Integrating 3D Printing and Smart Sensing into Permanent Formwork for Next-Gen Precast Concrete Structures

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Abstract:
This study investigates the influence of environmental factors on the self-sensing performance of 3D-printed cementitious composites for structural health monitoring. Square 3D printed column samples containing control mortar and self-sensing cementitious composite (SSCC) were fabricated and cured, then exposed to controlled drying cycles and temperature variations from room temperature to 60 °C. Under cyclic compressive loading, changes in electrical resistance were monitored to evaluate the fractional change in resistivity (FCR) and stress sensitivity. The results demonstrate that both internal moisture variation and elevated temperature significantly affect the piezoresistive sensitivity. Although resistance decreased with an increase in humidity and temperature, a better piezoresistive response was captured at the oven-dried low temperature state. The highest stress sensitivity of 1.805 %/MPa at 22.5 C at the lowest water saturation. This study highlights the critical role of environmental effects in the deployment of smart 3D-printed concrete for the monitoring of durable infrastructure.

1. INTRODUCTION

Three-dimensional concrete printing (3DCP), also referred to as additive manufacturing with concrete, employs extrusion-based 3D printing to deposit concrete layer by layer using either a robotic arm [1] or a gantry system [2]. The nature of 3DCP eliminates the need for traditional formwork. As an emerging construction method, it relies heavily on automation and has the potential to reduce construction costs, shorten project durations, and lower the risk of injury to workers. The unique material deposition method in 3DCP is the layer-by-layer extrusion of concrete. This attribute can be leveraged for a variety of multifunctional material depositions, one of which is self-sensing cementitious composites (SSCC). Special mixtures such as SSCC need precise embedment in the structural members not only due to lowering the cost but also to ensure high performance.

This study aims to investigate the self-sensing property of concrete columns that contain SSCC in a certain section of 3DCP permanent molds. The usage of SSCC is limited to a fraction of the total volume of the structural element. This could entail the reduction in material cost with satisfactory stress-sensing capability. Additionally, the effect of environmental conditions emanating from the change of internal moisture content and temperature of the self-sensing 3DPC will be analyzed.

2. METHODOLOGY

2.1 Materials and Mix Proportions

In this investigation, mortar mixes containing type IL Portland cement, densified silica fume, regular sand, and mCF were prepared. Densified silica fume constituted 20 wt% of the binder and was incorporated into the mixture to reduce the drying shrinkage after the 3D printing process, while IL Portland cement constituted the remaining 80 wt%. To achieve a satisfactory extrudability and consistency, the cement-to-sand proportion was kept at 1:1. To achieve piezoresistive capability, mCF was used at 0.5 wt%, which was previously determined [3], [4]. The W/B ratio of 0.32 was chosen, which leads to optimal printing properties. To ensure this low W/B ratio, a polycarboxylate (PCE) based superplasticizer (SP) was utilized. In total, one reference mix without conductive fillers and one sensing mix containing mCF were prepared.

2.2 Self-Sensing Property Measurement

To simulate different environmental conditions, the specimens were tested at varying temperatures and internal moisture contents. The specimens were placed in a convection oven at a temperature of 60 °C, and their weight was monitored at regular intervals. The moisture content and saturation degree were calculated using the corresponding equations (Eq 1. and Eq 2.).

$$MC = \frac{W_t - W_{dry}}{W_{dry}} * 100\% \quad (1)$$

$$SD = \frac{MC_t}{MC_0} * 100\% \quad (2)$$

Here, MC, W_t, and W_{dry} represent the moisture content, the weight of the specimen after a given drying time, and the weight of the specimen at constant weight, respectively. Similarly, SD, MC_t, and MC_0 denote the saturation degree, the moisture content after a given drying time, and the moisture content at the driest state, respectively. In addition, to study the effect of temperature, piezoresistivity tests were performed on the specimens at 22.5 °C and 60 °C. The 3D-printed column reached an oven-dry state after a cumulative 48 hours of drying in the oven. The corresponding moisture contents and saturation degrees were calculated. Hereafter, the saturation degrees of 100%, approximately 38%, approximately 14%, and 0% will be referred to as SSD, SD38, SD14, and OD, respectively.

