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Effect of the structuration rate on dimensional stability and mechanical performance of 3D printed mortars

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Digital concrete fabrication is a novel construction technique in which structural elements are built layer by layer without the use of formwork. This technology has introduced new challenges in materials engineering. More emphasis lies on the structuration behavior of cement-based materials. Concrete is designed to achieve adapted workability to flow during the pumping phase. It also requires proper build-up and stiffness to retain its shape after extrusion and sustain its own weight and, subsequently, the weight of successive layers. A high degree of structuration is recommended to ensure high printing quality. However, this may adversely affect the performance of the multi-layer printing process. In the present study, an experimental program was carried out to evaluate the impact of structuration rate on the dimensional stability and mechanical properties of the printed element at both early age and long term, respectively. Four different mixtures with various structuration rates were designed and printed. In the fresh state, variations in the layer's height and width were recorded to evaluate the dimensional stability of the printed structure. On the other hand, several specimens were cut out of the freshly printed elements for mechanical tests. The compression and flexural tests were conducted after 7 and 28 days of moist-curing. The obtained results showed that there exists an optimum rate of structuration above which the quality of the bonding interface is compromised, generating losses in mechanical properties. Under this threshold, anisotropic behavior dominates, leading to low dimensional stability.

1. Introduction

3D printing concrete is a novel construction technique that can bring significant changes to the construction and manufacturing industries. Various benefits may arise from this technology, such as reduced labor, enhanced architectural freedom, as well as time and cost savings. Despite its potential benefits, the technology faces several difficulties in its implementation, thus limiting its widespread adoption. One of the challenges is the limited understanding of the mechanical behavior of printed elements. Cement-based materials are generally designed to provide minimum strength and durability given their intended use and exposure conditions. However, in 3D printing applications, multilayer deposition is likely to induce anisotropic behavior because of the interface between layers, which can result in strength loss [1,2].

Both the material's intrinsic properties and printing parameters [3], such as deposition time interval [4], extrusion pressure, nozzle geometry [5], and ambient conditions, affect the quality of inter-layer bonding. This latter can significantly impact the mechanical performance of the printed element. Therefore, this study has been conducted to evaluate the effect of the structuration rate of printed material, i.e. the time evolution of the static yield stress (A_{thix}) [6], on dimensional stability and long-term mechanical performance. Four different mixtures with various structuration rates were designed and printed, by mainly varying their sand-to-cement ratio (S/C). The mechanical performance of printed mortars was evaluated in terms of compressive and flexural strength development after 7 and 28 days of age. In order to understand the mechanical behavior of 3D printed mortars, compression tests were performed in two phases. The first phase consisted of comparing the strength development of the printed and molded samples, while the second phase aimed to identify weak zones and the failure pattern. This phase was performed on prismatic sam-

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ples extracted from the printed element while maintaining the overall height of the printed layers.

2. Experimental program

The experimental program undertaken in this study is shown in Fig. 1. The details of the experimental procedures are described below.

2.1. Mixtures proportions and structuration rates

Four different printable mortar mixtures with various thixotropic behaviors were proportioned using a general use (GU) Portland cement and fine-graded quartz sand with a maximum aggregate size of 0.7 mm and a specific density of 2.66 kg/m³. The fluidity of the mixtures was adjusted using a polycarboxylate ether-based superplasticizer (SP) having a specific gravity of 1.09 and a modified starch-based viscosity modifying agent (VMA). The investigated mixtures were proportioned with a fixed water-to-cement ratio (W/C), and different sand-to-cement ratios (S/C) and SP dosages to achieve an initial mini-slump value of 40 ± 20 mm, in order to ensure the desired workability for the printing process. The mixture proportions of the investigated mixtures are summarized in Table 1. The yield stress of the investigated mortars was estimated by considering the evolution of slump loss and employing the Murata equation [7], as shown in Fig. 2. The rate of yield stress evolution was used to estimate the structuration rate of the investigated mortars (A_{thix}) (Table 1).

