



Smart High Performance Concretes with Self-Sensing Abilities Containing Steel Fibers and Graphite Fillers for Real-Time Structural Health Monitoring

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Abstract. Sudden collapses of infrastructure have resulted in numerous human deaths and significant economic losses. As a response, structural health monitoring (SHM) systems have gained considerable attention. Currently, various sensors, such as piezoelectric sensors (PZT), fiber optic, and strain gauges, are employed in SHM systems for real-time monitoring. However, these sensors have drawbacks, including low durability compared to the lifespan of the structures and localized influences, which lead to high costs. To address these issues, smart concrete materials with self-stress, strain, and damage sensing abilities have been developed by adding highly electrically conductive functional fillers (FFs), such as carbon fibers, carbon black, steel fibers, and multi-walled carbon nanotubes, have been incorporated. This study investigates the self-sensing properties of smart high-performance concrete (SHPC) containing steel fibers (13 mm in length, 0.2 mm in diameter, varied from 0 to 2 vol%) and graphite (produced from Lao Cai province, varied from 0 to 5% cement weight), which has potential applications in large-scale infrastructure projects. Test results indicated that as the graphite content increased from 1 to 5%, the electrical resistivity (two-probe measurement) of SHPCs notably decreased from 3182.9 to 2797.3 k Ω -cm while their fractional change in electrical resistivity (FCR) increased from 48.96 to 55.88%. Furthermore, the SHPCs containing 2 vol.% steel fibers and 5% graphite (G5F2) produced the highest (FCR = 67.24% at the peak stress) compared to other SHPCs.

Keywords: Self-sensing · Smart High-performance Concrete · Steel Fiber · Graphite · Structural Health Monitoring

1 Introduction

The alarming frequency of infrastructure collapses worldwide has underscored a critical need for robust and cost-effective methods of structural health monitoring (SHM). Such failures not only result in devastating human casualties but also incur substantial

economic burdens. In response to this pressing issue, SHM systems have emerged as a vital field of research and development, aiming to provide real-time insights into the structural integrity of critical infrastructure.

Current SHM practices often rely on discrete sensing technologies, including piezoelectric transducers (PZT), fiber optic sensors, and strain gauges. While these conventional sensors offer valuable data, they are not without limitations. Their long-term durability can be compromised compared to the intended lifespan of the structures they monitor, necessitating frequent replacements and increasing maintenance costs. Furthermore, their influence is often localized, requiring a dense network of sensors to achieve comprehensive structural assessment, which further escalates expenses.

To overcome these inherent drawbacks, the concept of “smart” construction materials with intrinsic self-sensing capabilities has gained significant traction [1]. These innovative materials possess the ability to monitor their stress state, strain levels, and the onset of damage by evaluating changes in their electrical properties, specifically the fractional change in resistivity (FCR), when subjected to external loads [2]. This built-in sensing functionality offers the potential for continuous, distributed monitoring, thereby addressing the limitations of localized and less durable conventional sensors.

However, the practical implementation of self-sensing concrete has faced challenges, particularly the often-noisy electrical response of conventional concrete to mechanical loading, which can obscure the subtle signals indicative of structural changes. To enhance the sensitivity and reliability of the FCR in smart concrete, significant research efforts have focused on the incorporation of highly electrically conductive functional fillers (FFs). A variety of such materials, including carbon fibers, carbon black, steel fibers, and multi-walled carbon nanotubes [3–9], have been explored for their ability to improve the conductive network within the concrete matrix. Recently, graphite, a highly conductive material, was studied as an FF for self-sensing concrete to improve the sensing ability under external loads [10, 11]. In general, the addition of graphite increased the conductivity of concrete but decreased the compressive strength. These studies investigate conventional concretes with low compressive strength and high water-to-cement ratios. The self-sensing of smart high-performance concretes (SHPCs) containing graphite with high compressive strength has limited information. Lao Cai Province in Vietnam possesses significant graphite reserves, which have the potential for producing graphite for SHPCs.

