Mechanical properties of 3D printable responsive cement mortar after magnetic intervention

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Abstract. Rheology and stiffening control can contribute in a significant way to the quality of concrete structures in general and can facilitate the promotion of 3D printing technology more specially. Active stiffening control (ASC) has the potential to solve conflicting rheological requirements of 3D printable materials during pumping, extruding and deposition. Responding to an external signal, the rheological properties of cementitious materials with mixed-in responsive components can be adjusted on demand. However, the mechanical properties of hardened responsive cementitious materials are unclear. This research investigates the mechanical properties of 3D printable cement mortar containing responsive aggregates after being exposed to a magnetic field. A customized nozzle equipped with magnetic intervention is designed. Two different magnetic field strengths (0.1 T and 0.3 T) are applied on the printing nozzle. The compressive and flexural strengths of specimens extracted from 3D printed wall elements printed with the help of ASC are explored at 7 days and 28 days. Magnetic field intervention adjusted the rheological properties in time and on demand without negatively affecting the mechanical properties after hardening when the responsive aggregates to cement mass ratio was 2.3:1. Compared with the 28-day strength, magnetic intervention has greater influence on the compressive and flexural strength at the age of 7 days.

Keywords: Active stiffening control; Magnetic field; Magneto-responsive aggregate; 3D printing

1 Introduction

Three-dimensional (3D) concrete printing needs to meet the contradicting rheological requirements regarding pumpability, extrudability and buildability [1, 2]. During the pumping process, a more liquid-like pumpable material is ideal. However, a quick increase in the yield strength is necessary after extrusion. The addition of additives and the enhancement intervention at the print head are the main methods to solve the above issue [1].

Compared with the addition in the mixtures, intervention at print heads has the advantage to increase the buildability after extrusion without influencing the pumpabil-

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ity. The potential intervention applied in a print head includes physical vibration [3], microwave heating [4], chemical addition [2] and magnetic field [5, 6], etc. Among them, magnetic intervention is one of the promising methods, because it can change the material from more fluid-like to more solid like reversibly to achieve active rheology and stiffening control in time and on demand after mixing [5, 7]. Meanwhile, there is no significant influence on the hydration of cement during the intervention [7]. Previous research has verified that magnetic intervention can change the fresh properties of cementitious materials containing pre-adding responsive additives [5, 6, 8]. However, there is a research gap on mechanical properties of printable cement mortar after magnetic intervention at print heads. It is worth exploring whether such kind of active rheology and stiffening control has a negative impact on the mechanical properties of the material after hardening due to the movement of magneto-responsive mineral particles.

This study investigates the mechanical characteristics of 3D printable cement mortar incorporating responsive fine aggregates when subjected to a magnetic field. A special nozzle with magnetic module was developed for this purpose. Two varying magnetic flux densities (0.1 T and 0.3 T) were applied on the printable mixtures with the customized printing nozzle during the extrusion process. Two directions of compressive strengths and one direction of flexural strength of samples derived from 3D printed wall elements were tested at the age of 7 days, and 28 days.

2 Experimental program

2.1 Materials

Portland cement CEM I 52.5N (Holcim) was used and the density of the cement was 3.16 g/cm^3. The magneto-responsive aggregates (MRAs) used in this study are magnetite (LKAB Minerals), with a density of 5.10 g/cm^3. The content of Fe is higher than 70.3 wt.% according to the supplier. MRAs with a diameter between 0 mm to 2 mm were applied in this study.

The magnetic properties of cement and MRAs were tested at around 20 ℃ by a vibrating sample magnetometer (VSM, LakeShore 7404) within ± 2.0 T. Fig.1 presents the hysteresis loops (magnetization versus magnetic field curves) of magneto-responsive aggregates. The saturation magnetization (M_s) and remnant magnetization (M_r) of MRAs were 91.22 emu/g and 4.28 emu/g, respectively. The coercive field (H_c) was 45.95 Gs.

