1. Report No. LS-24-RP-02	2. Government Accession No N/A	3. Recipient's Catalog No. N/A
4. Title and Subtitle 3D Printed Smart Permanent Concrete Formwork for Precast Structural Component		5. Report Date 12/01/2025 6. Performing Organization Code N/A
7. Author(s) Khalilullah Taj, Mr., 0000-0003-4746-936X Yen-Fang Su, Dr., 0000-0001-8410-0997		8. Performing Organization Report No. LS-24-RP-02
9. Performing Organization Name and Address Louisiana State University and Agricultural & Mechanical College 3255 Patrick F. Taylor Hall, Baton Rouge, LA, 70803		10. Work Unit No. N/A 11. Contract or Grant No. 69A3552348333
12. Sponsoring Organization Name and Address Transportation Infrastructure Precast Innovation Center (TRANS-IPIC) University of Illinois Urbana-Champaign. Civil & Environmental Engineering. 205 N Mathews Ave, Urbana, IL 61801 US Department of Transportation Office of Research, Development and Technology (RD&T) 1200 New Jersey Avenue, SE Washington, DC 201590		13. Type of Report and Period Covered Final Report January 2025-December 2025 14. Sponsoring Agency Code N/A
15. Supplementary Notes For additional reports and information visit the TRANS-IPIC website https://trans-ipic.illinois.edu		

16. Abstract

This project explores the integration of self-sensing cementitious composites (SSCCs) into additively manufactured permanent formworks to enable intelligent precast concrete components. Additive manufacturing allows targeted embedding of SSCCs in critical sections, providing strain-monitoring capability while minimizing material cost. The research includes material development, comprehensive characterization, and small-scale component testing to evaluate sensing reliability under mechanical loading. Digital image correlation (DIC) and a complementary Multiphysics model were employed to validate and predict the electromechanical response. The results confirm that the fabricated precast elements achieved high structural performance and strong piezoresistive sensitivity. This work demonstrates the feasibility and benefits of combining advanced materials with 3D-printed formworks, offering a promising pathway toward durable, intelligent infrastructure systems through additive manufacturing.

17. Key Words 3D concrete printing, Self-sensing cementitious composite, precast concrete		18. Distribution Statement No restrictions.	
19. Security Classification (of this report) Unclassified.	20. Security Classification (of this page) Unclassified.	21. No. of Pages 20	22. Price N/A

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Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

3D Printed Smart Permanent Concrete Formwork for Precast Structural Component
LS-24-RP-02

FINAL REPORT

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Executive Summary:

The transportation infrastructure in the United States continues to face significant deterioration, underscoring the urgent need for construction methods that enhance durability and extend service life. Traditional structural health monitoring approaches are often neither affordable nor adaptable across the diverse conditions encountered in large-scale infrastructure systems. In contrast, self-sensing cementitious composites (SSCCs) offer the potential for accurate, real-time structural health monitoring without the need for external sensors.

This project investigates the feasibility of developing precast concrete elements with integrated self-sensing capabilities using additively manufactured (AM) permanent formworks. The work focuses on advancing multifunctional cementitious materials (specifically self-sensing cementitious composites (SSCCs)) and embedding them strategically within structural components to enable real-time stress and damage monitoring. This approach has strong potential to improve long-term performance, reduce inspection costs, and extend the service life of transportation infrastructure.

The study begins with comprehensive materials development and characterization. Among different tested conductive fillers, milled carbon fibers (CF) were identified as the most cost-performance effective conductive filler, providing stable electrical pathways and high sensitivity under mechanical loading. The research then progresses to fabrication of small-scale precast specimens using AM permanent molds, which allow precise placement of the SSCC layer only where sensing is needed. This selective placement strategy significantly reduces material usage and overall cost while maintaining sensing performance.

Various testing, including compressive strength, bond strength, rheology, flowability, and setting time evaluation, confirmed that the developed mixes achieve structural-grade properties. The 3D-printed permanent molds produced precast columns with 28-day compressive strengths exceeding 6000 psi. Embedded self-sensing sections demonstrated strong piezoresistive response, with measured stress sensitivity reaching 15.43 %/ksi, validating their ability to detect mechanical loading and strain changes.

To support interpretation of the sensing behavior, a Multiphysics numerical model was developed to simulate the electrical–mechanical response of the SSCC region. The model correlates closely with experimental trends, providing a predictive tool for future design and optimization of multifunctional precast components.

The findings confirm that AM-enabled permanent formworks provide a practical pathway for integrating self-sensing materials into precast infrastructure. However, calibration protocols for piezoresistive response are needed to address variability between specimens. Additional large-scale testing and integration of reinforcement are also essential steps before field deployment. The methodology developed in this project is extendable to other precast components, including beams and panels, where SSCC embedment strategies may differ.

Overall, this work demonstrates the technical feasibility and strong potential impact of multifunctional precast elements produced using additive manufacturing. By embedding sensing capabilities directly into structural components, this approach offers a transformative avenue for improving durability, reliability, and safety across the transportation infrastructure network.

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1. **Problem description:**

The aging and degradation of transportation infrastructure in the U.S. due to material degradation, environmental and location-specific issues, overloading, and operational factors is a critical concern that requires immediate attention. Introducing emerging technologies such as advanced materials and structural health monitoring (SHM) technology into concrete infrastructure systems is a promising approach to address these concerns[1]. Advanced infrastructure materials with better mechanical performance and durability can significantly enhance the service life of infrastructure. Emerging SHM technologies would allow us to access in-situ structural conditions and evaluate maintenance needs. Although current SHM technologies are able to obtain reliable data for monitoring concrete structures with various instrumentations, limitations such as low durability, compatibility issues with materials, constant power supply needs, and high installation costs hinder widespread applications [2]. Specifically, addressing these disadvantages and integrating the critical features is necessary to enhance the durability and lifespan of precast concrete (PC) transportation systems. Thus, this research employs novel self-sensing cementitious composites (SSCCs) together with additive manufacturing (AM) to introduce stress-sensing capability into precast concrete components. Permanent molds produced through AM were used in place of conventional precast molds. The mechanical and electrical properties of the materials were comprehensively characterized to evaluate their feasibility for structural and sensing applications.

2. **Background:**

Precast concrete is an advanced construction method commonly employed in transportation infrastructure where concrete elements are cast in a controlled environment before being transported and assembled into their final position on site [3]. This technique boasts numerous advantages, such as shorter overall construction periods, superior quality control, and reduced disruption to traffic operations. Specifically, precast concrete can support the development of transportation infrastructure and help achieve Accelerated Bridge Construction (ABC) goals[4], which aim to drastically reduce the duration of onsite construction activities through the use of prefabricated bridge elements and systems. While PC provides more design versatility than cast-in-place concrete, producing unique shapes or incorporating intricate details remains challenging. This is primarily because of the requirement for expensive formwork or specialized molds. With the rise of additive manufacturing, AM concrete permanent formworks have emerged as a game-changing innovation in the construction industry. Additive manufacturing (or 3D concrete printing, 3DCP) uses extrusion-based 3D printing to deposit concrete layer-by-layer with the help of a robotic arm or a gantry system [5]. They offer unprecedented design freedom that obviates the necessity for formwork, allowing for the creation of intricate and bespoke shapes that would be challenging or even impossible with traditional formwork methods [6]. It is an emerging method for construction that leverages automation heavily to potentially make strides in reducing cost, construction duration, and risk of injury to workers. Due to the huge potential of this technology, it has generated a lot of interest in the automation and construction material research community. The shift from traditional formwork to 3DCP in concrete fabrication introduces an array of challenges but, more importantly, unique benefits. A layer-by-layer concrete deposition system in 3DCP offers the ability of very precise material modification. This is specifically suitable to be utilized in a range of multifunctional materials, such as self-sensing materials [7].

