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Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture

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HIGHLIGHTS

- A framework for performance-based laboratory testing of printing concrete was proposed.
- A laboratory-scale linear concrete printer was built for experimental study of printing mixtures.
- Four printing mixtures were designed to study effects of Nano-clay, silica fume and fiber inclusion.
- Layer settlement and cylinder stability tests were developed to study shape stability.
- Inclusion of silica fume and Nano-clay enhance shape stability of fresh printing mixture.

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ABSTRACT

In this study, a framework for performance-based laboratory testing of cementitious mixtures for construction-scale 3D printing is developed, where workability of a fresh "printing mixture" is studied in terms of print quality, shape stability, and printability window. Print quality is described using measures of surface quality and dimensions of printed layers. Details of two proposed test methods for evaluation of shape stability, namely, "layer settlement" and "cylinder stability" are also provided. Experimental study of four different mixtures revealed that inclusion of silica fume and Nano-clay significantly enhance shape stability. The results of five conventional test methods, as well as four proposed tests are used to discuss the performance of mixtures.

1. Introduction

After facing criticism for limited adoption of cutting edge technologies for several decades, the construction industry is undergoing some profound changes now. Building Information Modelling (BIM) is gradually becoming ubiquitous, in which the essential building design and project data are generated and managed in digital format throughout the building's life cycle [1–5]. Sensing automation technology is also being used in buildings to improve energy efficiency and occupants' satisfaction [6,7]. Use of drone technology in construction sites is also reported, where drones are adopted for applications such as safety inspection [8] and 3D modelling of construction sites [9]. Moreover, the novel idea of scaling up additive manufacturing techniques for automated building construction has been topic of research for several years. Additive manufacturing is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [10]". It should be noted that additive manufacturing technologies have previously been used for concept modelling in architecture [11]. However, full-scale automated building construction would be a revolution in construction industry. A well-developed automated construction process presents numerous advantages including design freedom, superior construction speed, and higher degree of customization. Some of the well-known processes for construction-scale 3D printing include Contour Crafting, Concrete Printing, and D-shape, which are invented in the U.S., U.K., and Italy, respectively [12,13].

Invented by Dr. Behrokh Khoshnevis of University of Southern California, Contour Crafting (CC) is an additive fabrication

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technology that uses computer control to exploit the surface-forming capability of troweling in order to create smooth and accurate planar and free-form surfaces out of extruded materials [14]. CC is commonly recognized as the first viable construction-scale additive manufacturing process for building construction [15–17]. Some of important advantages of CC include unprecedented surface quality of printed elements, increased fabrication rate, and a vast choice of materials [18]. The prototype CC machine has work envelope dimensions of 5 m × 8 m × 3 m, corresponding to a 120 m^2 printing zone, and is presented in Fig. 1-a. Furthermore, in the long-term plan to colonize the moon and Mars, CC technology has been considered as a viable way for building immediate infrastructures on the surface of these planetary objects [19,20].

Another well-known construction-scale 3D printing system which was developed by researchers at Loughborough University is called "concrete printing". The concrete printing machine is composed of a 5.4 m × 4.4 m × 5.4 m frame and a printing head on a mobile horizontal-beam, which moves in the y and z directions while the printing head only moves in the x-direction [21]. The printing head is able to move up to 83 mm/s depending on the curvature of a printing path. Concrete printing process mainly includes data preparation, material preparation, delivering, and printing. Interestingly, several companies also have been recently founded based on the idea of large-scale 3D printing for construction. For instance, Apis Cor™ is a newly established company which has developed a crane concrete printer with 132 m^2 printing zone (Fig. 1-b). Based on manufacturer, the compact dimensions of printer are 4 m × 1.6 m × 1.5 m and it weighs 2 tons [22].

A review of ongoing projects and research works reveals that Portland cement concrete is the most viable option as the material for widespread use in automated construction processes in near future [22–24,16]. The major reasons are the unique fresh and hardened properties of concrete which are well-understood, as well as an extensive variety of readily available admixtures to customize its performance.