In this study, for piezoresistive testing, 150 mm x 150 x 300 mm permanent square molds were additively manufactured, which were grouted afterwards. The height of the columns was divided into three sections, with only the middle section consisting of the self-sensing mixture. Additionally, 24 hours after printing, the column shells were grouted with the reference mix. All specimens were cured for 28 days, submerged in water at room temperature. The resistance between the inner electrodes is calculated using Ohm's law. Resistivity, fractional change in resistivity (FCR), and stress sensitivity (SS) were calculated using Eq 3-4.

$$FCR = \frac{(\rho_i - \rho_o)}{\rho_0} \quad (3)$$

$$SS = \frac{FCR}{\sigma} \quad (4)$$

3. RESULTS AND DISCUSSION

3.1 The Effect of Humidity and Temperature on Self-Sensing 3DCP Columns

The reduction in the internal moisture content of concrete is accompanied by a decrease in the volume of pore water solution [11]. Pore water, containing charged ions such as OH^-, Ca^{2+}, and Na^+, provides a low-resistance path for the flow of electrical current. Hence, it can be inferred that the electrical resistance in 3DPC is inversely related to its level of saturation. As can be seen in Figure 1.a., electrical resistance of 3D printed columns increased as the moisture in specimens evaporated. The highest resistance of 29 KΩ was obtained for the oven-dried (OD) state, whereas the lowest resistance of 1 KΩ was measured in the surface saturated (SSD) state. The variation in resistance between the lowest and the highest saturation level remained uniform across all measurements. On the contrary to resistance, both the peak and the clarity of FCR increased as the water saturation decreased (Figure 1.c.). The clearest correlation between the cyclic compressive loading and the FCR was captured in the OD condition. In the cases of SSD and SD38, the data were extremely noisy, and no correlation between the applied stress and the electrical signal could be made. A noticeable FCR response that corresponded to the mechanical loading emerged in SD14 and OD. These observations are contradictory to the postulations proposed by some, wherein the moisture content is positively correlated with piezoresistive performance [12], [13]. It is reported that the lower the resistance in self-sensing concrete, the higher the piezoresistivity [14]. This theory is supported by the higher sensitivity seen in the SSCC containing highly conductive fillers compared to those without a conductive filler. Additionally, increased sensitivity is observed in the specimens with higher dosages of conductive fillers. Hence, to achieve optimal piezoresistivity, the objective was to minimize electrical resistance. However, based on our observations, the reduced electrical resistance achieved through higher water saturation does not lead to improved piezoresistive capability. We hypothesize that the cause for this divergence in the relationship of resistance with piezoresistance might be two-part. First, the percolation network achieved through ionic conduction or ionic + electronic conduction is different in principle than electronic conduction. Contrary to the rigidly constrained state of conductive fillers in the SSCC hardened mixture, the pore water solution that facilitates the ionic conduction can flow under mechanical loading. Since concrete, especially 3DPC, is a permeable material [15], load-induced fluid transport can occur between macro or capillary pores. This redistribution of pore water might have an effect on the measured resistance, causing noise in the data. In the case of electronic conduction, however, under the application of loading, conductive fillers remain relatively undisturbed. Thus, a more stable resistance signal is observed in the OD condition. Second, the porosity and permeability of 3DPC are considerably different from those of the concrete fabricated through conventional means, such as mold-casting. The layer-by-layer deposition of concrete leads to the occurrence of more macro-pores and higher total porosity. Therefore, the load-induced transport of pore water might become exacerbated in 3DCP compared to the monolithic fabrication of structural members. Stress-sensitivity is calculated for each SD level and is shown in Table 1.

Figure 1.b. shows that raising the temperature from 22.5 °C to 60 °C lowered the resistance of self-sensing 3DCP columns from approximately 29 kΩ to 12.5 kΩ. Although the correlation between the electrical

response and the applied stress can be observed at both temperatures, a more pronounced sensitivity was achieved at 22.5 °C. It is reasonable to assume that piezoresistivity improves when the resistivity is lowered, given that the conduction of the system is controlled by electronic conduction (e.g., conduction via conductive fillers). The stress sensitivity at different temperatures sharply dropped from 1.805%/MPa to 1.15%/MPa once the temperature was elevated from 22.5 °C to 60 °C (Table 1).