Self-sensing cementitious composites (SSCCs) are an emerging category of composites that contain electrically conductive fillers in the mix design, which accommodate stress-sensing, strain-sensing, fracture, and damage monitoring [8]. A relatively small amount of these fillers, when dispersed well, can form a network that permits the transfer of electrons [9]. Additionally, the gaps in the network prevent the composite from behaving as conductive material. The application of mechanical loading or strain changes the length of the gaps between the conductive fillers, thus changing the electrical resistivity. By applying a current through the affected section and simultaneously measuring the change in voltage, the change in loading or strain can be detected. Sensing the properties without embedding expensive sensors is an affordable solution to structural health monitoring.

An eclectic range of conductive fillers has been explored for self-sensing. They can be categorized into metal and carbon-based fillers. Short steel fiber, nickel powder, and nickel fiber have been used to promote self-sensing properties in cementitious materials [10]–[12]. Carbon-based fillers have the advantage of being corrosion-resistant on top of providing self-sensing capability. Carbon nanotube (CNT), carbon black, graphene oxide, and graphene nanoplatelets are just some of the examples of this category of conductive fillers [10], [13], [14]. Chopped carbon fiber (cCF) has distinguished itself as a more affordable type of carbon-based filler. Recently, the excellent electrical properties of chopped carbon fiber have led researchers to investigate its potential as a conductive filler in SSCC. It was reported that the dosage necessary for forming the electrical network required for self-sensing is 0.5 wt% to 3 wt% [15], [16]. Another important parameter in the efficiency of conductive fillers is their aspect ratio. cCFs with lengths of 6 mm and 12 mm were used at the same dosage in an SSCC. The resultant gauge factor (an index used for quantifying self-sensing) was recorded as 74% and 227%, respectively.

There is a lesser-known type of carbon fiber, which is actually repurposed during the processing of the continuous fiber sheets. It is known as milled carbon fiber (mCF). It is both an affordable and environmentally friendly type of carbon-based filler [17]. During this thorough literature review, it was discovered that there is a lack of knowledge on the feasibility of mCF as a conductive filler in SSCCs. Similarly, carbon black (CB) is a cost-effective source of conductive filler in SSCC [18]. Although its aspect ratio is not impressive, its low price can accommodate its usage in higher dosages. Finally, pristine graphene, although more expensive than the rest of the fillers mentioned above, can be competitive due to its extremely high aspect ratio. Short CF has 2 subcategories: chopped CF and milled CF. Although both of these share similar diameters, their average length diverges from each other. Table 1. Summarizes the physical properties of the short CFs that are used for the purpose of self-sensing in concrete. Milled CF is a byproduct of the processing of continuous CF. It is a affordable source of conductive filler that is chosen for this study. We found out that despite the impressive properties that milled CF possesses, investigation on the self-sensing characteristics of this fiber has been severely limited. Furthermore, it has a significant advantage over chopped CF. Since it is a byproduct of the CF industry, its fecundity and cost-effectiveness can be leveraged for mass use in the transportation infrastructure.

Table 1. The list of short CF usage in the self-sensing concrete.

Type	Length (mm)	Diameter (μm)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Resistivity (10^{-3}.Ω.cm)	Reference
Copped CF	3	7	4137	242	1.55	[2]
	5	7	3800	220	N/A	[19]
	6	11	2600	N/A	2.30	[13]
	6	7	4000	240	N/A	[20]
	6	7	3500	230	1.50	[21]
	6	7	4000	240	1.50	[8]
	6	7	3000	230	1.50	[22]
	6	7.5	4000	240	1.50	[9]
	6.25	7	3800	228	1.55	[23]
	9	10	4000	220	1.50	[24]
	18	7	4900	230	1.60	[25]
Milled CF	0.15	7.2	3800	242	1.52	[26]

Given the growing synergy between additive manufacturing and advanced materials, a number of studies have investigated the incorporation of multifunctional concrete into 3D concrete printing. These range from self-sensing concrete to self-cleaning concrete, from concrete that acts as a shield against electromagnetic waves to functionally graded concrete [2], [27], [28]. Vlachakis et al. [7] were the first ones to use 3DCP for the purpose of fabricating self-sensing concrete. To attain the self-sensing property, they employed alkali-activated materials as the binder, which is rich in ions such as Na and K ions that facilitate the ionic conduction. In this study, only 45 mm by 45 mm self-sensing patches and 6 mm tall rings were 3D printed. Dulaj et al. [29] introduced conductive fillers such as graphene nanoplatelets (GnPs) to the mixture of 3D printed concrete. In this study, the effect of such conductive filler on the resistivity of concrete was measured. They report a slight increase in the resistivity sensitivity. Wang and Aslani [2] used cCF and activated carbon powder (ACP) in 3D printed cementitious mixes. They postulate that the process of 3D printing results in the alignment of fibers in one orientation and that the piezoresistive response is promoted significantly in the loading direction that is perpendicular to the printing direction. Even though 3DCP causes mechanical anisotropy, self-sensing behavior, both in terms of fractional change in resistivity (FCR) and repeatability that is superior to traditional mold-casting, was captured. Afterwards, they followed this research by embedding the self-sensing cementitious sensor in 1.5 m-long beams [30]. Although the electrical resistivity of the 3D printed sample was drastically lower than that of the mold-casted counterpart, the embedment of the cementitious sensor in the beam was not conducive to stable strain-sensing. Then, they investigated the self-sensing behavior of 1 m tall columns with shells that are entirely 3D printed with a self-sensing cementitious mixture [31]. They lowered the electrical resistivity of columns by two-thirds by shifting from mold-cast to 3D printing deposition. However, the self-sensing response of the small-scale concrete prisms was not successfully replicated in the larger-scale columns. The indiscriminate application of self-sensing concrete in 3DCP of structural envelopes, whatever the primary driving factor for the subpar piezoresistive behavior, does not alleviate the problem. In another study, Li and Aslani [32] investigated the mechanical and piezoresistive performance of slabs. They underline the necessity of further investigation on the utilization of self-sensing concrete in the structural members.

The unique attributes that 3DCP possesses can sometimes pose a challenge in achieving certain goals. For instance, fiber alignment caused by the extrusion of material through a nozzle that is smaller in diameter than the fiber length leads to mechanical anisotropy. However, these attributes can also be leveraged for the seamless adoption of multifunctional materials in additive manufacturing. One such attribute is the layer-by-layer deposition of concrete. For the purpose of structural health monitoring (SHM), which is an umbrella term for damage assessment of all kinds in infrastructure, strategic employment of self-sensing material in the critical zones is only possible via 3DCP. Instead of fabricating entire structural envelopes with piezoresistive concrete, deposition of multifunctional material in the sections that resist the maximum bending moments, axial, and shear loads will be the ideal approach. For instance, in members under flexural loading, such as beams, the loading effect is concentrated the most on the lower (tension) and upper (compression) surfaces. Thus, measuring the self-sensing only at the exterior is the better practical approach. Based on the findings of multiple studies, a higher FCR and stress sensitivity index were obtained in face-sustaining tension [33]–[35]. Therefore, only substituting the face undergoing tension with self-sensing concrete is the ideal way. This will not only increase the sensitivity of the SSCC but also decrease the cost.

Building upon prior research, this study conducts a comprehensive investigation into integrating self-sensing materials into additively manufactured permanent formworks for future transportation infrastructure applications. We began with material development and characterization, then extended the work to small-scale component testing to establish a standardized testing protocol. Additionally, numerical modeling was performed to predict the Multiphysics material properties and assess their feasibility for structural implementation. This unique capability enabled by additive manufacturing holds significant potential to advance precast concrete technologies, improving safety and extending the service life of critical infrastructure components.

3. <u>Research scope and objectives:</u>

The general goal of this project is to utilize advanced fabrication methods such as additive manufacturing and multifunctional materials, such as self-sensing cementitious composites, to equip stress and strain sensing capability in PC structural members. The detailed objectives of this project are the following:

- Find ways to incorporate SSCCs via the layer-by-layer AM nature; thus, tailoring materials and properties within a single PC component.
- Assess the feasibility and efficacy of strain and stress sensing capability of AM PC members that embedded SSCC sections to determine the right material formulations.
- Develop a Multiphysics numerical model to optimize the design through comprehensive simulations across materials, geometries, and performance metrics.