Limited research has been carried out on properties of printing concrete. In 2016, Perrot et al. [24] studied the time-dependent structural build-up of cementitious materials in layer-wise construction. This is important since during the layer-by-layer construction process, the previously deposited layers should be able to withstand the load caused by following layers. Based on comparison of vertical stress acting on the first printed layer with the critical stress related to the plastic deformation, a theoretical framework was proposed. Assuming linear evolution of yield stress over time, these researchers defined a critical failure time (t_f) as a function of concrete specific weight, concrete yield stress with no time at rest, structuration rate, construction rate and a geometric factor (α_{geom}). Finally, layer-wise construction of a 70 mm diameter column with building rates of 1.1–6.2 m/h was used to validate the findings. Except for the smallest building rate, 1.13 m/h, the experimentally measured t_f values were highly correlated with values calculated based on proposed expressions. In another study, Le et al. [23] developed a high-performance fiber reinforced printing mixture for concrete printing process. A high cementitious materials content of 827 kg/m^3 and low water/cementitious materials ratio of 0.26 was employed to achieve desirable fresh state properties and a 28-day compressive strength of 110 MPa. A shear vane apparatus was used to describe workability of printing concrete, and 0.3–0.9 kPa was suggested as the acceptable shear strength range for a printable mixture. Finally, the suitability of proposed mixture was validated by construction of a 2 m-long concrete bench, consisting of 128 filaments of 6 mm thickness.

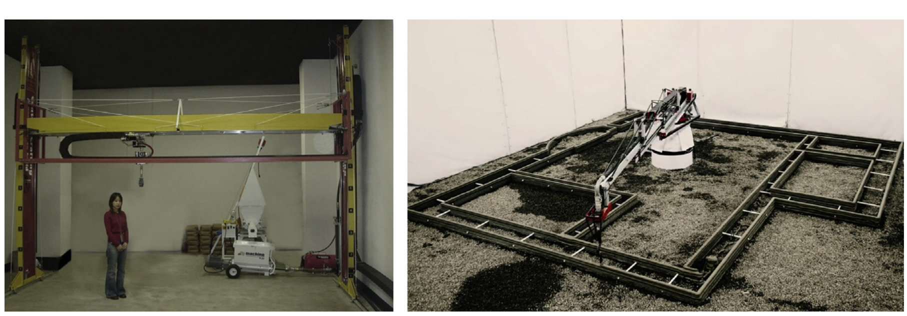
While few past studies have provided an initial understanding of some of the desirable properties of printing concrete, extensive research and experimental data is still needed. In specific, characterization of fresh state behavior of a printing mixture requires deeper investigation. It seems that the traditional definition for workability of fresh concrete as "a measure of ease by which fresh concrete can be placed and compacted [25]" is not accurate enough and new measures should be developed for describing the fresh state behavior of a printing mixture.

2. Research objectives

Perceiving "printing concrete" as the latest special concrete, there exists no relevant guideline or proposed procedure for evaluating mixtures and new materials, or any set of well-defined acceptance criteria for this type of concrete. As mentioned before, few previous studies have focused on specific properties of printing mixtures such as shape stability (also called shape retention and green strength) [24,23,26,27]. However, a comprehensive list of performance requirements and test methods for a printing mixture has not yet been suggested.

The goal of current study is to present and examine a framework for performance-based laboratory testing and evaluation of printing mixtures. It should be noted that only fresh properties of a printing mixture are considered herein, while further research is needed to investigate the structural requirements for hardened printing mixture. Development of a comprehensive framework for laboratory testing of printing concrete would be a starting point for systematic investigation on this special concrete by researchers, and a basis for future specifications and guidelines. Establishing universal acceptance criteria for printing concrete would be possible only after a large number of relevant studies have been carried out, and a reasonable amount of data is available on performance of different printing mixtures used in actual construction projects.

In this paper, the proposed framework for laboratory testing of fresh printing concrete is initially introduced and some relevant details are provided. Then, an experimental program which was



(a) (b)

Fig. 1. (a) Contour Crafting machine (b) Crane printer developed by Apis Cor™ [22].