This study investigates the self-sensing properties of SHPC, a material system with promising applications in large-scale infrastructure projects where both high mechanical performance and integrated monitoring capabilities are paramount. The research utilizes short, smooth steel fibers, serving both as functional fillers to enhance electrical conductivity and as reinforcement to improve mechanical strength. Furthermore, graphite, renowned for its exceptional electrical conductivity, is introduced as an additional conductive filler to further optimize the conductive network within the SHPC matrix. The study aims to investigate the synergistic effects of steel fibers and graphite on the workability, mechanical strength, electrical conductivity, and the self-stress sensing abilities of SHPC. The findings of this research are expected to contribute valuable insights into the development of advanced construction materials for real-time structural health monitoring, paving the way for safer and more resilient infrastructure.

2 Materials and Experimental Program

The experimental program was designed to investigate the self-sensing abilities of smart high-performance concrete (SHPC) containing steel fibers and graphite fillers. Based on previous research, we indicated that as the graphite content increased from 1 to 10%, the workability and the compressive, flexural strengths significantly decreased, even the electrical conductivity notably increased. The studies also indicated that as the graphite content varied from 1 to 5%, the strength, workability of SHPCs were satisfactory. Thus, in this study, the graphite was changed from 1 to 5%. Besides, 2 vol% steel fibers were added to compare the sensing characteristics of SHPCs. Table 1 summarizes the matrix compositions (cement, silica sand, silica fume, water, superplasticizer, and graphite) of different SHPCs by weight ratio of cement. The fiber volume content varied from 0 to 2 vol%. The effects of adding graphite on the mechanical and sensing properties were investigated by increasing the graphite content from 0 to 5% by cement weight. In addition, a combination of both graphite and fiber content in the G5F2 matrix was investigated.

Table 1. Matrix composition of SHPCs by cement weight ratio, flow, and compressive strength

No.	Cement	Silica sand	Silica fume	Water	Super-plasticizer	Graphite	Steel fibers (Vol%)	Flow (mm)	Compressive strength (MPa)
G0F0	1.0	1.25	0.25	0.2	0.067	0	0	200	97.9
G1F0	1.0	1.25	0.25	0.2	0.067	0.01	0	180	90.1
G5F0	1.0	1.25	0.25	0.2	0.067	0.05	0	160	70.0
G5F2	1.0	1.25	0.25	0.2	0.067	0.05	2	175	48.1

2.1 Materials

Cement PCB40 But Son and silica fume (90% SiO₂) were used as binders in the SHPC matrices. Graphite (Fig. 1) produced from Lao Cai province was utilized as a functional filler (FF). Short smooth steel fibers (Fig. 1) with 0.2 mm in diameter, 13 mm in length, 3000 MPa in tensile strength not only reinforce the mechanical resistance but also enhance the conductivity and self-sensing ability of SHPCs. The water-to-cement ratio was 0.2 for all mixtures. Superplasticizer-based carbonxylate was added to enhance the workability of fresh matrices. Stainless steel wire mesh with a grid size of 10 mm × 10 mm and a wire diameter of 1 mm was used as embedded electrodes to measure the electrical resistance of the SHPC specimens .

2.2 Specimen Preparation

A 30 L capacity mixture was used to prepare SHPC specimens. The cement, silica sand, silica fume, and graphite were first mixed for 5 min. The water and the superplasticizer.



Fig. 1. Images of steel fibers and graphite

The flowability of fresh mixtures was tested (Fig. 2a). Steel fibers were slowly added to ensure uniform distribution within the mixtures.

For compressive strength tests, cubic specimens with a size of $50 \times 50 \times 50 \text{ mm}^3$ were cast according to the ASTM C109/C109M standard [12] for cement composites without coarse aggregates. For self-sensing tests under compression, cubic specimens with embedded electrodes were prepared. The stainless steel wire mesh electrodes were placed at a distance of 20 mm from each other during casting to facilitate electrical resistance measurements. All specimens were demolded after 48 h and then cured in a hot water tank at a temperature of $60 \pm 5^\circ \text{C}$ for 3 days.