4. <u>Research description:</u>

The project encompassed assessing material properties, fabricating specimens and identifying preliminary SSCC placement, conducting load testing with strain monitoring, and developing a preliminary Multiphysics model.

4.1. Material Properties and Mix Design

After conducted the thorough literature review and sourced the materials, three types of conductive fillers were chosen including pristine graphene, milled carbon fiber, and carbon black. Pristine graphene (PG) is a carbon-based conductive material that possesses impressive mechanical properties. It is the building block of graphite, which has numerous utilities, such as pencil tips. Its extraordinary physical properties, such as its high aspect ratio of low electrical resistivity, are evidenced by **Error! Reference source not found.**, are suspected to enhance the piezoresistive properties of cementitious composites. Although there is a noticeable difference in the material cost between milled carbon fiber (CF) and pristine graphene, the latter's aspect ratio and electrical resistivity are orders of magnitude higher. SEM images taken from the conductive fillers used in this study are shown in Figure 1. Carbon black (CB) is a low-cost by-product that can enhance the piezoresistive properties of concrete significantly. The physical properties of the carbon black used in this study are shown in Table 3. The mix design of 3D printable cementitious mixes is presented in Table 4. A series of mortar mixes with these conductive fillers were evaluated for rheological, mechanical, and self-sensing properties.

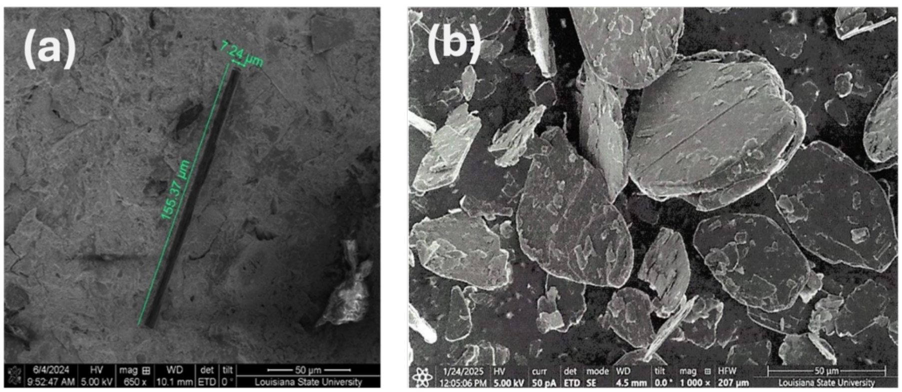


Figure 1. SEM images from (a) milled CF and (b) pristine graphene.

Table 2. Physical characteristics of the milled CF and pristine graphene in this report.

Characteristic	Pristine Graphene	Milled CF
Number of layers	2-4	-
Z-axis dimension	7.011 x 10-4	7.2
Lateral dimension	26.4	155
Aspect ratio	37655.11	21.52
Particle shape	Flake/sheets	rod
Bulk density (g/cm3)	0.3	0.49
Resistivity (ohm · cm)	6.85 x 10-5	1.55 x 10-3

Table 3. Physical characteristics of the CB used in this report [36].

Characteristic	CB
Iodine absorption (mg/g)	82
STSA (m2/g)	7.76
Oil absorption number (ml/100g)	102
Heating loss at packing (%)	<1.0
Sieve residue 325 mesh (ppm)	<500
Individual pellet hardness (g)	<45
Pour density (g/dm3)	350

To achieve a printable mix, a preliminary study was done. The parameters for an acceptable print were the extrudability and buildability. Extrudability is the term used to describe the constant flow of the material that is extruded from the nozzle of a 3D printer. Buildability is commonly used for the ability of mortar filaments to be stacked on top of each other. To ensure the same printing properties after the addition of conductive fillers, the rheological properties of the successful print were evaluated. The dosage of binder to sand was kept as 1:1 to obtain a high-cohesion mortar mix that doesn't result in any discontinuities during the printing process. To prevent the drying shrinkage and increase the cohesion of the mortar even further, OPC was replaced with silica fume at 20 wt%. Finally, to obtain the optimum mix design to satisfy the 3D printing needs, such as extrudability, buildability, and open time, W/C of 0.4 and a certain dosage of polycarboxylate ether (PCE)-based superplasticizer were incorporated. The dosage of conductive filler incorporated is also a critical parameter in the self-sensing concrete. When the electrically conductive fiber or particles are used in the optimal dosage, a significant decrease in the resistivity of the cementitious composite is observed. There is considerable research on the effect of the different dosages of carbon-based fillers. The ideal content of conductive fillers in self-sensing concrete is also influenced by their resistivity and aspect ratio. Based on the reports on the effect of different conductive fillers with comparable properties, the ideal dosage of milled CF in cementitious composite seemed to be 0.1%-1%. The W/B Once the range for the dosage of milled CF was finalized, a preliminary study on the feasible dosage of PG was done. The upper threshold for the PG dosage was its effect on workability. The effect of milled CF and PG on the mix was evaluated using a flow table. It is revealed that both milled CF and PG had minimal effect of the fresh properties at the dosages used in this study.

Table 4. Weight-based mix design ratios

Mix	OPC	Silica Fume	Sand	W/C	Filler Type	Superplasticizer	Filler Dosage*
C	0.8	0.2	1	0.40	-	PCE derivative	-
CF01					Milled CF		0.001
CF05							0.005
CF10							0.01
PG005					Pristine graphene		0.0005
PG01							0.001
PG02							0.002
CB01					Carbon black		0.01
CB03							0.03
CB05							0.05

* By weight of cement

4.2. Testing Procedures

The fresh, mechanical, and electrical properties of the samples were assessed through flowability and setting time measurements, rheological characterization, compressive strength testing, bond strength evaluation, and self-sensing performance assessment.

Flowability of cementitious mixes was measured according to the flow diameter test described in ASTM C1437 [37]. An automatic Vicat apparatus was used for measuring the initial and final setting times. The procedure of the test conformed to ASTM C191 [38]. The shear stress and viscosity of the fresh mixes were evaluated with a Brookfield rheometer. For the mechanical behavior, the compressive strength test was performed on the 28th days on the hardened cubic specimens. The average of three specimens were taken for each age. The compression test was conducted via a Gilson AC-325MR compression machine. ASTM C39 and C109 [39] was followed for this test; the loading rate was 50 psi/s and the preload was 200 lbf. The bonding strength of the concrete was evaluated following ASTM C1583 standards [40] using DeFelsko pull-off adhesion testers.

The self-sensing properties of the cubic specimens were gauged via cyclic loading of the specimens with a loading rate of 200 psi/sec. The upper and lower loading thresholds were 100 psi and 1000 psi. The upper threshold of 1000 psi represented ~10% of the f'c; therefore, the loaded specimen remained in the elastic region. To negate the polarization effect, the 4-probe method is used to measure the electrical impedance. In this method, the electrical current is supplied through the outer electrodes, and the inner electrodes are used to take measurements of the impedance. Instead of direct current (DC), alternative current (AC) is used. The applied electrical current and its frequency are 10 mA and 5 kHz, respectively. The relationship between impedance, voltage, and current is given in Equation 2. Fractional change in resistivity (FCR) is calculated using Equation 3.

$$Z = \frac{V}{I} \tag{2}$$

$$FCR = \frac{Z_i - Z_0}{Z_0} \tag{3}$$

Electrical impedance (Z) is obtained by dividing the voltage (V) by the current (I). FCR is a unitless value obtained from the initial impedance (Z0) and the impedance at a given load (Zi). Stress sensitivity (SS) is obtained via the ratio FCR per applied stress (Equation 4).

$$SS = \frac{FCR}{\sigma} \tag{4}$$

5. Project results:

5.1. Compressive Strength

The 28th day compressive strength of the reference mix and the self-sensing cementitious composites (SSCCs) designed in this study are shown in **Error! Reference source not found.** (a). The effect of milled CF on the compressive strength was supplementary. It increased the compressive strength from 4750 psi to over 7000 psi with the addition of 0.5 wt%. The compressive strength, however, decreased once the dosage exceeded 0.5 wt%. At 1 wt%, the compressive strength dropped to 5410 psi. The mechanism behind the effect of carbon fiber in cementitious materials is thought to be the increase in the nucleation sites for hydration products due to the high specific surface milled CF. Additionally, it might have decreased the volume capillary and larger voids by the bridging effect. Nevertheless, once the milled CF content exceeded the critical threshold, it is postulated that it led to the formation of agglomerations. Agglomerations can be the hotbed of anisotropy and lead to stress concentration, which reduces the ultimate strength in concrete. The pristine graphene, on the other hand, displayed a negligible effect. Its addition didn't result in a significant change in the compressive strength. This might be due to the relatively low dosage that pristine graphene that was used. The effect of carbon black was mostly detrimental to the strength.

