Research Development in 3DCP: Cured-on-Demand with Adhesion Enhancement Delivery System

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Abstract

There are four major parameters of cementitious materials that are the key to successfully printing a 3D structure: 1) pumpability, 2) printability, 3) buildability, and 4) open time. These four parameters, however, vary from material to material (i.e., paste, mortar, geopolymer, clay, etc.). Moreover, the requirements of the aforementioned parameters are also driven by the capabilities and features of the 3D printer. Thus, there are no definite acceptable limits of these parameters as there are no 3D printer or material standards established to date. There are various types of 3D printers which have been developed by multiple parties (i.e., KKRANE in Virginia, USA, 3D Printhuset in Copenhagen, Denmark, etc) with each printer having its own unique setup and features (i.e., delivery system, pump, nozzle, etc.). Thus, having a robust 3D printing material that can accommodate various types of printers is critical. A research team at Laticrete International, Inc. has developed a prototype of 3D printing mortar which is pumpable, has a long open time preventing hardening in the delivery system, and has a controllable curing feature of (i.e., rapidly set only after the material being extruded) which makes it buildable. To prove the feasibility of this controllable curing concept, the same team has developed prototypes of a delivery system that enables rapid curing and improved bonding strength between layers.

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1. Introduction

In recent years, innovation in construction has led to more efficient, safer, and greener structures. One of the leading innovations in the area of digital fabrication and automation is building structures via 3D printing or also known as 3D construction printing (3DCP), rapid prototyping (RP) and additive manufacturing (AM). 3D printing is defined as the process of joining materials layer by layer to build objects from 3D model data [1]. In this technique, the target structure is manufactured layer by layer, based on a digital model where the material is deposited at the coordinate defined in the model [2]. Started in the 1980s, 3D printing had been successfully applied in a wide range of applications including modern product development [3], prototyping [4], aerospace and automotive industries, biomedical [5], consumer and food [6].

The application of 3DCP technique in construction enables customization of structure elements including walls, beams, columns, floors, panels, partitions, and façades with unique designs and dimensions [7–9]. This method is also reported to be more efficient in terms of the time [10–12], cost [7,10,11,13], material [7,10,11,13], and labor [14] as compared to conventional construction methods. Moreover, 3DCP promotes a safer work environment through the elimination of dangerous situations, such as the installation of structural elements at high elevations [10]. These potentials have been the main forces behind the rapid development of 3DCP in the past decade. To contribute in the area of 3DCP, a research team at Laticrete International, Inc., has developed a prototype of 3D printing mortar and a delivery system that enables the material to set rapidly after the extrusion process. Moreover, the team also developed a delivery system that can improve the interlayer bonding strength between layers.

2. Key features of 3D printing materials

The scope of this section is limited to the four key features that were reported to be essential for the 3DCP materials. These features include pumpability [9,15], printability [9] and/or extrudability [8,16], buildability [9,15], and open time [9,15]. Some measurements of these parameters are also discussed briefly in this section.

2.1. Pumpability

Pumpability is defined as the ease and reliability with which material is moved through the delivery system [9]. The pumpability of a material can be assessed by measuring some of its properties in

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a fresh state. In their study, Le at al. [15] found that mortars with a yield stress of 0.3 kPa to 0.9 kPa tend to have desirable pumpability. This finding was in agreement with the results reported by Thrane et al. [17] regarding the yield stresses of pumpable and extrudable self-consolidated concrete (SCC) which are 0.59±0.08 kPa (for mixes with CEM I and fly ash) and 0.27±0.03 kPa (for mixes containing CEM I and limestone filler). Moreover, Thrane et al. [17] also reported the plastic viscosities of the SCC mixes which are 38.7±4.5 Pa.s (for CEM I + fly ash mixes) and 21.1±2.4 Pa.s (for mixes with CEM I and limestone powder).

2.2. Printability and/or extrudability

Lim et al. [9] defined printability of a 3D printing material as its easiness and reliability to be deposited through a deposition device. Another term which is close to printability is extrudability. Extrudability is defined as a parameter that reflects a materials ability to be protruded as a continuous filament through a nozzle [8]. In their study, Ma et al. [8] evaluated the extrudability of their materials via the continuity and the stability of the extruded paste through a 8×8 mm^2 printing nozzle. The total length of the tested filament is 2,000 mm which was stacked in layers 250 mm in length [8]. By this method, a good extrudability is characterized by the length of the filament that can be extruded continuously (no breaking) and the ability of the material to maintain its stability (no segregation, no bleeding, no clogging) when being extruded through a smaller size of nozzle [8]. Le et al. [15] assessed the extrudability of their materials by evaluating the stability and continuity of filaments which were extruded through a 9 mm diameter nozzle. The material is defined as extrudable if a total length of 4,500 mm can be successfully deposited without a blockage or fracture [15].

