Construction and Building Materials 174 (2018) 263–271

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Fresh properties of a novel 3D printing concrete ink

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HIGHLIGHTS

- The application study of thixotropic nano clay on novel 3D printing concrete ink.
- The buildability and rheology property of novel 3D printing concrete ink.
- The thixotropy model of novel 3D printing concrete ink is provided.
- The relationship between structure re-build and hydration heat is presented.

ARTICLE INFO

Article history:
Received 2 December 2017
Received in revised form 6 April 2018
Accepted 13 April 2018

Keywords:
3D Printing
Additive manufacturing
Clay
Thixotropy
Green strength

ABSTRACT

3D printing technique is an opportunity for the development of architecture industry altered by the emergence of 3D printing concrete ink that shows unconventional characteristics mainly originated from its geometric design. In this paper, a novel 3D printing concrete ink that has good fluidity during movement and satisfying standing behavior at static state due to the structural rebuilding of cement paste advanced by the addition of nano clay (NC) and silica fume (SF) was specially designed to be extruded through a nozzle to print layer-over-layer components for an innovative additive manufacturing process. The buildability, rheological properties (viscosity, yield stress and thixotropy), workability, green strength, open time and hydration heat of the fresh 3D printing concrete were systematically investigated. Results indicated that the buildability of this concrete with a small quantity of NC or SF were increased by 150% and 117%, respectively, and remarkably enhances the thixotropy and green strength. The double-doped NC and SF optimize the buildability.

1. Introduction

In the past few years, a new generation of concrete, such as slip form concrete [1,2] and semi flowable self-consolidating concrete [3] (SFSCC), has been attracting increasingly attention from researchers around the world. Compared with the ordinary concrete, such concrete shows the advantages: (a) excellent fluidity; (b) wonderful shape stability; (c) lower concrete formwork pressure, which are determined by its own thixotropic behavior. Thus, these advantages make the concrete a promising candidate for replacing the ordinary concrete and/or self-consolidating concrete (SCC) in architecture engineering applications.

In colloid science, thixotropy is often characterized by the consecutive decrease of viscosity with time when the sample is in a shear state that previously at rest, and the recovery of the viscosity when the shear stress disappeared. In the field of concrete, thixotropy is usually described as the structural re-building rate of the fresh paste [4,5]. Generally speaking, when cement particles meet together in a typical solution, they are free to touch, nucleation growth, flocculation, forming a lapped network, which are completely related to the hydration pace of cementitious materials [6]. As a result, flocculation structures or networks are subjected to damage when shear stress is applied but rebuild subsequently once the stress is removed. In short, a reversible path, flocculation-deflocculation-refloculation is explained as thixotropic behavior.

Thixotropic behavior-a rheological characteristic, can be also used for describing the shape stability of the fresh paste. Literatures [7] have said that such shape stability can be improved by adding a special kind of NC. Kawashima et al. [8]. found that the significant effect of a tiny quantity of NC on the cohesiveness and structural evolution of the fresh cement pastes by the tack test. Gilson et al. [3,9]. stated that a small amount of this clay addition reducing significantly formwork pressure of self-consolidating

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https://doi.org/10.1016/j.conbuildmat.2018.04.115
0950-0618/

concrete due to obtain a much higher thixotropy. Tregger et al. [10]. found that a small addition of such clay can significantly improve the green strength and microstructure of the fresh concrete. Zhuojun Quanji et al. [11]. observed that the thixotropic value of cement paste was clearly increased by adding a small amount of NC, and the results raised the optimum dosage in the cementitious materials (1–1.5% by mass). For the 3D printing concrete ink, nice standing ability, i.e. shape stability, has to be done after printing that designed to sustain the continuous layers' deposition. In this regard, replacing a small amount of cement served as 3D printing concrete ink was a suitable application for this NC. However, few literatures can be captured on the effect of NC on 3D printing concrete ink. Therefore, there is an urgent need to explore the effect of NC on the manufacture of real 3D printing architectural engineering components.

3D printing (3DP) is an emerging approach [12–14] to build concrete components employing layer deposition construction technique that influences severely on the design of the module, the data process, the manufacturing process and even the cost or business models. Shortly, all objects are created as volumetric shape through commercially available CAD software, they are drawn as a series of two-dimensional digital images in the front of computer. Afterwards, the layered manufacturing machine sequentially adds each layer to fabricate the 3D components directed by the imported data.