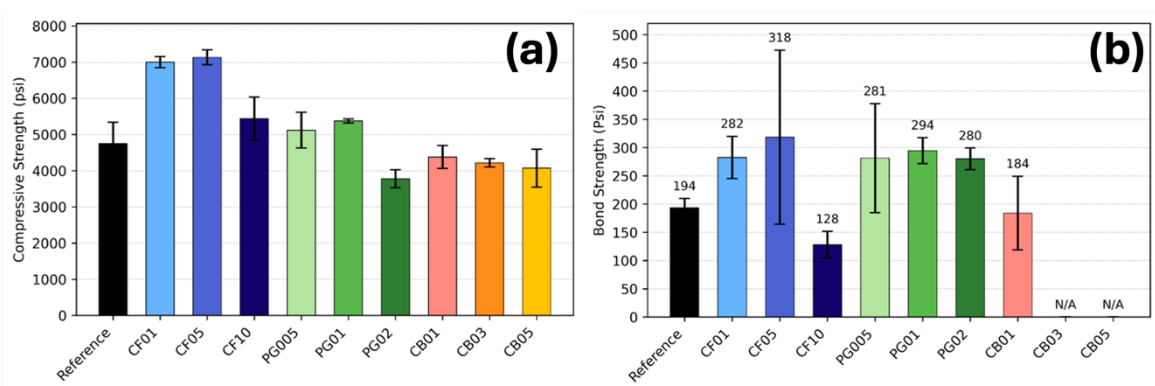


Figure 2 (a) 28th-day compressive strength of SSCCs; (b) Bond strength development of SSCCs

5.2. Bond Strength

The interlayer bond strength was evaluated according to the ASTM C1583 standard. Both milled CF and PG are effective in improving the bond strength of the cementitious mortar (**Error! Reference source not found.** (b)). Lower dosage of milled CF (0.1% and 0.5%) increased strength from 194 psi to 282 psi and 318 psi, respectively. However, at 1%, CF had an unwanted effect on the bond strength. PG, on the other hand, had promising results in all the dosages tested (0.05%, 0.1%, and 0.2%). However, the variation in the effect of different dosages was minimal. On the other hand, CB reduced the bond strength significantly. For the lowest CB dosage of 1%, the bond strength was 184 psi. Upon further increase of the dosage, the layer of mortar was completely stripped from the concrete substrate during coring. Therefore, no data was obtained for these dosages.

5.3. Fresh and Rheological Properties

The fresh properties of all the mixes, details of which are shown in Table 4., were analyzed. This was done to verify if the rheological properties of the mixes accommodate the 3D printing method of fabrication. With this aim, the setting time, flowability, viscosity, and shear stress of the mixes were tested (Figure 3). Flowability revealed in Figure 3 (a) that the addition of conductive fillers, in general, led to a reduction in the flowability. The highest flowability was observed in the control mix. The range of 160-180 mm allowed for high printability and extrudability. The extreme decrease in the flowability due to the incorporation of CB does not associate well with 3D printing. The sharp decline in flowability correlated with the increase in the dosage of CB, to the extent that the test couldn't be performed for CB05. The observations from the flowability show that milled CF and PG mixes are compatible for 3D printing.

The addition of various conductive fillers at different dosages has not affected the final setting time significantly (Figure 3 (b)). However, the initial setting time appears to be influenced by the type and content of the conductive filler. Setting time is a crucial metric for the mortar intended for 3D printing because "Open Time", which is a term used for the amount of time that the mix stays printable, is correlated with setting time. The longer the initial setting time, the bigger the open time is. The setting time reveals that all the tested conductive fillers are compatible with 3D printing. However, CB can only be used at lower dosages. The higher tested dosages might lead to rapid setting and cause issues with the extrusion.

Figure 3 (c) and (d) show the shear stress and dynamic viscosity of the cementitious mixes right after mixing. The presented data show the stress and viscosity values for the shear rate of 1/s to 1/100s. The collected data correlates with the finding of flowability. The shear stress was observed in the Control mix. The addition of conductive fillers increased the viscosity and shear stress at all shear rates. The test was not successfully performed on the CB mixes due to their extreme dryness.

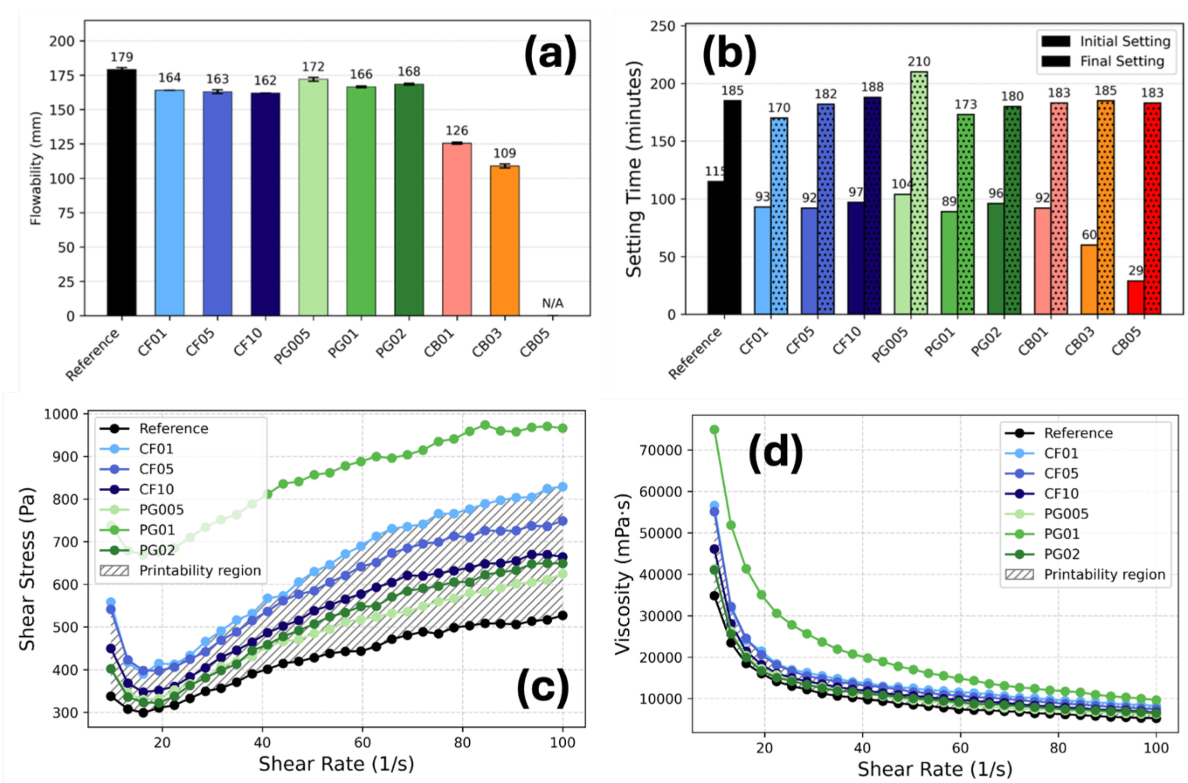


Figure 3 (a) Flow diameter of SSCCs; (b) Initial and final setting time of SSCCs; (c) Dynamic shear stress of SSCCs; (d) Viscosity of SSCCs