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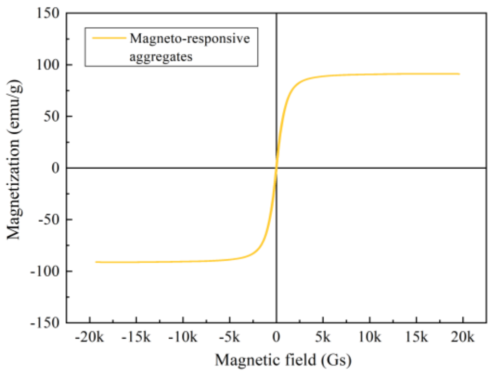

Fig. 1. Hysteresis loops (magnetization versus magnetic field curves) of magneto-responsive aggregates (1 T = 10000 Gs).

2.2 Mixture proportion and testing procedures

The mixture proportion of magneto-responsive printable cement mortar is shown in Table 1. The water to cement ratio (w/c) was 0.35. The MRAs to cement ratio was 2.3:1 by mass. This aggregate to cement ratio is a commonly applied volume ratio in research to achieve an excellent printing quality [9, 10].

Table 1. Mixture proportion of magneto-responsive printable cement mortars.

Cement (g)	w/c	Water (g)	Magneto-responsive aggregate (g)	Sand gradation (mm)
100.00	0.35	35.00	230	0/2

Fig. 2 shows the sample preparation and testing procedures for mechanical tests. The samples were extracted from the printed wall. A 6-axis robotic arm (ABB IBR 6650) was employed combined with a flow rate controlled pump equipped with pressure sensors (ranging from 0 bar to 40 bar), a tailor-made non-magnetic nozzle, and a pumping pipe measuring 3 m in length and 25.4 mm in diameter for the purpose of 3D printing. The customized non-magnetic nozzle comprised two components: a standard PVA pipe integrated with a magnetic field module and a 3D printed rectangular nozzle measuring 50 mm by 10 mm. The rectangular nozzle was made of PLA. Different numbers of the tile sintered NdFeB magnets (80.0 mm in length, 20.0 mm in inner diameter and 23.2 mm in outer diameter) were applied to achieve two magnetic flux densities of 0.1 T (denoted as NS-1) and 0.3 T (denoted as NS-2) in the middle of the nozzle at the air gap.

The printing speed was set as 150 mm/s. The layer thickness of the printed layers was approximately 10 mm and the layer width was around 50 mm.

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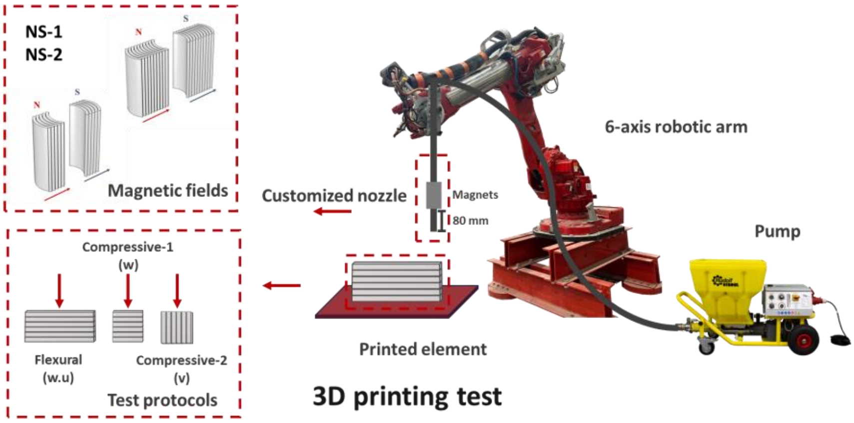

Fig. 2. Sample preparation and testing protocol for mechanical tests.

