first layer is substantially above the