5.4. Sensing Performance Quantification

Figure 4 illustrates the piezoresistive properties of the SSCC mixes via fractional change in resistivity (FCR). As can be seen, no significant change in resistivity is measured for the Control mix. The addition of milled CF at 0.5 wt% resulted in a strong correlation of the applied cyclic load with a change in resistivity. The addition of PG did not affect the piezoresistive performance of the mortar considerably. At 0.1 wt%, however, a change in resistivity was observed. CB, on the other hand, influenced the resistivity at all the tested dosages significantly. Even at a dosage of 1 wt%, a clear change in the line representing the resistivity can be detected. Although this trend did not continue with the increase in the dosage of CB. It is reasonable to say that CB resulted in high sensitivity SSCCs at all the dosages. Whereas the milled CF was mostly effective at 0.5 wt%. Although PG, as a conductive filler, showed rheological and mechanical properties fit for 3D printing, its weak piezoresistive property makes it a less ideal candidate as a conductive filler. Table 5. Details the stress sensitivity, an index used for self-sensing, of different SSCC mixes. It is clear that the CB mixes show impressive performance, but due to the low mechanical strength and undesirable rheological properties, CB mixes are not fit for 3D printing. Milled CF, on the other hand, on top have demonstrated high piezoresistivity, and it also satisfies the printing parameters. CB shows potential at lower dosages.

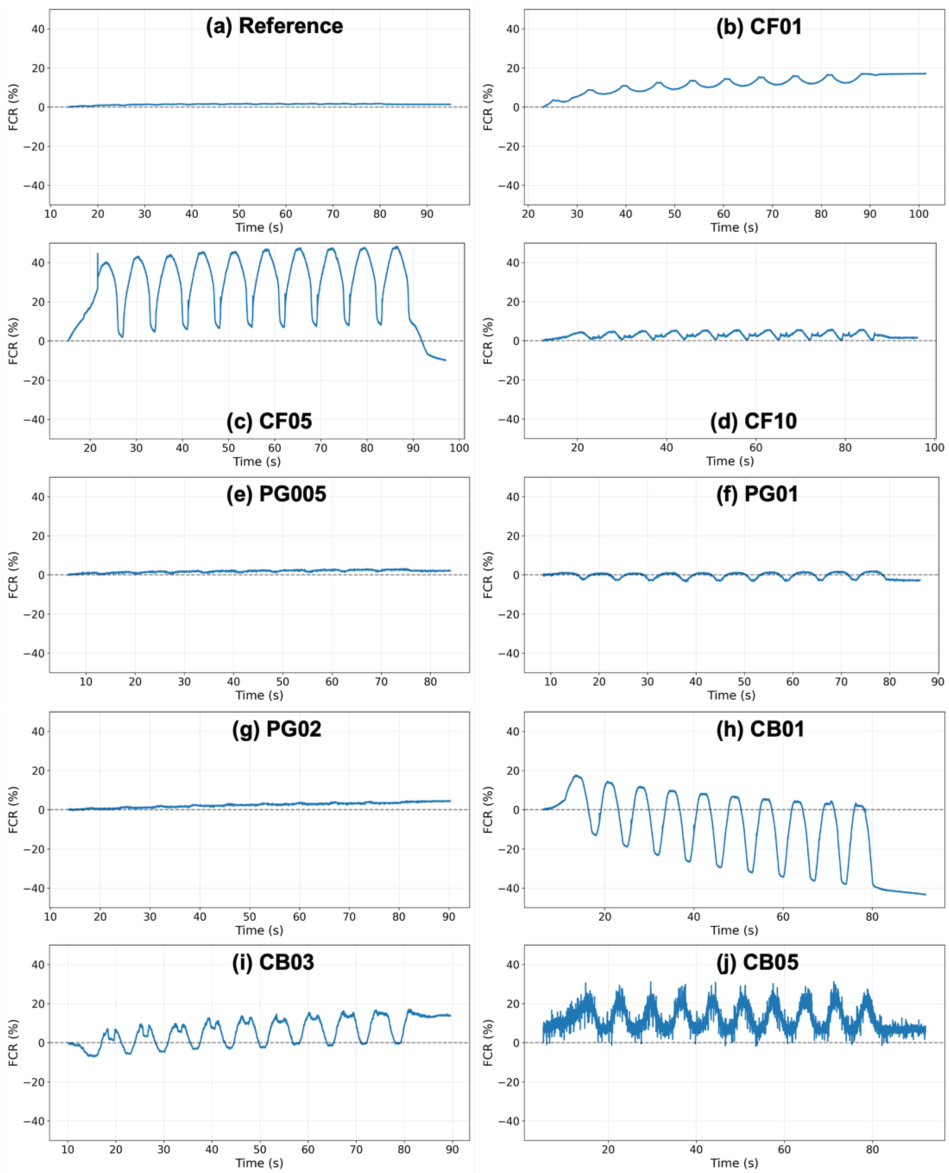


Figure 4. Fractional change in resistivity versus cyclic compressive loading.

Table 5. Stress sensitivity of different SSCC mixes.

Mix	Stress Sensitivity (%/ksi)
Reference	-
CF01	5.09
CF05	35.65
CF10	3.85
PG005	-
PG01	2.72
PG02	-
CB01	42.48
CB03	16.71
CB05	32.43

5.5. Specimen Fabrication and Self-Sensing Performance

Based on the rheological, mechanical, and piezoresistive performances of the cementitious mixes with varying types and dosages of conductive fillers, milled CF at 0.5 wt% was chosen for the next step. In this step, an additively manufactured 3D printed mortar shell was aimed. To this end, 6”x6”x12” shells were printed (Figure 5 (a)). These shells contained a reference mix at the top 1/3 and bottom 1/3. The middle 1/3 consisted of the self-sensing mix (e.g., CF05). Six specimens with the same mix designs and configurations were printed simultaneously. This is done to ensure the ability to replicate the testing on more than one specimen. Additionally, solid blocks of mortar with a height of 8” were 3D printed to be used in the future for obtaining a stress-strain curve. At the end of 28 days of curing, specimens will be subjected to compressive cyclic loading, and the change in the electrical voltage will be detected using a galvanostat (Figure 5 (b)). The 4-probe method will be used for performing the self-sensing test. Images seen in Figure 5 (c) and (d) show the coring process of the 3D printed mortar block and the 4”x8” specimen. After 28 days of curing, a compressiometer with two LVDTS will be fixed on the shown specimen, and the specimen will be loaded until failure compressively.