Wall elements with 6 layers (length 1 m) were printed for specimen extraction. Cubic specimens (40 × 40 × 40 mm³) and prismatic specimens (40 × 40 × 160 mm³) in one direction (parallel to the printing direction) were prepared (see in Fig. 2) at the age of 1 day. All prepared samples were cured at 20 ℃, RH = 65% until the age of 7 days and 28 days.

The compressive strength of cubic specimens was measured at the age of 7 days and 28 days, in accordance with NEN-EN 12390–3 [9]. Definition of orientation of specimens tested in the mechanical tests was referred to [11]. Two directions of compressive strength (direction w and direction v) were tested as shown in Fig. 2. The flexural strength (direction w.u) of prismatic specimens was measured at the age of 7 days and 28 days based on NEN-EN 12390–5 [9]. The prism samples were positioned atop two support rollers, spanning a distance of 100 mm. Each test was repeated three times at each age. The compressive strength and flexural strength are calculated according to [9].

3 Results and discussion

The 3D printed wall elements with or without the intervention of magnetic field are shown in Fig. 3. It can be observed that there were more cracks on the surface of fresh samples than their counterparts with an intervention of a magnetic field. The surface of fresh samples with the intervention of NS-2 was smooth. Some specific magnetic intervention combinations can improve the printing quality at the fresh stage.

Fig. 4 presents the flexural strength of printed responsive mortar with the intervention of different magnetic field. At the age of 7 days, standing at 4.8 MPa, the flexural strength (w.u) of printed samples in absence of a magnetic field increased to 5.8 MPa

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after applying an inline magnetic field (NS-2). However, the flexural strength (w.u) shows no significant difference at the age of 28 days. A NS inline magnetic field improved the flexural strength (w.u) at the age of 7 days, while there was limited influence on the flexural strength at the age of 28 days.

Fig. 5 shows the compressive strength of printed responsive mortar with the intervention of different magnetic fields. The compressive strength of NS-2 exhibited anisotropy at the age of 7 days. The compressive strength-1 (w) of NS-2 was only 54.3 MPa, while the compressive strength-2 (v) of NS-2 reached 76.5 MPa. Considering the standard deviation, the compressive strength of printed samples with and without NS magnetic intervention showed limited differences, especially for the value at the age of 28 days.

The strength development of cement might play an important role to show such a phenomenon. At the age of 7 days, the spatial distribution of magneto-responsive aggregates influenced the strength of printed samples, especially for flexural strength (w.u). At the age of 28 days, when the cement matric was fully hydrated. The influence of distribution of magneto-responsive aggregates could be ignored. This result shows that while active rheology control can adjust the fresh properties of cementitious materials, while it has no negative effect on the mechanical properties in the later hardened stage.

The distribution of air voids in the printed samples might play the major role in the mechanical properties of printed samples in this case. The MRAs moved and tended to align along the magnetic field induction line during the process of applying a magnetic field. However, the volume of MRAs was relatively high in the mixture design of this research. There was limited space for the MRAs to move in the paste. The MRAs suffered magnetic force squeezed the paste and redistributed the air voids in the samples. As a result, the surface quality and mechanical properties of fresh samples were influenced.

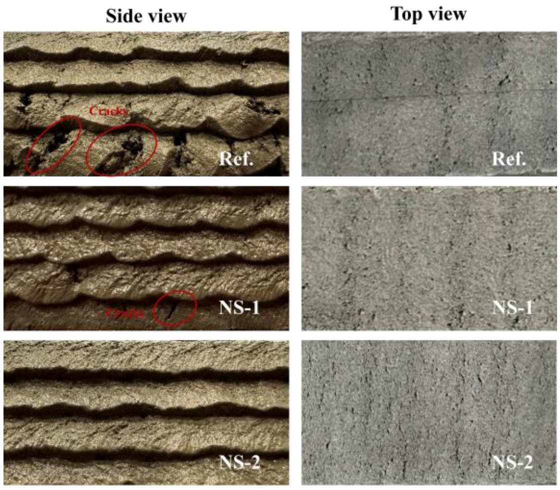


Fig. 3. 3D printed wall elements with or without the intervention of magnetic field.