Design of 3D printing concrete ink with proper fluidity is critical in the first step of rapid manufacturing process, from the fresh concrete conveying process and quality control to the subsequent rapid standing behavior. The standing behavior (shape stability) of this concrete ink is primarily controlled by the microstructural evolution of cementitious materials during the first seconds after extruding and placing. Briefly, this concrete must be able to extrude consistent filaments deposited layer by layer without significant deformation or collapsing due to self-weight before setting. It both possesses some advantages of self-consolidating concrete [15–17] (i.e. avoid the use of vibrator and smaller pressure is transmitted to formwork) and sprayed concrete [18,19] (i.e. fresh concrete is conveyed from pipeline to a nozzle and generates green strength rapidly without formwork), also contains a certain merit of extruded concrete [20–22] (i.e. keep the intrinsic shape after extrusion). Some reports have been done on exploiting proper 3D printing concrete ink by this advanced technique. The use of calcium sulfoaluminate cement of 3D-printing mortars was proposed for setting [23]. A high-performance printing concrete was reported [24,25] and rapid hardening Portland cement [26] was also used to improve the weak green strength in D-Shape process. Furthermore, fiber-reinforcement [24,27–29] was placed in the slurry in order to improve flexural strength of concrete filament. Fly ash based geopolymer cement [28,30–32] is regarded as a sustainable environment material and its use in additive manufacturing. However, the potential of rapid manufacturing in the design of the novel 3D printing concrete ink is to be developed, and there are few literatures investigated from rheology standing point, especially thixotropic behavior.

In this study, the buildability, rheological behavior, workability, green strength, open time and hydration heat of the fresh 3D printing concrete were tested in the laboratory. Height of layers built were utilized to determine the buildability. Hysteresis loop test was utilized to investigate the concrete thixotropic behavior, viscosity and yield stress. The green strength and thixotropic value were performed to relate the buildability results. Isothermal calorimeter curves for the fresh 3D printing concrete were investigated to have mutual relationship between the hydration pace and the structural rebuilding rate.

2. Experimental programme and methods

2.1. Materials and mix design

Tap-water and type II 52.5 Portland cement (PC) were used in all mixes. A nano clay (NC) by grinding, calcining and refining from bulk clay ore, was selected for this study. It has been dryly or wetly ground to preserve their uniform shape and a sheet of clay particles exfoliated from the matrix clay minerals while eliminating all impurities. SF was also used in this study. Their chemical compositions and specific surface area (SSA) of SF and NC by Nitrogen adsorption method were given in Table 1. The fine aggregate (F. Agg) with a fineness modulus of 2.84 and a maximum particle size of 1 mm. The chemical admixtures were retarder agent (RA), thicker agent (TA) and polycarboxylate based high range water reducer (HRWR).

Table 2 shows five mix proportions that had a water to binder (W/B) ratio of 0.35 by mass. NC and SF were used as a partial cement substitute in the content of 2 wt%. This SF based 3D printing concrete ink presents better adhesiveness, and the pozzolanic characteristics was also guaranteed [33,34]. The water together with HRWR was added to the mixing dry components to reduce the water consumption and improve its workability as well as strength. Mixtures with a TA suitable for extrusion exhibit

Table 1
Properties of PC (Type II), SF and NC (by mass%).

Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	K_2O	SO_3	TiO_2	L.O.I	SSA (m^2/kg)
PC (Type II)	64.85	21.65	5.56	4.32	0.24	0.84	0.76	2.58	–	1.27	312
SF	0.35	95.01	0.82	1.86	–	1.24	–	0.32	–	1.58	23,092
NC	0.52	56.00	25.50	0.36	0.36	0.25	3.21	–	0.03	1.19	29,769

Table 2
Mix design for 3D printing Concrete (kg/m^3).

Material	CM	CS	CC	CCR	CCS
PC	900	882	882	882	864
HRC	0	0	18	18	18
SF	0	18	0	0	18
F. Agg	900	900	900	900	900
W/B	0.35	0.35	0.35	0.35	0.35
HRWR/%	0.26	0.26	0.26	0.26	0.26
TA/%	0.0125	0.0125	0.0125	0.0125	0.0125
RA/%	–	–	–	0.1	–