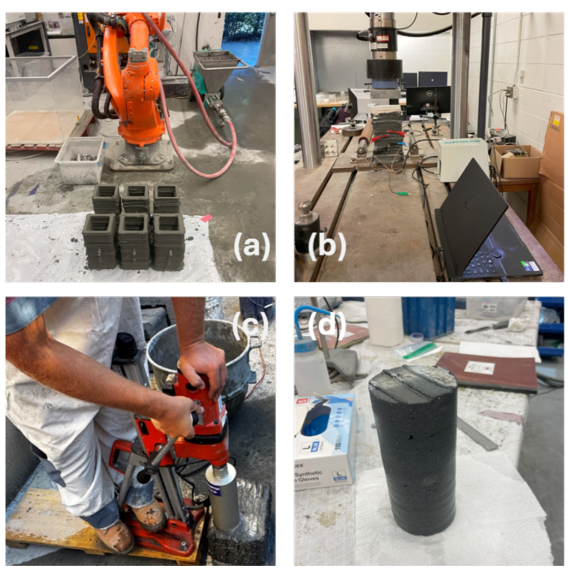
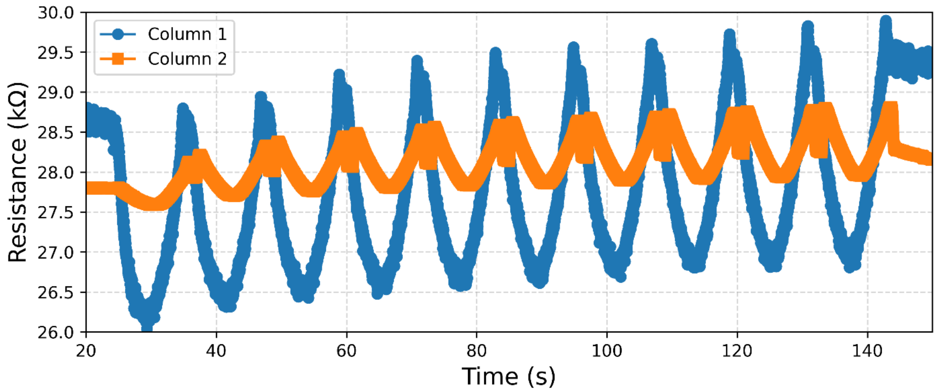


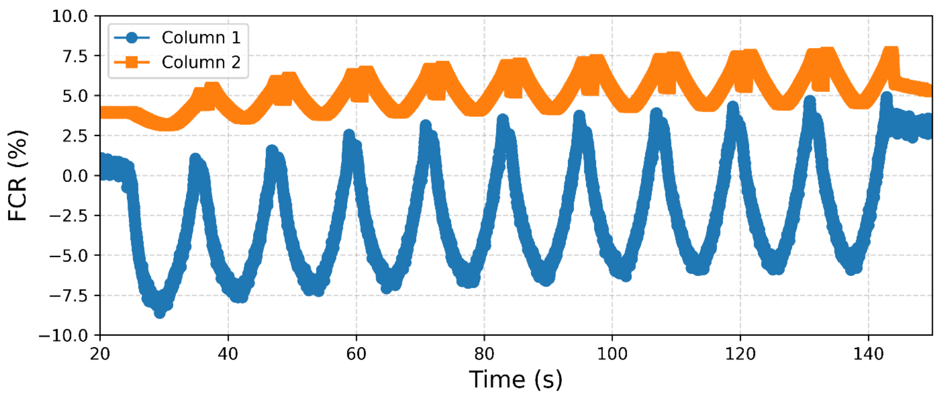
Figure 5. (a) 3D printed 6”x6”x12” specimens (b) piezoresistivity test on 3DCP specimens (c) coring process from 3DCP block (d) cored 4”x8” specimen

The self-sensing performance of the columns with embedded SSCC is shown in Figure 6. From the total of 6 columns with identical permanent molds, sensor placement, and mix design, 3 were used for testing the 28th-day compressive strength. The remaining 3 were used for piezoresistivity-based self-sensing testing. The average 28th-day compressive strength for the columns was 6253 psi. For self-sensing, 10% of this f'c was applied in a cyclic loading regime on the specimens. Figure 6 (a) and (b) show the resistance obtained from the test and the normalized FCR. The Figure only shows the results for 2 column specimens; comparable results were not obtained from the 3rd one.

The inclusion of a sensing section in the permanent mold decreased the electrical resistance of the column. Additionally, this was verified by more than one specimen. The average resistance measured is 28.33 KΩ. The application of mechanical loading resulted in a gradual decrease in the resistance. The lowest measured resistance is 26 KΩ. Although the valleys for Column 1 are deeper than Column 2, the measured average resistances are similar to each other, which points to the repeatability of the process. The FCR shows that with the application of 10% f'c, an FCR of more than 7.5% is observed. The stress sensitivity calculated is 15.43 %/ksi. This shows that with the introduction of an SSCC sensor in the mid-section of the column, stress sensitivity can be achieved.



(a)



(b)

Figure 6. (a) resistance change and (b) FCR under cyclic loading for columns 1 and 2.

5.6. Construction of a Preliminary Multiphysics Model and DIC Analysis

A preliminary multiphysics model developed using COMSOL Multiphysics simulation software was further refined to better simulate the self-sensing behavior of concrete. The Electric currents and the Solid Mechanics interfaces were employed for this purpose.

The specimen was modeled as 2×2×2 in^3 cubes with four electrodes embedded in them. Concrete was assigned an elastic modulus of 25 GPa, Poisson's ratio of 0.2, and a relative permittivity of 1. Electrodes were modeled as steel with an elastic modulus of 205 GPa, Poisson's ratio of 0.28, and a relative permittivity of 1.

To simulate the self-sensing behavior of concrete, strain-dependent electrical conductivity was defined using the exponential model in Eq. 5:

$$\sigma(\varepsilon) = \sigma_0 e^{-k\varepsilon} \tag{5}$$

where σ_0 is the base conductivity, k is the piezoresistive constant, and $\mathcal{E}$ is the strain.

The model was calibrated to match the resistance response observed in the CF05 specimen. It was supplied with a 1 mA DC current and subjected to loading at a rate of 200 psi/s, oscillating between an upper threshold of 500 psi and a lower threshold of 25 psi. The corresponding resistance signal for CF05 is presented in Figure 7.

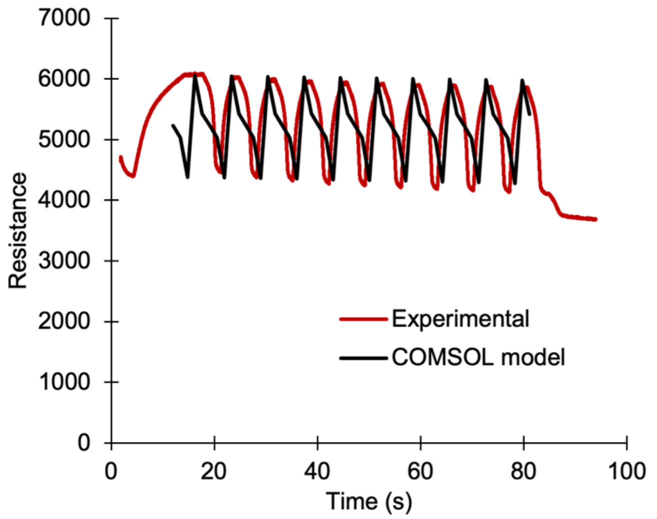


Figure 7. Comparison of experimental resistance and resistance obtained from the multiphysics simulation.

Calibration yielded a σ_0 of 0.00096 S/m and a k of 25,695. Figure 7 shows the resistance output obtained using the model. The model successfully captured the amplitude and the frequency of the signal. It also predicts the downward trend observed in the experimental resistance response as the number of cycles increases. The comparison of the experimental and model results yielded a coefficient of determination (R^2) of 0.25 for cycle 2. However, the experimental-to-model ratio of 0.999 indicates a strong match between them. The strains obtained from CF05 are shown in Figure 8 (a) and (b). The data obtained from DIC were noisy and slightly higher than the expected values. However, it is observed that the strain decreases as the loading rate is increased. This finding validates that the increased loading rate in cyclic loading decreases the risk of irreversible change. Further work is being conducted to verify the accuracy of the data and reduce noise.