2.3. Buildability

In the context of 3DCP, the buildability of a material is defined as its resistance to deformation under load when it is not fully cured [9]. This property is essential considering that in 3DCP, the filaments are stacked layer-by-layer by which the bottom layer sustains the weight of the upper layers. When the structure is built in a vertical orientation, as the height of the build increases, the self-weight that is sustained by the bottom layer increases [18]. It is a common practice to maintain a constant layer height during printing without considering the potential deformation of the lower layers which are compressed by the self-weight of its upper layers [18]. As this deformation

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progresses, the distance between the nozzle and the working surface increases, changing the shape of the extruded filament and contact area between the layers which potentially affects the adhesion between layers [19]. The extent of this occurrence leads to a collapsed structure [15]. There are two approaches that are suggested to alleviate this issue: 1) dynamic adjustment of the nozzle height during printing and [20], 2) increase the hardening rate which potentially could be done by injecting accelerator prior to extrusion. This will speed up the hardening process and increase the capacity of the lower layer in sustaining loads. One of the methods used to assess the buildability of fresh mortar is quantifying the number of filament layers that can be built up without noticeable deformation of the lower layers [15]. In their study, Lee et al. [15] found that the optimum buildability was achieved by a mix with a 0.55 kPa shear strength that could built up to 61 layers without collapsing. It needs to be noted that shear strength is not the only parameter that determine the buildability of a material.

2.4. Open time

The open time of a material is time interval when the aforementioned properties (i.e., pumpability, printability, and buildability) are consistent within the acceptable tolerances [9]. The end of open time is marked by the disruption in the extrusion process of the filament (i.e., the filament breaks) [8].

3. Cure-on-demand and interlayer bonding improvement systems

A prototype of cure-on-demand or controllable curing 3D printing mortar has been developed by a research team at Laticrete International, Inc. To accommodate this cure-on-demand concept, the team developed a delivery system which allows an accelerator to be delivered close to the tip of the nozzle. Moreover, the team also developed a system which enables a primer to be sprayed between layers to improve its bonding strength.

3.1. Cure-on-demand system

The set time of a material plays an important role in 3D printing cementitious materials. Sufficient open time (before the material starts gets too hard and becomes unpumpable) is required to prevent potential clogging in the delivery system (i.e., hose, pump, extruder). On the other hand, the material is expected to cure shortly after it is extruded from the delivery system. This behavior of

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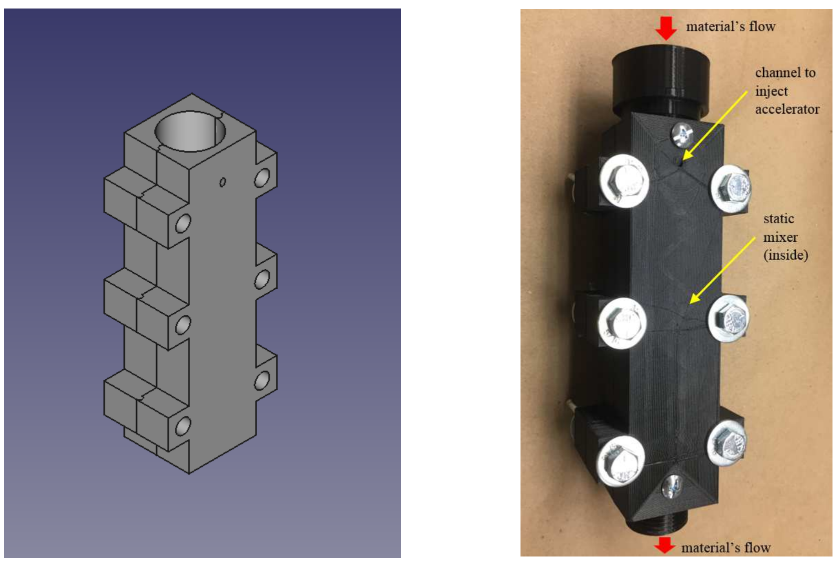
the material, to cure rapidly once extruded from the nozzle, is beneficial to assure that the material will have sufficient strength to sustain the upper layers. To address this challenge, Laticrete's team has developed a material and a delivery system which allows rapid curing (initial set within 5-20 minutes as per ASTM C226 [21]) after the material leaves the nozzle. The prototype 3D printing mortar that was developed by Laticrete's team has a long open time (more than one hour for the suggested range of water) and can be rapidly cured when it is mixed with an accelerator component. For this work, the team developed a delivery system (named prototype X1), which enables the mixing of the two components prior to extrusion. Prototype X1 consists of two channels (one for the mortar and a small channel to deliver the accelerator) and a static mixer. The 3D model and the prototype X1, developed by Laticrete's team, are presented in Figure 1 (A) and (B), respectively. The prototype X1 shown in Figure 1 (B), was conventionally 3D printed by the team.



