Salt Scaling Resistance of 3D Printed Concrete

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Abstract. Extrusion-based 3D concrete printing is an emerging technology in the construction field due to the many advantages associated with it as compared to conventional mould casting technology. However, many aspects like durability and long-term service performance are yet to be investigated in detail. The present study focuses on understanding the salt scaling resistance of 3D printed concrete samples. 3D printed concrete samples were prepared with a Portland cement mixture on the one hand and a mixture containing a blend of Portland cement and blast furnace slag on the other hand. The printed samples were subjected to freeze and thaw cycles with a 3% saltwater concentration. It was observed that the 3D printed samples exhibited better resistance against salt scaling compared to the mould cast samples made with the same mixture. The pore structure of the 3D printed samples was characterized by mercury intrusion porosimetry. It was observed that the presence of a higher amount of interconnected and coarser pores at the interlayer region of the 3D printed samples, acting like pockets of air voids, facilitates the release of ice crystallization pressure during the freezing phase. The study gives insights into the durability characteristics and feasibility of using 3D printed concrete elements exposed to aggressive environmental conditions.

Keywords: Concrete · 3D printing · Salt scaling · Slag · Porosity

1 Introduction

Extrusion-based 3D concrete printing (3DCP) is a novel method of constructing structures based on a pre-defined computer model [1]. The concrete is deposited in a layer-by-layer manner without the need for formwork. 3DCP is getting wide popularity in the construction sector due to different advantages such as enhanced geometrical freedom, which enables topological optimization and thus increases material usage efficiency, cost effectiveness, sustainability, etc. [1, 2].

Although several aspects of the 3DCP technology are being studied, there exist seldom studies on the long-term durability performance. Salt scaling is one of the major durability issues of concrete. Salt scaling is defined as superficial damage caused by freezing a saline solution on the surface of a concrete body. The damage is progressive and consists of the removal of small chips or flakes of material. The damage induced by freeze–thaw cycles result into surface scaling attributable mainly to the crystallization pressure generated when the liquid water in the pore system changes to ice [3, 4].

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De-icing salts and contact with sea water could exacerbate the salt scaling lowering the melting point of ice, which may induce thermal shock-mediated stress. Salt precipitation may also damage the pore system of the element. Other mechanisms involved in decay include internal crystallization and a physical development known as glue spalling [5].

The current study compares the salt scaling performance of 3D printed concrete elements with mould cast concrete samples with two different binder systems. Also, with the pore structure of the samples were characterized by mercury intrusion porosimetry.

2 Methodology

2.1 Materials and Mixtures

The materials used in this study include a CEM 52.5 N Portland cement, CEM 52.5 R Portland cement and ground granulated blast furnace slag (GGBFS). Fine aggregates with a maximum particle size of 2 mm were also used to make the mixtures [6–9]. A polycarboxylate ether-based superplasticizer and a cellulose-based viscosity modifying agent were used as the chemical admixtures. The mixtures were prepared with a constant water-to-binder ratio of 0.35. The composition of the mixtures are given in Table 1. The detailed procedure of the mixture design is described in previous publications by the authors [6–8].

Table 1. Composition of the mixtures

Material	Quantity (kg/m^3)	
	Mixture 1	Mixture 2
CEM I 52.5 N	376	–
CEM I 52.5 R	–	795.4
GGBFS	376	–
Sand	1279	1193.1
Water	263	302.3
Superplasticizer	5.27	3.12
Viscosity modifying agent	0.75	10.97
Total weight	2301.3	2285.6
w/b	0.35	0.38
Aggregate/binder	1.7	1.5

2.2 3D Print Experiments and Sample Preparation for Salt Scaling Tests

3D printing experiments were carried out using a six-axis industrial robot connected with a screw-based extrusion system. To assess the influence of interlayer on the salt scaling performance, about 1 m long, eight layered wall elements (40 mm wide and 10 mm height layers) were printed with both the mixtures. After printing, the wall elements were cured until the age of 7 days at 25 °C and 95% relative humidity. 50 mm diameter and 50 mm height cylindrical samples were extracted from the wall elements as shown in Fig. 1.

Salt scaling resistance was determined from the damage induced during freeze–thaw cycles based on the weight of the scaled material following the procedures mentioned in European standard CEN/TS 12390-9:2016 [10]. At the end of every 7 freeze thaw cycles, the mass of the scaled material was measured accurately and the average value was reported. The experiments were conducted on six 50 mm ϕ × 50 mm height samples per series. The samples were named as Mixture number-P for printed samples and Mixture number-MC for mould cast samples.