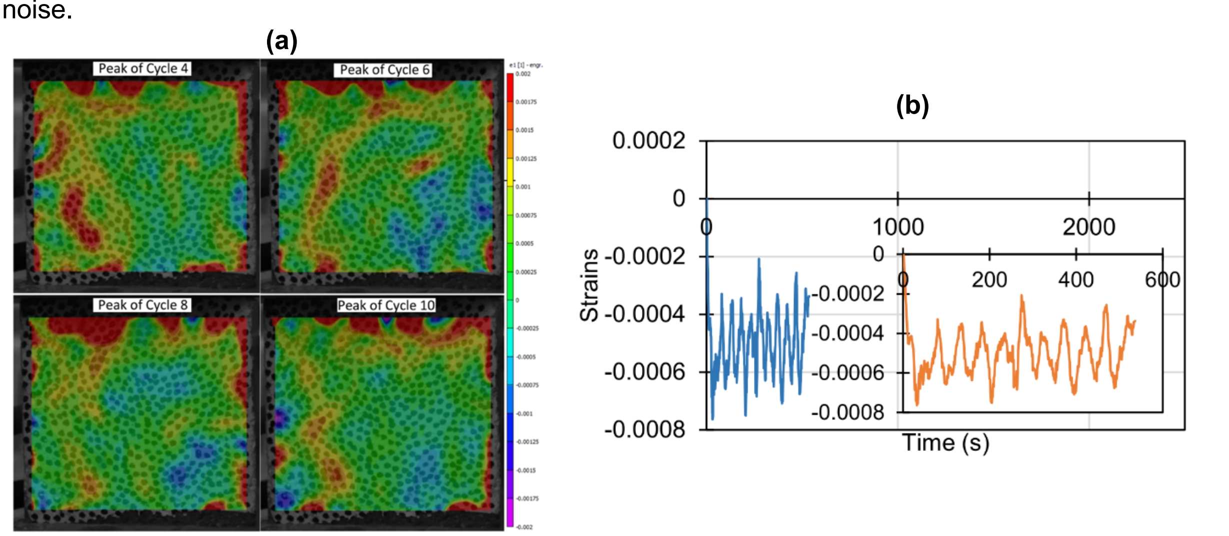


Figure 8. (a) contour plot of strain at different loading cycles (b) the strains from the first to the last cycle.

6. Conclusions and recommendations:

The feasibility of producing durable precast concrete columns with self-sensing capability was demonstrated in this report. The results indicate that milled carbon fibers (CF) are an excellent conductive filler for the SSCC portion of the column. Embedding the sensor only within the mid-section of the permanent mold reduces material cost while still achieving a strong and reliable self-sensing response. This approach is enabled by additive manufacturing, which allows precise placement and fabrication of the permanent formwork. The columns with AM-based permanent molds achieved an impressive 28-day compressive strength exceeding 6000 psi, and the calculated stress sensitivity reached 15.43 %/ksi. Furthermore, a Multiphysics model that closely correlates with the experimental observations was developed.

Calibration of the piezoresistive response after fabrication is necessary for practical implementation. Although the absolute resistance values among replicate specimens were similar, the magnitude of resistivity change during loading exhibited noticeable variability. Larger-scale structural component testing is therefore required to establish repeatability and to refine the calibration procedure. In addition, incorporating reinforcement is essential to ensure structural practicality and compliance with design standards. Extending this method to other precast elements (such as beams) is also recommended, as the optimal embedment configuration of the SSCC section may differ depending on the member geometry and loading conditions.

7. Practical application/impact on transportation infrastructure:

The outcomes of this research present a feasible and high-value pathway for enhancing the durability, safety, and maintainability of transportation infrastructure. By integrating self-sensing cementitious composites (SSCCs) into additively manufactured permanent formworks, precast concrete members can be equipped with built-in strain and damage monitoring capabilities without relying on external sensors or complex instrumentation. This enables continuous, real-time structural assessment throughout a component's service life, reducing the need for costly inspection programs and allowing early identification of deterioration, overstress, or abnormal loading conditions.

The selective placement of SSCCs only in critical regions further enhances the practicality and affordability of implementation. Additive manufacturing enables precise embedment and rapid fabrication, making it compatible with current precast workflows and adaptable to common structural elements such as columns, beams, and bridge components. The compressive strengths achieved (> 6000 psi) and the demonstrated stress sensitivity confirm that the developed system meets structural performance requirements while providing added sensing functionality.

Potential implementation can follow a phased approach. Initially, the technology may be deployed in non-critical precast elements or demonstration projects to validate performance at scale. After establishing calibration protocols and verifying repeatability, integration into reinforced structural members can enable full-scale field deployment. In the long term, smart precast components produced through this method could support predictive maintenance, improve asset management strategies, and extend the operational lifespan of bridges and other transportation infrastructure systems.

8. References:

[1] G. Jing, M. Siahkouhi, J. Riley Edwards, M. S. Dersch, and N. A. Hoult, "Smart railway sleepers - a review of recent developments, challenges, and future prospects," *Constr. Build. Mater.*, vol. 271, no. 121533, p. 121533, Feb. 2021.

[2] L. Wang and F. Aslani, "Structural performance of reinforced concrete beams with 3D printed cement-based sensor embedded and self-sensing cementitious composites," *Eng. Struct.*, vol. 275, no. 115266, p. 115266, Jan. 2023.

[3] S. Reichenbach and B. Kromoser, "State of practice of automation in precast concrete production," *Journal of Building Engineering*, vol. 43, p. 102527, Nov. 2021.

[4] M. P. Culmo, B. Lord, M. Huie, and B. Beerman, “Accelerated bridge construction: Experience in design, fabrication and erection of prefabricated bridge elements and systems: Final manual,” United States. Federal Highway Administration. Office of Bridge Technology, FHWA-HIF-12-013, Jan. 2011.
[5] M. Abedi, M. B. Waris, M. K. Al-Alawi, K. S. Al-Jabri, and A. H. Al-Saidy, “From local earth to modern structures: A critical review of 3D printed cement composites for sustainable and efficient construction,” *J. Build. Eng.*, vol. 100, no. 111638, p. 111638, Apr. 2025.
[6] Y. Chen, Y. Zhang, Z. Liu, Y. Zhang, C. Liu, and B. Pang, “3D-printed concrete permanent formwork: Effect of postcast concrete proportion on interface bonding,” *Mater. Lett.*, vol. 344, p. 134472, Aug. 2023.
[7] C. Vlachakis, J. McAlorum, and M. Perry, “3D printed cement-based repairs and strain sensors,” *Autom. Constr.*, vol. 137, no. 104202, p. 104202, May 2022.
[8] A. D’Alessandro, H. B. Birgin, and F. Ubertini, “Carbon microfiber-doped smart concrete sensors for strain monitoring in reinforced concrete structures: An experimental study at various scales,” *Sensors (Basel)*, vol. 22, no. 16, p. 6083, Aug. 2022.
[9] J. Zhang *et al.*, “Piezoresistivity and piezopermittivity of cement-based sensors under quasi-static stress and changing moisture,” *Constr. Build. Mater.*, vol. 425, no. 136052, p. 136052, Apr. 2024.
[10] S. Wang, A. Singh, and Q. Liu, “Experimental study on the piezoresistivity of concrete containing steel fibers, carbon black, and graphene,” *Front. Mater.*, vol. 8, p. 652614, Sept. 2021.
[11] B. G. Han, B. Z. Han, and J. P. Ou, “Experimental study on use of nickel powder-filled Portland cement-based composite for fabrication of piezoresistive sensors with high sensitivity,” *Sens. Actuators A Phys.*, vol. 149, no. 1, pp. 51–55, Jan. 2009.
[12] H. V. Le, M. K. Kim, S. U. Kim, S.-Y. Chung, and D. J. Kim, “Enhancing self-stress sensing ability of smart ultra-high performance concretes under compression by using nano functional fillers,” *J. Build. Eng.*, vol. 44, no. 102717, p. 102717, Dec. 2021.
[13] F. Azhari and N. Banthia, “Cement-based sensors with carbon fibers and carbon nanotubes for piezoresistive sensing,” *Cem. Concr. Compos.*, vol. 34, no. 7, pp. 866–873, Aug. 2012.
[14] H. Chu, Y. Zhang, F. Wang, T. Feng, L. Wang, and D. Wang, “Effect of graphene oxide on mechanical properties and durability of ultra-high-performance concrete prepared from recycled sand,” *Nanomaterials (Basel)*, vol. 10, no. 9, p. 1718, Aug. 2020.
[15] G. Yıldırım, O. Öztürk, A. Al-Dahawi, A. Afşın Ulu, and M. Şahmaran, “Self-sensing capability of Engineered Cementitious Composites: Effects of aging and loading conditions,” *Constr. Build. Mater.*, vol. 231, no. 117132, p. 117132, Jan. 2020.
[16] F. J. Baeza, O. Galao, E. Zornoza, and P. Garcés, “Effect of aspect ratio on strain sensing capacity of carbon fiber reinforced cement composites,” *Mater. Eng.*, vol. 51, pp. 1085–1094, Oct. 2013.
[17] B. Newman, C. Creighton, L. C. Henderson, and F. Stojcevski, “A review of milled carbon fibres in composite materials,” *Compos. Part A Appl. Sci. Manuf.*, vol. 163, no. 107249, p. 107249, Dec. 2022.
[18] B. Han, L. Zhang, and J. Ou, “Influence of water content on conductivity and piezoresistivity of cement-based material with both carbon fiber and carbon black,” *J. Wuhan Univ. Technol. (Mater. Sci. Ed.)*, vol. 25, no. 1, pp. 147–151, Feb. 2010.
[19] W. Tian *et al.*, “Electrical performance of conductive cementitious composites under different curing regimes: Enhanced conduction by carbon fibers towards self-sensing function,” *Constr. Build. Mater.*, vol. 421, no. 135771, p. 135771, Mar. 2024.
[20] A. Belli, A. Mobili, T. Bellezze, F. Tittarelli, and P. Cachim, “Evaluating the self-sensing ability of cement mortars manufactured with graphene nanoplatelets, virgin or recycled carbon fibers through piezoresistivity tests,” *Sustainability*, vol. 10, no. 11, p. 4013, Nov. 2018.
[21] T. Luo, Y. Ma, H. Xie, F. Li, Z. Li, and J. Fu, “Piezoresistivity of carbon fiber-reinforced alkali-activated materials: Effect of fly ash microspheres and quartz sands,” *Constr. Build. Mater.*, vol. 425, no. 136125, p. 136125, Apr. 2024.
[22] Y. Ma *et al.*, “Self-sensing properties of alkali-activated materials prepared with different precursors,” *Constr. Build. Mater.*, vol. 409, no. 134201, p. 134201, Dec. 2023.
[23] X. Fan, D. Fang, M. Sun, and Z. Li, “Piezoresistivity of carbon fiber graphite cement-based composites with CCCW,” *J. Wuhan Univ. Technol. (Mater. Sci. Ed.)*, vol. 26, no. 2, pp. 339–343, Apr. 2011.
[24] J. Han, J. Pan, and J. Cai, “Self-sensing properties and piezoresistive effect of high ductility cementitious composite,” *Constr. Build. Mater.*, vol. 323, no. 126390, p. 126390, Mar. 2022.