2.2. 3D printing pattern and samples preparation

Zig-Zag-pattern elements of 80 mm height were printed using the investigated mortars. Each mixture was prepared in an 80-liter batch to print elements and cast samples for mechanical testing. A gantry-type 3D concrete printer was used. This printer has a maximum printing volume of 2 200 mm × 1 800 mm × 2 000 mm (L × W × H), with an auger-type extruder with Ø25 mm circular nozzle. A progressive cavity pump was used to pump the material to the extruder through a 10 m-long hose. Preliminary tests were performed to adjust the printing speed and extrusion rate given the workability of the mixtures to achieve the target dimensions of the printed layer ($w_{design} = 75$ mm, $h_{design} = 15$ mm). The dimen-

sions of the tested specimens are indicated in Fig. 3. Six specimens with a length of 600 mm were pre-cut in the fresh state of the printed element and then kept in the moist room 24 h after casting until the testing age. The curing conditions are in accordance with ASTM C31 specifications. After 7 and 28 days, cubic and prismatic specimens were saw-cut from the six printed specimens. Six cubic samples were cast for compression tests, and four prismatic samples for flexural tests in accordance with the ASTM-C109 and ASTM-C1609 specifications, respectively. These samples were demolded 24 h after casting and stored in a moist room to maintain the same curing conditions as the printed specimens. In total, three cast samples and six printed samples were prepared.

2.3. Mechanical tests

The mechanical properties of the printed and molded samples, including compressive and flexural strength, were evaluated. For the printed samples, two loading directions were applied, as shown in Fig. 3. (b): a loading direction D1 perpendicular to the printing direction and a loading direction D2 parallel to the printing direction. The size of each sample was measured by a digital caliper before testing. This value was then used to calculate the strength and evaluate the dimensional stability. An additional polishing process was performed on the prismatic samples to achieve a flat surface for testing. The final size thus corresponds to the outer surface of each specimen, including the irregularly layered side surface, used for strength calculation (Fig. 3).

3. Results and discussions

3.1. Dimensional stability

Printable cement-based materials require a fairly high structuration rate to ensure dimensional stability during multilayer deposition due to the absence of formwork [8]. The dimension variations of the printed prismatic samples of the investigated mortars are shown in Fig. 4. The higher the rate of structuration of the material, the better the dimensional stability (M2 and M3). However, such high structuration can interfere with adequate bonding between layers, hence resulting in the formation of a weak interface between layers [9]. The addition of VMA improved the dimensional stability of the M1-V mixture compared to that of

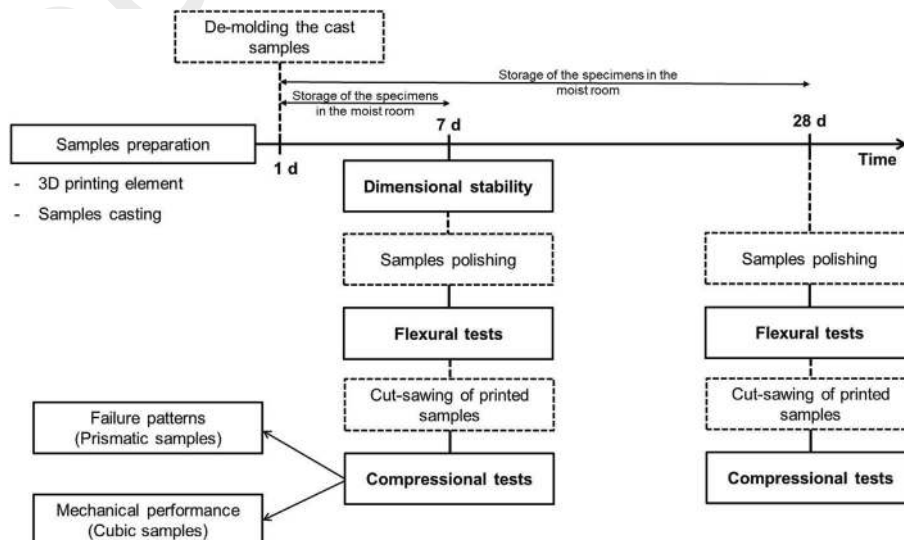


Fig. 1. Overview of the experimental program.