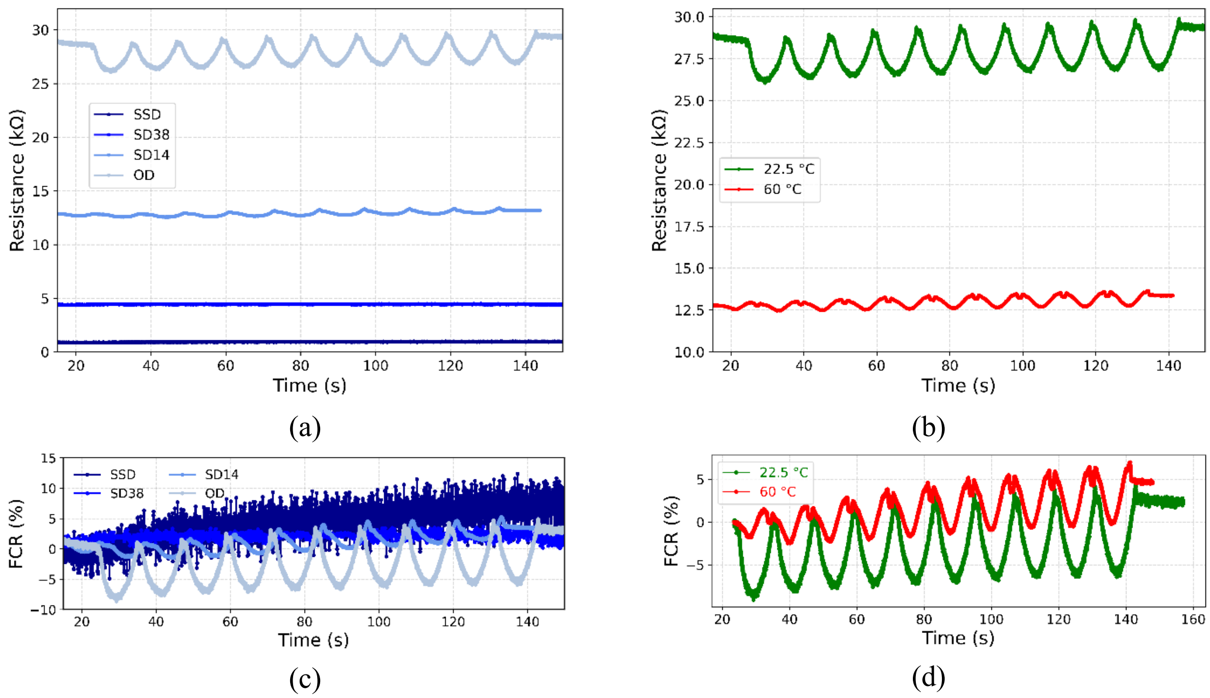

Figure 1. (a) Electrical resistance vs. saturation level, (b) electrical resistance vs. temperature, (c) FCR vs. saturation level, (d) FCR vs. temperature

Table 1. Stress Sensitivity change due to environmental conditions

Environmental Effect		Stress Sensitivity (%/MPa)
Saturation Degree	SSD	-
	SD38	-
	SD14	0.460
	OD	1.805
Temperature (°C)	22.5	1.805
	60	1.150

4. CONCLUSIONS

This study explored the effect of internal humidity and temperature on the self-sensing property of 3D printed concrete (3DCP) columns. The piezoresistive property, particularly the peak fractional change in resistivity (FCR) and stress sensitivity (SS), is affected by the environmental conditions. Humidity and temperature led to a decrease in resistance, which was expected. However, their influence on the piezoresistive behavior was contrary to the prevailing assumption. The high saturation and temperature lowered stress sensitivity and increased the noise in FCR. It is postulated that the percolation network formed by the ions in the pore water could be the driving force in the observed change. Our future work

will concentrated on analysis of the pore structure and distinguishing the ionic and electronic conduction in 3DCP structural members.

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