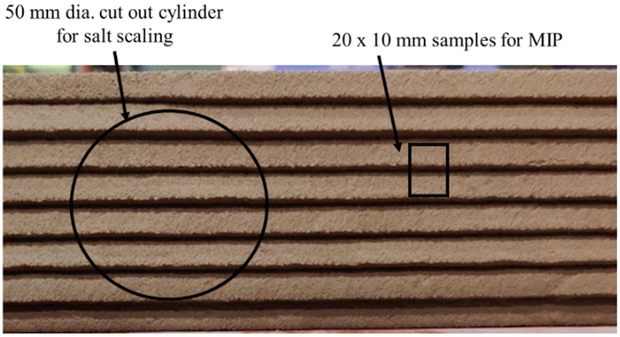


Fig. 1. Location of the samples for 3D printed samples

2.3 Mercury Intrusion Porosimetry

About 1 cm × 2 cm size samples from the printed elements were cut for MIP studies. For comparison, same size samples are cut out from mould cast specimens. The experimental details are provided in previous publications of the authors [11]. At the age of 7 days, the samples were stored in isopropyl alcohol for up to 4 days to stop hydration by the solvent exchange method. After four days of immersion in isopropyl alcohol, the samples were stored inside a vacuum desiccator until testing. The MIP tests were carried out by using a Pascal 140–440 series porosimeter from Thermo Scientific. Mercury was intruded into each of the samples using a pressure range varying from vacuum to a maximum pressure of 200 MPa. MIP tests were repeated twice to check the repeatability and a representative curve from the two tests is presented.

3 Results and Discussions

3.1 Salt Scaling

Shows the cumulative scaled of mass due to salt scaling for both the mixtures in 3D printed and mould cast conditions. The cumulative mass loss was normalized with the area of the exposed surface. It is interesting to note that the mass of scaled off material is significantly higher in the case of mould cast concrete compared to 3D printed samples. This drastic difference in salt scaling performance can be observed from Fig. 1 as well. In order to understand the possible mechanisms involved in such a different behaviour, a closer look at the pore structure characteristics and crystallization pressure due to the formation of ice is needed. It was reported that long and interconnected pores exist at the interface region of the 3D printed concrete elements [12]. This could result in the absorption and transport of water though the printed element [1]. The formation of ice crystals in interlayers may cause a similar effect to that of freezing in air voids. This in turn could cause a suction on the pore fluids of the bulk concrete which may compensate the glue spall stress [5] (Table 2 and Fig. 2).

Table 2. Results of the salt scaling study

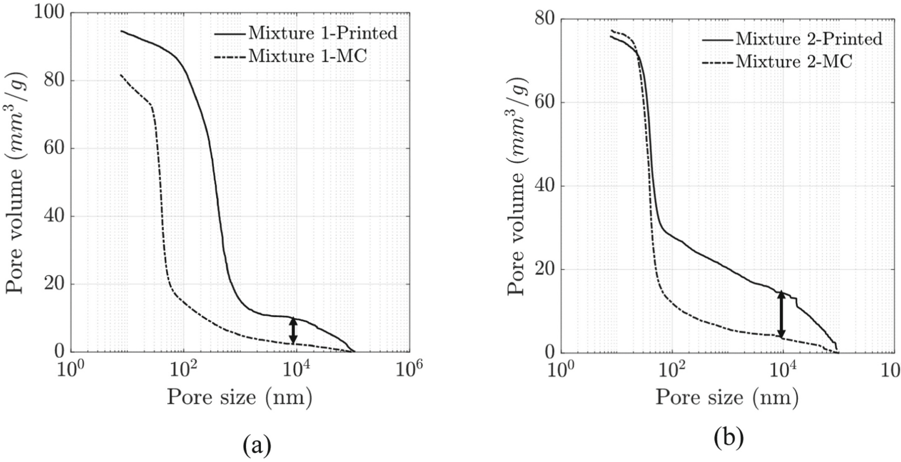
Sample name	Cumulative mass of scaled material per unit area in kg/m^2 (after 56 freeze-thaw cycles)
Mixture 1-P	0.11 ± 0.02
Mixture 1-MC	0.51 ± 0.03
Mixture 2-P	0.14 ± 0.02
Mixture 2-MC	0.57 ± 0.03


(a) (b)

Fig. 2. Salt scaling damages observed on (a) printed and (b) mould cast samples.

3.2 Total Porosity from MIP

Figure 3 shows the cumulative pore volume vs pore entry diameter plots for both the mixtures. The main difference between the 3D printed and mould cast samples lies on the pore volume at different pore size ranges. From Fig. 3, it can be observed that the volume of pores in the size range of 100–0.1 μm is lower in the case of 3D printed samples compared to the corresponding mould cast concrete samples for both the mixtures 1 and 2. Also, it must be noted that the volume of pore in the size e range of 50 μm is higher in the case of 3D printed samples and therefore, it can be considered as a system with higher amount of air voids (similar to air entrained concrete). The formation of the ice crystal in an air void imposes suction in the pore fluid thereby contracting the porous skeleton. This compensates the glue spall stress generated from thermal expansion mismatch [5].



(a) (b)

Fig. 3. Cumulative pore volume vs pore size curve of the 3D printbale mixtures (a) Mixture 1 (b) Mixture 2

4 Conclusions

The current study attempts to characterize the salt scaling phenomenon in 3D printed concrete elements and compares this with mould cast concrete elements. The study was conducted with two different mixtures as among which a Portland cement-blast furnace slag system and a rapid hardening PC system. The salient conclusions from the study are listed below:

- The printed concretes showed much higher resistance to salt scaling as compared to mould cast concrete. This could be due to the suction created from the ice formation in the interlayers of printed concrete, thereby compensating the glues spall stress from the ice formation on the surface concrete.
- The volume of pores at a size range of 100–0.1 µm reduces nearby interfaces as observed from the MIP studies. This could indicate that the interfaces can act as air voids present in the system.

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