2.3 Testing Program

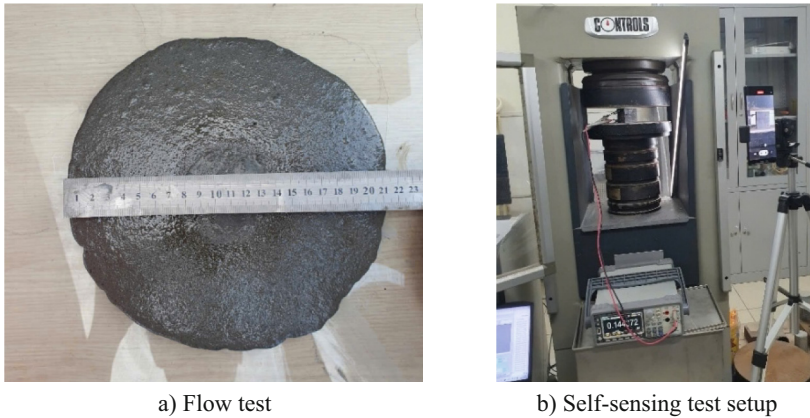


Fig. 2. Flow test and self-sensing test

Compressive strength tests were conducted according to the ASTM C109/C109M standard [12] on three specimens for each matrix using an Advantest 9 machine (3000 kN capacity). The average value was reported for each mix.

Self-sensing tests under uniaxial compression were conducted on cubic specimens with embedded electrodes (Fig. 2). A constant DC power supply was used to apply a small current through the embedded electrodes, and the electrical resistance was continuously measured using a Gwinstek digital multimeter. The fractional change in resistivity (FCR) was calculated using the following equation:

$$FCR = \frac{\rho - \rho_0}{\rho_0} \cdot 100\% = \frac{R - R_0}{R_0} \cdot 100\% \quad (1)$$

where ρ_0 , R_0 , ρ , and R are the initial electrical resistivity, initial resistance, electrical resistivity, and the electrical resistance at the calculated point, respectively.

The influence of steel fiber and graphite on the self-sensing abilities of SHPC was evaluated based on the change in FCR in correlation with stress response under loading.

3 Results and Discussion

The flow values and compressive strength of SHPCs are summarized in Table 1. In general, as the graphite content increased from 1 to 5%, the flow value clearly decreased from 200 mm to 140 mm. The compressive strength of G1F0, containing 1% graphite, is slightly lower than that of the controlled HPC (G0F0 without graphite). As the graphite content increased from 1 to 5%, the compressive strength decreased from 90.1 to 70.0 MPa.

Figure 3 shows the electrical resistivity response of SHPCs under compression. The red line presents the FCR response, while the blue line shows the compressive stress change under external loads. As the compressive stress increased, the FCR decreased, i.e., the electrical resistivity decreased. The minus values of FCR in Fig. 3 indicate that the electrical resistivity of SHPCs decreased with increasing compressive stress. Table 2 summarizes the electrical resistivity, the FCR at the maximum stress.

Table 2. The electrical resistivity, FCR, and stress of SHPCs under compression

No.	ρ_0 (k Ω -cm)	FCR at the peak stress (%)
G1F0	3182.9	−48.96
G5F0	2797.3	−55.88
G5F2	1127.1	−67.24

As the graphite content increased from 1 to 5%, the electrical conductivity of SHPCs clearly increased. The electrical resistance decreased from 3182 to 2797.3 k Ω -cm. The utilization of steel fibers produced a better electrical conductivity of SHPCs than graphite. A combination of steel fibers and graphite produced the lowest value of electrical resistivity (1127.1 k Ω -cm).

Under compression, the electrical resistivity can be divided into three main parts. First, the electrical resistivity gradually decreased with increasing compressive stress.

Then, the electrical resistivity significantly decreased as the compressive stress nearly reached the peak stress. Then the electrical resistivity increased after the peak stress as the main cracks opened.