Table 1
Mix design proportions and structuration rates of the investigated printable mortars.

Mix design	S/C	W/C	SP (%weight of cement)	VMA (%weight of cement)	A _{thix} (kPa/min)
M1	1.00	0.35	0.02	-	0.86
M1 - V	1.00		0.04	0.05	1.00
M2	1.25		0.2	-	1.60
M3	1.40		0.25	-	2.00

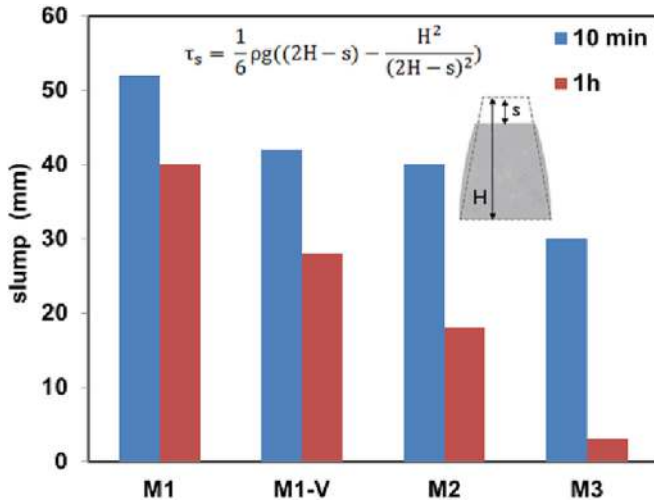


Fig. 2. Slump values for the investigated mortars after 10 min and 1 h of age.

the M1 reference mixture. This can be explained by the positive effect of VMA on improving the ultimate elastic and plastic stresses of the material by improving its consistency [10,11].1

3.2. Mechanical performance of 3D printed mortars

The 7 and 28-day flexural strength of the investigated mortars are presented in Fig. 5. The molded samples showed higher flexural strength than the printed ones. The losses of flexural strength at 7 days were **16%, 37%, 35%, and 34%** for **M1, M1-V, M2, and M3**

mortars respectively. After 28-d of age, these percentages were **15%, 13%, 25%, and 40%**. This result clearly reveals that the extrusion printing process weakens the flexural strength. Similar results have been reported in the literature [1,3,12]. This strength loss is more significant for mortars with high structuration rates, such as M2 and M3 mortar mixtures. The difference could be attributed to the difference in consolidation conditions between printed and molded samples, where the latter was more compact. Besides, the interface between the layers may also have induced some weak zones [2,13,14]. A close examination of the fracture surface observed with the M3 mortar under flexural test reveals the presence of macro-pores at the interlayer bonding interface (Fig. 6), which may account for its relatively low flexural strength value. Conversely, the addition of VMA reduced the relative loss of flexural strength of the M1-V mortar at 28 days compared to the M1 mortar. However, its effect was found to be limited at an early age.

The 7 and 28-day compressive strength of printed and molded cubic samples are shown in Fig. 7. The compressive strength of molded samples is significantly higher than that of the printed ones. This can be attributed to the lack of compaction of the printed samples. The compressive strength along the D1 direction is greater than that along the D2 direction for all the investigated mixtures, except the M3 mortar. As a result of the consolidation effect caused by the normal force applied during the test, the samples' compressive strength improved when loaded into D1. On the other hand, loading along the D2 direction generates tensile stress perpendicular to the inter-layer interface, whose strength is generally lower. This anisotropy, in terms of compressive strength, is an inherent consequence of the 3D printing process and appears to be more pronounced for mortars with a very high structuration rate, such as the case of M3 mortar. The percentage loss in compressive

