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Hydration and rheology control of concrete for digital fabrication: Potential admixtures and cement chemistry

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A B S T R A C T

Concrete digital fabrication is an innovative construction approach where infrastructural elements can be built additively without using formwork. This represents a significant advantage, but also introduces materials engineering challenges, as the requirements normally fulfilled by the formwork are now imposed on the concrete. In this paper, it is discussed how admixtures can be employed to achieve the rheological and hydration properties necessary for printable concrete. An overview of various admixtures currently implemented in standard practice is presented. Then, the main required concrete states for extrusion and deposition processes are analyzed with respect to required performances and potential admixtures. Finally, possible side effects and incompatibilities are discussed, as well as how they could be unconventionally used for printable concrete purposes. The main objective is to demonstrate how admixtures will be critical in the development of concrete systems to realize digital fabrication, and to ultimately motivate investigation in the key areas discussed.

1. Introduction

The use of concrete in construction has primarily been limited to static and standardized formwork casting, where fresh concrete is poured into formwork, often vibrated to allow sufficient placement, and left to set. In standard practice, it is expected that concrete reaches sufficient strength a day later, at which time the formwork is stripped and the hardening concrete is cured to sustain hydration. The properties of the fresh mix, which are workability, compactibility, and resistance to segregation, are generally controlled or fine-tuned through the use of admixtures to facilitate the casting process. On the other hand, admixtures also allow the control of the hydration kinetics of the mix: first to avoid premature setting during transport or placement, and second for the formwork to be removed on time. In general, admixtures have contributed to numerous essential developments in concrete technology [1] and will continue to do so in novel approaches that are part of the emerging concrete digital fabrication [2,3].

Digital fabrication with concrete is a family of novel fabrication processes that offers greater freedom of shape by combining computer-aided design with additive, subtractive or forming manufacturing [3–7]. Many approaches exist, but this paper focuses on those that allow structures to be built additively and thereby eliminate the need for formwork. This mainly concerns extrusion printing, although other techniques, such as slip casting or spraying, could also benefit from the concepts presented in this analysis.

Building without formworks introduces a number of advantages, namely savings in cost, time, and materials associated with formwork construction. However, at the same time, it implies some significant materials engineering challenges as all the requirements that are normally fulfilled by the formwork are now directly imposed on the mix design of the concrete and the way it is deposited. Therefore, in absence of formwork, controlling the hydration and rheological properties becomes even more critical for successful execution [4]. Hydration kinetics must be delayed and accelerated in relatively extreme manners so that the material does not set during the printing process but, instead, right after deposition in order to support its own weight and that of subsequently deposited layers of material [8,9]. Concerning rheology, there must be a balance between flowability during printing and rate of structuration immediately after deposition. In addition, given the time-sensitive nature of the technique due to the continuous progression of hydration, prediction of flow rate is important to control the printing speed.

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The aim of this paper is to discuss how various admixtures can be employed to achieve the desired properties for successful additive manufacturing, from the pumping and deposition characteristics to the hardening and curing stage. The key rheological and hydration properties for overcoming the challenges of form-free casting are presented along with required performance properties and potential use of admixtures. This includes the description of suitable chemical and mineral admixtures, their attributes and potential side effects with respect to cement hydration, as well as their possible incompatible combinations. While this paper mainly focuses on chemical aspects and working mechanisms on the physico-chemical level, complementary information with a focus on the control of structural build-up is offered in another paper of this special issue [8]. Rheological questions are also then detailed by Roussel [10].

2. Background: rheology, cement hydration and admixtures

2.1. Rheological aspects of hydrating cementitious systems

Controlling the rheological properties, expressed in practical terms as workability, of fresh concretes is important as it will determine the efficiency of the casting process during construction. In the case of novel applications like digital fabrication, it will determine its success or failure. A standard among field-friendly methods used to quantify concrete workability is the slump test [11]. However, workability is better described through fundamental rheological parameters, primarily yield stress and plastic viscosity. Yield stress is the stress above which flow initiates, or below which flow terminates. It also determines suspension stability [12] and accounts for the results of stoppage tests, such as slump or slump flow [13,14]. Plastic viscosity describes the resistance to flow, which increases with increasing shear rate – an important parameter for robustness [15]. In addition, fresh cement-based materials exhibit thixotropy, which is a time-dependent property. It can be generally defined as the continuous decrease of apparent viscosity with time under shear and a subsequent recovery at rest [16]. However, for concretes, it is often used to describe fresh-state structural build-up, which can be quantified as an increase in yield stress over time. This, for instance, has important implications on stability and formwork filling and pressure [17–21].