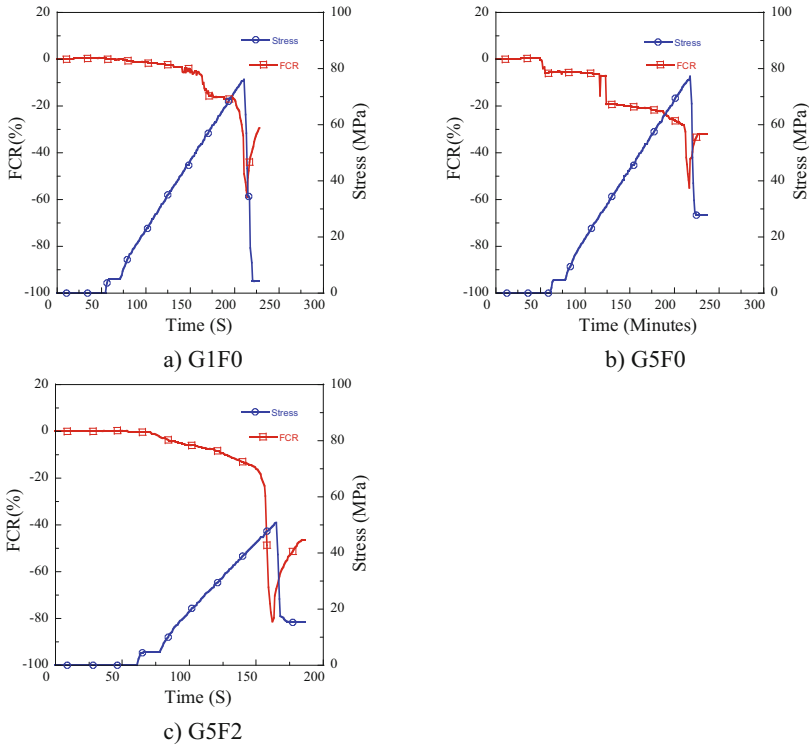


Fig. 3. FCR response of SHPCs under compression

At the peak stress, as the graphite content increased from 1 to 5%, the FCR increased from 48.96 to 55.88%. Graphite with a high electrical conductivity notably enhanced the conductive network of SHPCs. Under compression, the distance between graphite layers was closer and enhanced the conductive pathway in the composite and resulting in a decrease in the electrical resistivity. The increase in the content of graphite enhanced the contact conduction and/or tunneling conduction. This phenomenon leads to the formation of a more extensive and interconnected network of conductive pathways within the material. When the composite material is subjected to external load, its internal microstructure undergoes alterations (e.g., changes in inter-particle distances, formation or disruption of conductive contact) [13]. Hence, SHPCs containing higher graphite content produced a larger FCR.

The combination of both graphite and steel fibers (G5F2) produced the highest FCR at the peak stress (67.24%). Le et al. [8] also indicated that a combination of steel fibers with particle conductive fillers (steel slag aggregate) produced a higher FCR under compression. Steel fibers, also possessing high electrical conductivity, contribute to the

conductive network in conjunction with graphite. The extended geometry of steel fibers facilitates the electrical interconnection, establishing a more continuous and efficient three-dimensional conductive pathway throughout the composite bulk. While graphite can create localized conductive paths, steel fibers act as “bridges,” spanning gaps and linking these regions on a larger scale. Upon the application of compressive loads, the steel fibers within the composite can undergo displacement, tension, or even micro-cracking. These mechanical alterations significantly influence the electrical contact between individual fibers and between the fibers and the surrounding graphite particles. In addition, the particulate nature of graphite contributes to an increased density of conductive points, while the steel fibers enable the effective connection of these points over larger distances. This combination of both material types results in a sensing system that exhibits enhanced electrical sensitivity to mechanical alterations.

4 Conclusion

This study has successfully investigated the self-sensing capabilities of smart high-performance concrete (SHPC) incorporating short smooth steel fibers and graphite fillers for potential application in structural health monitoring (SHM). The experimental findings demonstrate the significant influence of both conductive fillers on the electrical properties and self-stress sensing abilities of the composite material.

The addition of graphite, while slightly impacting workability and compressive strength, effectively enhanced the electrical conductivity of SHPC and improved its capacity for self-stress sensing. As the graphite content increased from 1 to 5%, the electrical resistivity (two-probe measurement) of SHPCs notably decreased from 3182.9 to 2797.3 k Ω -cm while their fractional change in electrical resistivity (FCR) increased from 48.96 to 55.88%.

Notably, the incorporation of short, smooth steel fibers led to a substantial increase in the overall conductivity of the SHPC matrix. Crucially, the synergistic combination of both steel fibers and graphite resulted in a demonstrably superior self-stress sensing ability compared to SHPC containing only graphite. This highlights the potential for a hybrid filler approach to optimize the conductive network and enhance the sensitivity of smart concrete for SHM applications.