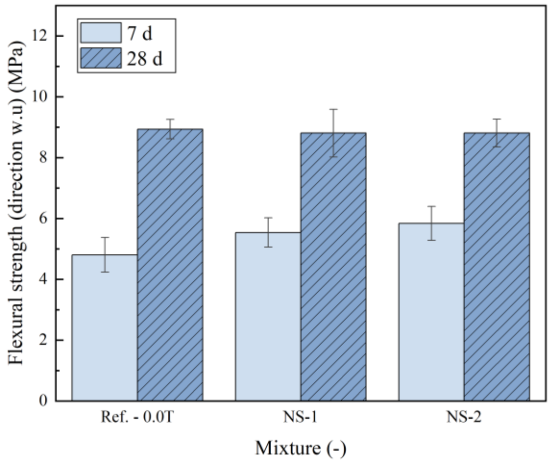
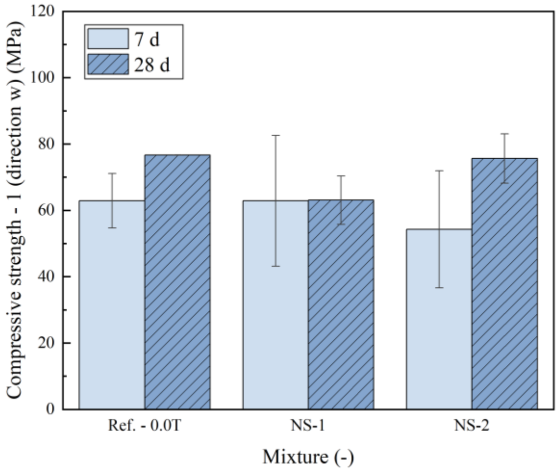
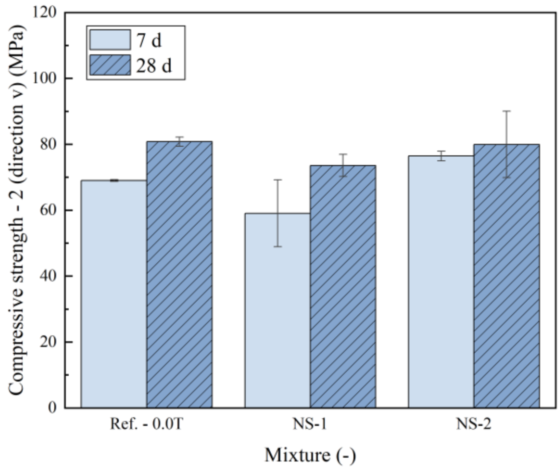


Fig. 4. Flexural strength of printed responsive mortar with the intervention of different magnetic field.



(a)



(b)

Fig. 5. Compressive strength of printed responsive mortar with the intervention of different magnetic field.

4 Conclusions

The study explored the mechanical properties of 3D printable cement mortar containing responsive aggregates after being exposed to a magnetic field. By using a customized nozzle, two varying magnetic field strengths (0.1 T and 0.3 T) are applied during the printing process and printed walls made of mortar containing responsive aggregates (MRAs) were prepared. The compressive and flexural strengths of extracted cubic and prismatic samples derived from 3D printed wall components were tested at the age of 7 days and 28 days. The results indicate that for the printable cementitious mixture with a MRAs to cement mass ratio of 2.3:1, magnetic intervention can improve the surface quality of the fresh sample. The rheological properties were effectively adjusted in real time and on demand through magnetic field intervention, with no negative impact on the mechanical properties after printing and hardening. Magnetic intervention was able to influence the compressive and flexural strength at the age of 7 days. At the age of 7 days, the compressive strength shows anisotropy after the magnetic intervention of NS-2 (0.3 T) was applied. The flexural strength was increased after applying a magnetic field. There was limited effect on the 28-day compressive and flexural strength.

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