In general, the rheology of concretes is affected by the mix design, including the volume fraction of the binding system, its composition (e.g. presence of supplementary cementitious materials) and attributes of the aggregates (i.e. particle size distribution and shape). Admixtures can be used as an effective tool to tailor the rheology. Superplasticizers, which act as dispersants to lower yield stress [22], and viscosity modifying agents, which increase plastic viscosity, are now regularly used in concretes to control workability [23,24]. Clays can also be used as thixotropy modifiers [25–27]. For successful additive manufacturing, it will be key to control rheology through the use of suitable admixtures, likely in combination. Most of them are considered to be chemically inert as they alter rheological properties through physical effects. However, they can induce strong physicochemical side effects, as is the case for superplasticizers that influence the rate of cement hydration [28,29]. So, in addition to the main properties of these admixtures, it is important to consider any secondary effects. Given the broader range of chemical admixtures [30], we provide here an overview that, although only concerned with additive manufacturing, remains selective and incomplete.

2.1.1. Superplasticizers

Dispersing agents and superplasticizers, such as lignosulfonate (LS), polynaphthalene sulfonate (PNS), and polycarboxylate ether (PCE), are polymeric dispersants used in cementitious materials to reduce yield stress and viscosity at a constant solids content (Fig. 1) [30–32]. The enhancement of the material workability is essential for mixing, casting and extrusion in concrete digital fabrication. Moreover, it allows for a decrease in liquid content at a constant yield stress, which can decrease the porosity of the hardened material and enhance the mechanical performance and durability [33]. Also, as many processes of digital fabrication use mix designs without coarse aggregates, the volume fraction of finer particulate fractions is increased. Bringing these closer to the maximum packing density of the mix [34] increases the apparent viscosity and is something that superplasticizers can only partially remedy.

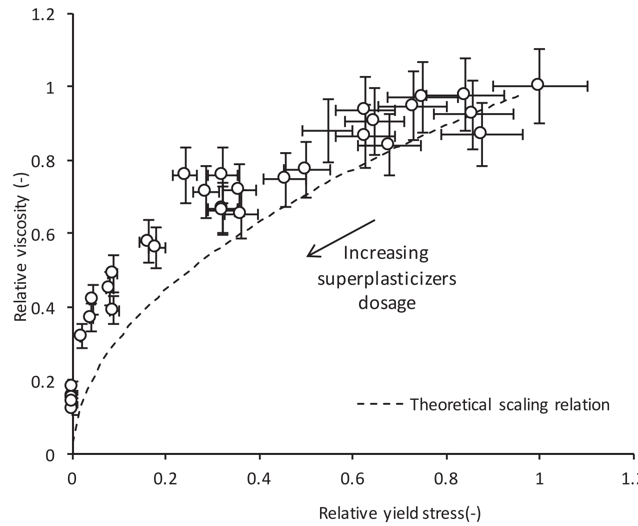

Fig. 1. Relative viscosity (i.e. the ratio between the viscosity of the paste with polymer and the viscosity of the reference paste) as a function of relative yield stress (i.e. the ratio between the yield stress of the paste with polymer and the yield stress of the reference paste). The superplasticizers are different PCEs. Adapted from [35].

LSs are natural polymers with relatively moderate water-reducing ability [36]. In current applications, these plasticizers are commonly employed for mobile concrete extrusion of roads [37]. This is due to their robustness and ability to induce moderate workability to fill the slip form, and yet maintain its shape within seconds of the initial cast as slip forms are removed. These features are of great interest for extrusion or slip forming in digital fabrication. PNSs, polymelamine sulphonates and vinyl copolymers are synthetic polymers with a higher dispersing ability than LSs [22]. Their mechanism of action is due to both their electrostatic and steric effects, and not to electrostatic effects alone as often stated in literature, particularly in the case of LSs [22,30].

The most effective superplasticizers for current use are PCEs (Fig. 2). These admixtures are comb copolymers composed of an anionic backbone on which side chains are grafted. The backbone is at the origin of the polymer adsorption on the surface of cement particles, whereas the side chains that tangle into the solution prevent close

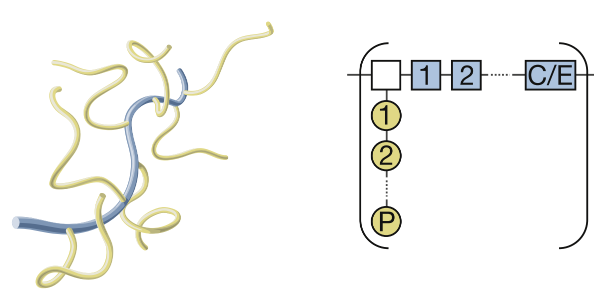

Fig. 2. Schematic representation of a PCE superplasticizer (left) with its descriptive structural parameter, *C/E*, *n* and *P* (right). *n* represents the number of side chains/repeat units in one molecule. *C/E* represents the number of carboxylate functions *C* per ester group *E* through which a side chain with *P* monomers is grafted. Adapted from [29].