(A) (B)

Figure 1. (A) A 3D model and (B) Prototype X1 – part of delivery system with accelerator channel and static mixer developed by Laticrete's team

By utilizing the prototype X1 as part of the delivery system as shown in Figure 1 (B), where the mortar is mixed with an accelerator close to the extruder tip, the set time of the printed mortar can be controlled by adjusting the amount and the concentration of the accelerator. As the mortar cures (as designed, within minutes after being extruded), its capacity in sustaining load imposed by the

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upper layers increases and thus, minimizes or eliminates deformation. This method, to a large extent, will negate the deformation under self-weight (especially those bottom layers) which has been reported as one of the challenges in the 3D printing-cementitious area [18]. This method also will enable a continuous printing process, since it eliminates the delay time for the bottom layer to cure. The possible drawback of this method, which is yet to be confirmed, is the potential reduced adhesion between layers. To address this issue, the team has developed a system which enables improved bonding strength between layers. The adhesion improvement method is discussed in section 3.2.

3.2. Interlayer adhesion improvement method

The process of 3DCP, where the structure is built by printing layer-by-layer of cementitious filaments (i.e., mortars), imposes a concern on the adhesion strength between layers. As the delay time between the placement of two consecutive layers increases, the adhesion (between those two layers) decreases [19,22]. This is due to the formation of cold joints which can occur when significant surface moisture of the previous layer is lost due to evaporation and chemical reaction. A study by Sanjayan et al. [13] indicated that the inter-layer bonding strength is related to the surface moisture. However, the result in this study [13] is in contrast to the widely held trend where the inter-layer bonding strength decreases as the delay time increases [22]. Laticrete's team has developed a 3DCP delivery system, which will enable improved the bonding strength between layers. This is accomplished by adding a channel which delivers (sprays) primer, a liquid chemical that is used to increase the bonding strength between substrate and underlayment, on the top of the mortar filament prior to the delivery of the next layer. This channel can be designed in such a way that it will move and spray the primer ahead of the printing nozzle which dispenses the mortar. The schematic of this part of the 3D printing delivery systemis presented in Figure 2.

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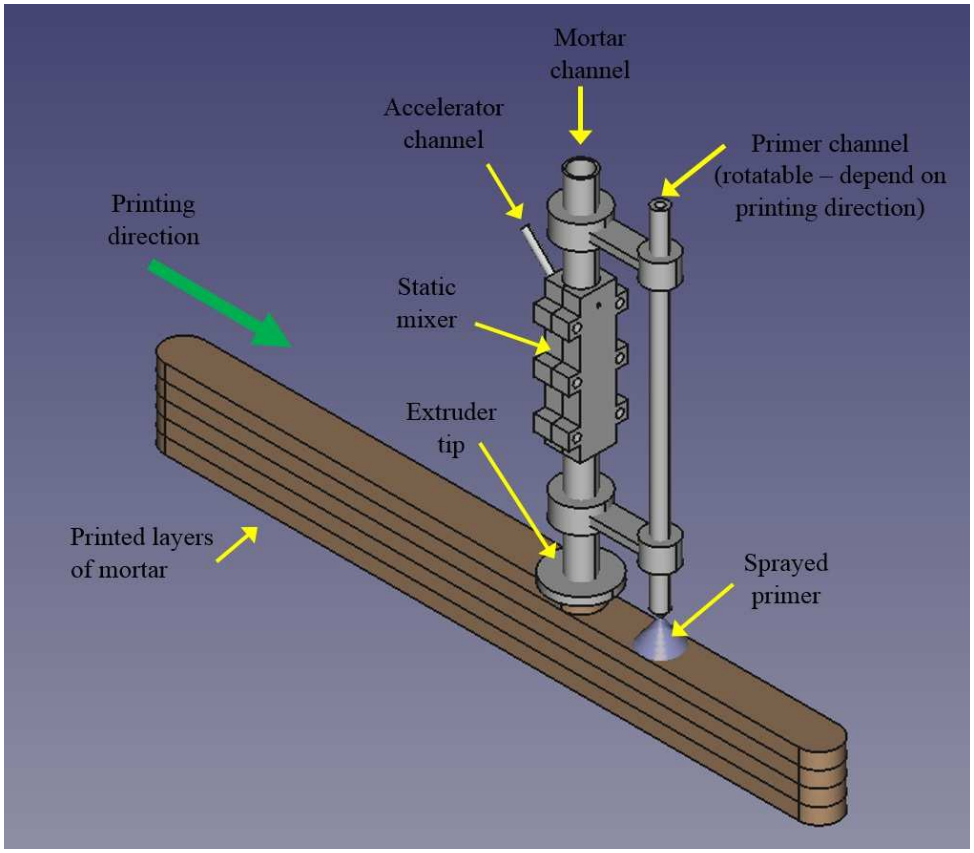

Figure 2. A schematic of cure-on-demand 3D printing mortar with adhesion enhancement delivery system

4. **Summary and future work**

The two systems, cure-on-demand, and interlayer adhesion improvement systems, developed by the team at Laticrete International, Inc., have the potential of addressing the challenges in 3DCP related to the setting time and buildability. As per date, the assessment of the feasibility of these two systems is still ongoing.

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