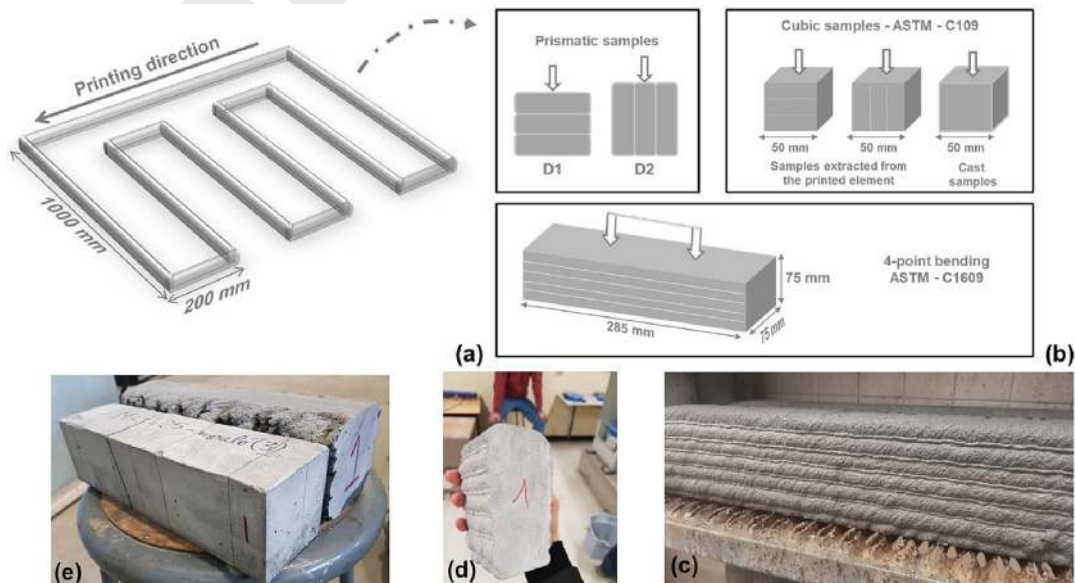


Fig. 3. (a) Schematic of the printing path; (b) Summary of the performed mechanical tests; (c) Printed specimen stored in the moist room; (d) Prismatic samples used for the second phase of compression tests; (e) Specimens used for flexural tests.



Fig. 4. Dimension variations of the printed specimens.

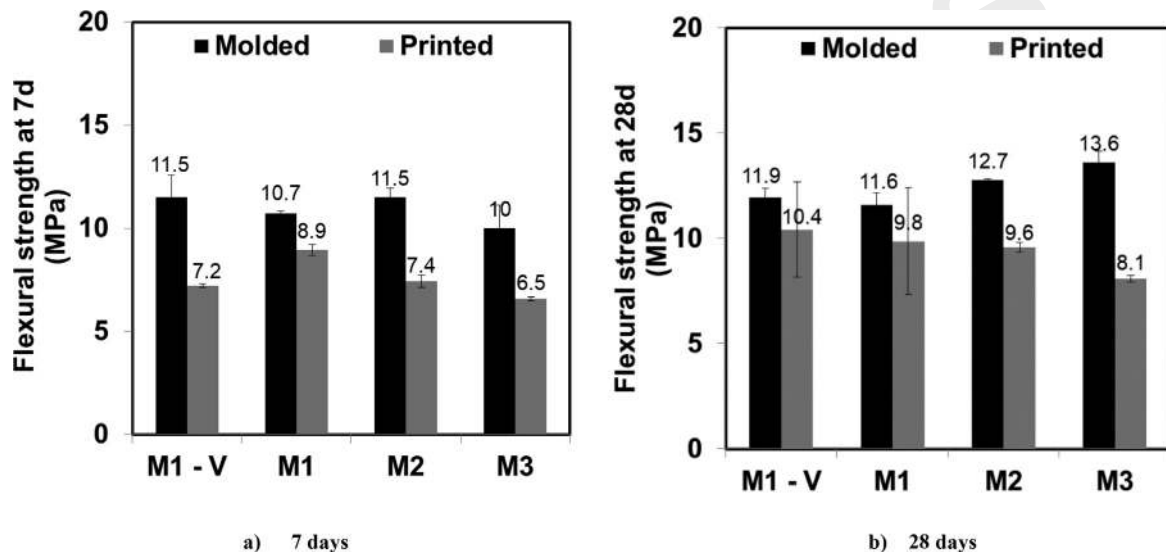


Fig. 5. Flexural strength of the investigated mortar mixture mixtures at 7 and 28 days.