[25] H. Ran, M. Elchalakani, F. Boussaid, S. Yehia, M. A. Sadakkathulla, and B. Yang, “Development and evaluation of conductive ultra-lightweight cementitious composites for smart and sustainable infrastructure applications,” *Constr. Build. Mater.*, vol. 375, no. 131017, p. 131017, Apr. 2023.
[26] F. J. Baeza, O. Galao, I. J. Vegas, M. Cano, and P. Garcés, “Influence of recycled slag aggregates on the conductivity and strain sensing capacity of carbon fiber reinforced cement mortars,” *Constr. Build. Mater.*, vol. 184, pp. 311–319, Sept. 2018.
[27] J. Sun *et al.*, “Electromagnetic and mechanical performance of 3D printed wave-shaped copper solid superstructures,” *J. Mater. Res. Technol.*, vol. 27, pp. 6936–6946, Nov. 2023.
[28] H.-Q. Sun, J.-J. Zeng, G.-Y. Hong, Y. Zhuge, Y. Liu, and Y. Zhang, “3D-printed functionally graded concrete plates: Concept and bending behavior,” *Eng. Struct.*, vol. 327, no. 119551, p. 119551, Mar. 2025.
[29] A. Dulaj, T. A. M. Salet, and S. S. Lucas, “Mechanical properties and self-sensing ability of graphene-mortar compositions with different water content for 3D printing applications,” *Mater. Today*, vol. 70, pp. 412–417, Jan. 2022.
[30] X. Wang, B. Cao, C. Vlachakis, A. Al-Tabbaa, and S. K. Haigh, “Characterization and piezo-resistivity studies on graphite-enabled self-sensing cementitious composites with high stress and strain sensitivity,” *Cem. Concr. Compos.*, vol. 142, no. 105187, p. 105187, Sept. 2023.
[31] C. D. Atkinson and F. Aslani, “Performance of 3D printed columns using self-sensing cementitious composites,” *Constr. Build. Mater.*, vol. 375, no. 130961, p. 130961, Apr. 2023.
[32] Z. Li and F. Aslani, “Performance of 3D-printed beams and slabs using self-sensing cementitious composites and DIC method,” *Sensors (Basel)*, vol. 23, no. 20, Oct. 2023.
[33] S. Wang and D. D. L. Chung, “Self-sensing of flexural strain and damage in carbon fiber polymer-matrix composite by electrical resistance measurement,” *Carbon N. Y.*, vol. 44, no. 13, pp. 2739–2751, Nov. 2006.
[34] S. Wen and D. D. L. Chung, “Spatially resolved self-sensing of strain and damage in carbon fiber cement,” *J. Mater. Sci.*, vol. 41, no. 15, pp. 4823–4831, Aug. 2006.
[35] A. Cholker and M. Tantray, “Strain and damage sensing property of self-compacting concrete reinforced with carbon fibers,” *International Journal of Engineering*, vol. 32, no. 11, pp. 1577–1583, Nov. 2019.
[36] “Orion Engineered Carbons – SUPER BLACK COATINGS,” *Orion* | *Coatings*, 28-Feb-2020. [Online]. Available: https://superblackcoatings.com/. [Accessed: 28-Sept-2025].
[37] “Standard Test Method for Flow of Hydraulic Cement Mortar.” [Online]. Available: https://store.astm.org/c1437-20.html. [Accessed: 28-Sept-2025].
[38] “Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle.” [Online]. Available: https://store.astm.org/c0191-21.html. [Accessed: 28-Sept-2025].
[39] C01 Committee, “Test method for compressive strength of hydraulic cement mortars (using 2-in. Or [50mm] cube specimens),” ASTM International, West Conshohocken, PA, 2021.
[40] “Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method).” [Online]. Available: https://store.astm.org/c1583-04.html. [Accessed: 22-June-2025].

9. Acknowledgements:

The authors want to gratefully acknowledge the Louisiana Transportation Research Center (LTRC) and Dr. Zhen Liu for their technical assistance in the testing, which was critical to this study. Special thanks are extended to Zoltek, Holcim, TMTP Labs, and Orion Engineered Carbons for providing the materials used in this research. This work would not have been possible without their contributions.

10. Appendices:

10.1. Educational Outreach Activities

This project provided extensive educational and training opportunities across multiple academic levels. Two undergraduate students, three graduate students, and one postdoctoral researcher were directly involved in carrying out the project tasks, gaining hands-on experience in advanced materials development, additive manufacturing, mechanical testing, and Multiphysics modeling. In addition, one middle school student and one high school student participated through supervised research engagement activities, offering them early exposure to engineering concepts and laboratory practices.

Collectively, these outreach efforts supported workforce development and broadened participation in transportation infrastructure research.

(a) Angie Sanchez (Middle School Student), who worked with Ph.D. student Taj in our group, on the **Third Place** in the **Louisiana Region VII Science & Engineering Fair** - Junior Competition (Engineering Technology).

(b) Rodrick Joseph (High School Student), who worked with us over the summer on Additive Manufacturing, and presented his work in the **LSU HSSR Poster competition**.