The SHPCs containing 2 vol.% steel fibers and 5% graphite (G5F2) produced the highest electrical conductivity (1127.1 k Ω -cm in the electrical resistivity) and FCR (67.24%) at the peak stress compared to other SHPCs. These results suggest that SHPC, incorporating both steel fibers and graphite, has promise for the development of cost-effective and durable self-sensing materials for large-scale infrastructure projects. The enhanced self-stress sensing capabilities offer a pathway to overcome the limitations of traditional, discrete sensors by providing an intrinsic, distributed monitoring system.

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References

1. Han, B., Yu, X., Ou, J.: Self-Sensing Concrete in Smart Structures. Butterworth Heine-mann/Elsevier, Kidlington (2014). <https://doi.org/10.1016/C2013-0-14456-X>
2. Chung, D.D.L.: Piezoresistive cement-based materials for strain sensing. *J. Intell. Mater. Syst. Struct.* **13**, 599–609 (2002). <https://doi.org/10.1106/104538902031861>
3. Le, H.V., et al.: Self-sensing characteristics of smart high-performance cementitious composites containing multiwall carbon nanotubes, steel fibers, and steel slag aggregates under compression. *Sens. Actuators A Phys.* **365** (2024). <https://doi.org/10.1016/j.sna.2023.114920>
4. Nguyen, D.L., Nga, V.T.B., Son, D.X., Tran, M.P.: Nghiên cứu dùng muội than đen và xi lô cao nghiền mịn trong việc cải thiện khả năng tự cảm biến của bê tông tính năng cao. *Tạp Chí Khoa Học Công Nghệ Xây Dựng NUCE*. **13**, 151–158 (2019)
5. Han, B., Yu, X., Kwon, E.: A self-sensing carbon nanotube/cement composite for traf-fic monitoring. *Nanotechnology*. **20**, 1–5 (2009). <https://doi.org/10.1088/0957-4484/20/44/445501>
6. Yoo, D.Y., You, I., Lee, S.J.: Electrical properties of cement-based composites with carbon nanotubes, graphene, and graphite nanofibers. *Sensors*. **17**, 1–13 (2017). <https://doi.org/10.3390/s17051064>
7. Kim, M.K., Kim, D.J.: Electromechanical response of high-performance fiber-reinforced cementitious composites containing milled glass fibers under tension. *Materials (Basel)*. **11** (2018). <https://doi.org/10.3390/ma11071115>
8. Viet, L.H., Dao Phuc, L., Thuong, N.T., Thanh, N.T., Nguyen, D.L., Kim, D.J.: Improvement of the stress sensing ability of ultra-high-performance concrete using short steel fibers and steel slag aggregates under high compression. *Sens. Actuators A. Phys.* **362**, 114616 (2023). <https://doi.org/10.1016/j.sna.2023.114616>
9. Le, H.V., Do, A.D., Nguyen, V.M., Nguyen, T.K., Nguyen, D.L.: Compressive and electrical resistivity properties of UHPC containing different steel fibers (Đặc trưng nén và điện trở suất của bê tông cường độ siêu cao sử dụng các loại sợi thép khác nhau). *Xây Dựng*, **11**, 110–114 (2023)
10. Dinesh, A., Suji, D., Pichumani, M.: Self-sensing cementitious composite sensor with inte-grated steel fiber and carbonaceous powder for real-time application in large-scale infras-tructures. *Sens. Actuators A Phys.* **353**, 114209 (2023). <https://doi.org/10.1016/j.sna.2023.114209>
11. Sun, S., et al.: Nano graphite platelets-enabled piezoresistive cementitious composites for structural health monitoring. *Constr. Build. Mater.* **136**, 314–328 (2017). <https://doi.org/10.1016/j.conbuildmat.2017.01.006>
12. ASTM: ASTM C109/C109M standard test method for compressive strength of hydraulic cement mortars. *ASTM Int.* **04**, 9 (2020)
13. Han, B., Zhang, K., Yu, X., Kwon, E., Ou, J.: Nickel particle-based self-sensing pavement for vehicle detection. *Meas. J. Int. Meas. Confed.* **44**, 1645–1650 (2011). <https://doi.org/10.1016/j.measurement.2011.06.014>