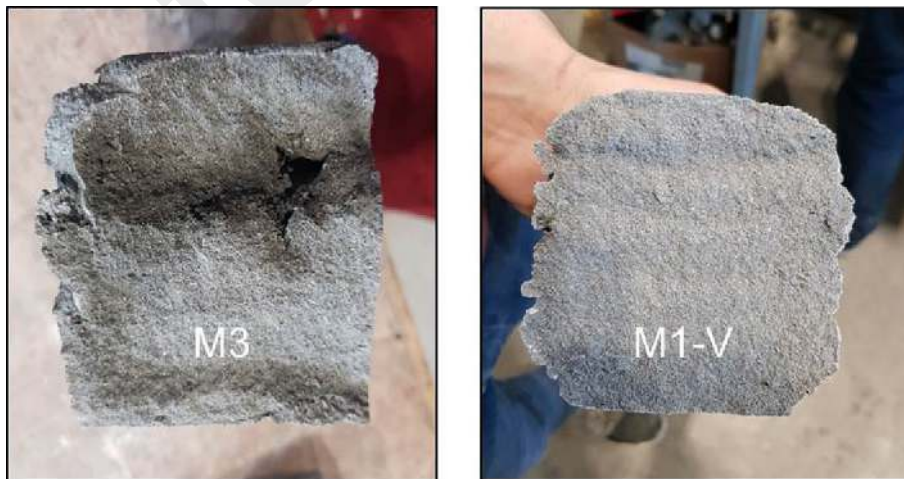


Fig. 6. Fracture surface of printed samples of M1-V and M3 mortar mixtures after the flexural test.

strength of printed samples at 7 and 28 days is summarized in Table 2. In contrast to the results obtained in the flexural tests, the loss of compressive strength decreased in the case of M3 mortar. On the other hand, its anisotropic behavior evolved over time,

determined by the difference in the relative loss of compressive strength between the two directions. This anisotropy decreased at 28 days in the case of the M1-V mortar, as well as its loss of com-

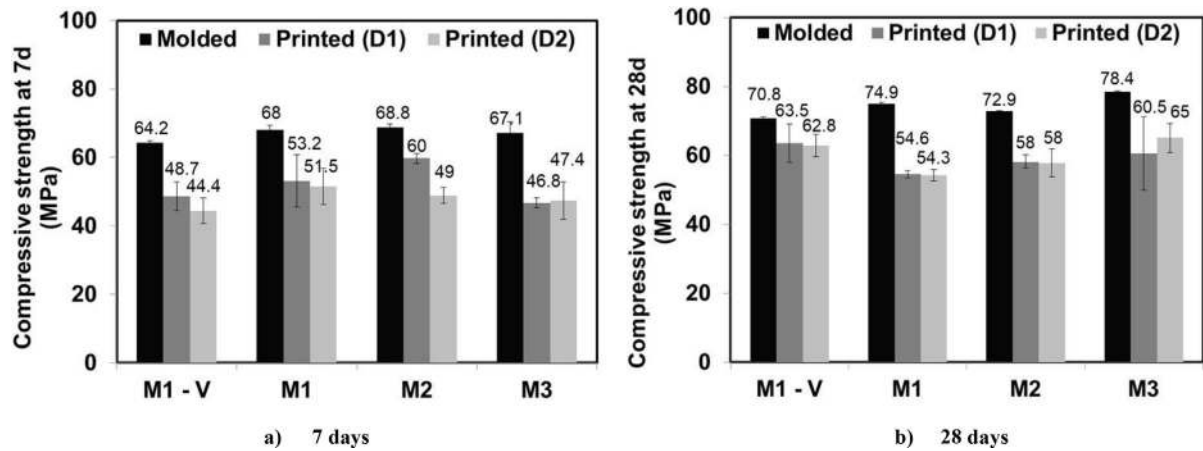


Fig. 7. Compressive strength of the investigated mortar mixtures at 7 and 28 days.

Table 2
Loss of compressive strength of printed samples at 7 and 28 days (%).

Mix design	Loss of compressive strength as a function of loading direction (%)			
	7 days		28 days	
	D1	D2	D1	D2
M1 - V	24	31	11	11
M1	22	25	27	27
M2	13	29	20	21
M3	30	29	23	17

pressive strength, which supports the use of viscosity-modifying agents in 3D printing inks.

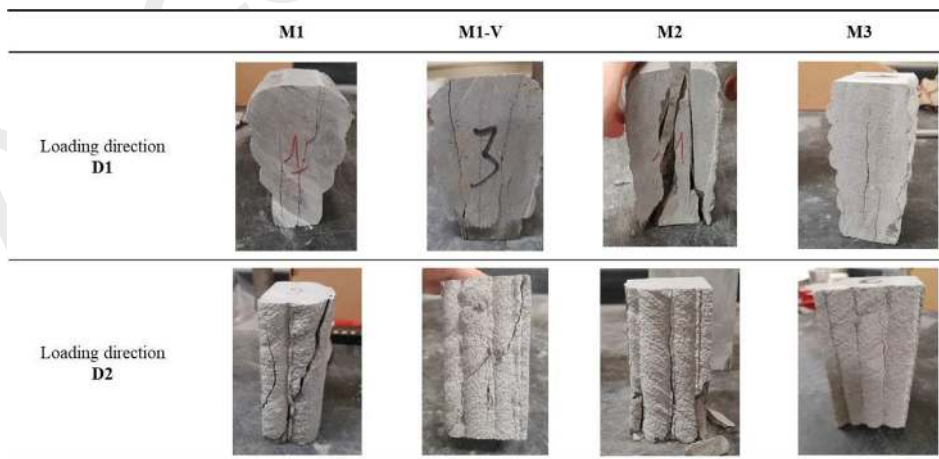
3.3. Failure pattern

The printed prismatic samples exhibited different failure patterns depending on the direction of applied loading. Table 3 summarizes the observed failure patterns of the investigated mortars. A 'conical' failure is observed in the loading direction D1 in the case of mortar mixtures M1, M1-V, and M2, accompanied by the propagation of inclined cracks along the height of the specimens, as shown in Table 3. This failure pattern implies that these samples exhibit monolithic behavior similar to molded samples. In the D2 direction, aligned cracks are observed along the interlayer interface

in M2 and M3 mortars with high structuration rates, and inclined cracks in M1 and M1-V mortar mixtures.

If the interface between the layers does not present a zone of weakness, the propagation of cracks between the layers will be limited. This explains the inclination of cracks and discontinuities which depends mainly on the quality of the interface. Thus, the mixture M3 shows continuous vertical cracks, which can be explained by poor interlayer bonding. It can be assumed that the crack pattern may give an insight into the interlayer bonding quality.

Table 3
Failure patterns of printed prismatic samples according to loading directions.



4. Conclusions

The layer-by-layer casting process can result in interlayer discontinuities, which can alter the strength development of the printed element. One of the key materials' properties that can affect this behavior is its build-up kinetics. This phenomenon has been largely overlooked in previous studies. In this study, the impact of the structuration rate on the quality of the bonding interface is investigated. The obtained results revealed that the strength of printed elements is generally lower than that of cast elements, due to the lack of consolidation and the quality of the interface between the layers. Based on the results presented in this study, the following conclusions can be pointed out.

- There is an optimum structuration rate above which the quality of the interlayer bonding interface is compromised, generating losses in mechanical properties, and below which dimensional stability is limited. The typical value for the structuration rate in this study is around 1.5 kPa.
- The failure pattern of printed samples varies depending on the quality of the interlayer bonding interface and the loading direction. The strength of printed samples is generally higher in a loading direction perpendicular to the printing direction due to the consolidation effect of the applied stress.
- The presence of macro-pores and the lack of bonding between the layers are the main reasons for the degradation of the quality of the interlayer bonding interface of cement-based materials with very high structuration rates, which may generate anisotropic behavior.

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