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The workability, compressive strength, flexural strength, and electrical conductivity of smart high-performance concretes containing graphite and steel fiber

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KEYWORDS

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Graphite
Smart high-performance concrete
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Workability

ABSTRACT

Smart high-performance concretes (SHPCs) containing highly electrically conductive functional fillers (FFs) were a new type of material to apply for structural health monitoring systems or smart city infrastructures. This study investigated the mechanical properties, such as the compressive strength, flexural strength, and the electrical resistivity of SHPCs incorporating graphite powder (0 to 5% of cement by weight) and steel fibers as FFs (0 to 2 vol %). The electrical resistivity of each specimen was measured using a direct current (DC) with the two-probe method to evaluate the conductivity of SHPCs. The results indicated that the addition of graphite decreased the workability, compressive, and flexural strengths but notably increased the electrical conductivity of SHPCs. The SHPCs containing 5 % graphite and 1 vol % steel fibers produced the highest compressive strength (72.8 MPa) and flexural strength (14.7 MPa) in comparison with SHPCs containing 5 % graphite and other fiber contents. As the fiber volume content increased from 0 to 2 vol %, the volume weight of SHPCs varied from 2216 to 2363 kg/m3. The flexural strength per compressive strength of SHPCs was varied from 18.7 to 20.1 %. In addition, the electrical conductivity of the SHPCs showed a notable increase with higher contents of graphite and steel fibers, forming effective conductive networks within the concrete matrix. The findings suggest that the integration of graphite and steel fibers can effectively improve the multifunctional performance of SHPCs, making them suitable for structural health monitoring applications in advanced civil infrastructure.

1. Introduction

The integrity and safety of civil infrastructure are paramount concerns in modern society. Sudden structural failures can lead to catastrophic consequences, resulting in loss of life and significant economic disruption. In response to this challenge, the field of structural health monitoring (SHM) has been of interest, aiming to provide real-time assessment of structural conditions and maintenance strategies. Traditional SHM techniques often rely on sensors, such as strain gauges, accelerometers, and fiber optic sensors. While effective, these methods can be costly to install and maintain over large structures, and their localized nature may limit the detection of widespread or distributed damage.

In recent years, the development of smart concrete materials with intrinsic self-sensing capabilities has emerged as a promising alternative or complementary approach to conventional SHM [1]. These materials, typically engineered by incorporating electrically conductive functional fillers within the cementitious matrix, exhibit a measurable change in their electrical properties, particularly electrical resistivity, in response to applied mechanical stress or damage. By continuously monitoring these electrical signals, it becomes possible to assess the structural state of the concrete element itself, offering a potentially cost-effective and distributed sensing network.

To enhance the self-sensing capabilities of smart concrete, various electrically conductive functional additives have been investigated, including carbon fibers, carbon black, metallic powders, steel fiber, steel slag aggregate, and carbon nanotubes [2], [3], [4], [5], [6], [7], [8], [9]. Among these, graphite powder and steel fibers have shown particular promise due to their relatively low cost, availability, and ability to form conductive networks within the concrete matrix. Graphite, a layered carbon allotrope with high electrical conductivity, can improve the overall conductivity of the composite and enhance its sensitivity to stress-induced changes. Steel fibers, commonly used for reinforcing concrete to improve its tensile and flexural strength, also possess excellent electrical conductivity and can contribute to a more robust and interconnected conductive network, particularly bridging

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micro-cracks that may form under load.

While the individual effects of graphite and steel fibers on the electrical resistivity response of concrete under mechanical loading have been studied [10], [11], [12], [13] a comprehensive understanding of their synergistic interaction in smart high-performance concrete (SHPC) remains crucial for optimizing self-sensing performance. SHPC, characterized by its superior strength, durability, and workability compared to conventional concrete [14][15], [16], presents an ideal matrix for incorporating these functional additives in advanced civil infrastructure applications.

This study aims to address this gap by systematically investigating the aforementioned properties of SHPCs incorporating varying contents of graphite powder (0–5 % by weight of cement) and steel fibers (0–2 vol %). The influences of these additives on the flowability, the compressive strength, the flexural strength, and the electrical resistivity were investigated. The findings of this research will provide valuable insights into developing optimized mix designs for SHPCs, facilitating their application in advanced civil infrastructure for effective SHM and the realization of smart cities.

2. Material and experiement

Table 1 summarises the matrix compositions of SHPCs containing different graphite and fiber contents. G and F characters in the notation mean the SHPCs containing graphite and fiber, respectively, while the following numbers indicate their content. E.g., G5F1 means SHPCs containing 5 % graphite and 1 vol % steel fibers. Our research group investigated that as the graphite content varied from 1 to 5 %, the compressive strength and flexural strength were little influenced. Whereas as the content of graphite was higher than 10 %, the flow ability as well as the mechanical properties significantly decreased, even though it notably improved the electrical conductivity of SHPCs. Thus, in this study, the authors used 0 and 5 % graphite in matrix compositions. The fiber volume content was varied from 0 to 2 vol %.

Table 1. Mix designs for SHPCs by cement weight ratio.

Composition	G0F2	G5F0	G5F0.5	G5F1	G5F2
Cement	1	1	1	1	1
Silica sand	1	1	1	1	1
Water	0.2	0.2	0.2	0.2	0.2
Superplasticizer	0.05	0.05	0.05	0.05	0.05
Silica fume	0.25	0.25	0.25	0.25	0.25
Silica powder	0.25	0.25	0.25	0.25	0.25
Steel fiber (vol %)	2	-	0.5	1	2
Graphite (%)	-	5	5	5	5

2.1. Materials

Figure 1 presents images of the main materials in SHPCs. Cement PCB40, and silica fume (SF90) were utilized as binders in the matrix composition. Silica sand has an average diameter of 0.4 mm. Superplasticizer was used to enhance the workability of fresh concretes while the water-to-cement ratio (W/C) was controlled at 0.2. Short, smooth steel fibers with 0.2 mm in diameter, 13 mm in length, and 2100 MPa in tensile strength were added to improve the mechanical properties as well as the conductive network of SHPCs. Graphite was produced in Lao Cai province in Vietnam.

a) Cement b) Silica sand c) Superplasticizer

d) Silica fume e) Steel fibers f) Graphite

Figure 1. Images of materials.

2.2. Specimen preparation

A 30 *L* mixer was used to prepare SHPCs containing graphite and steel fiber specimens. Cement, silica fume, silica powder, silica sand, and graphite were first mixed for 5 minutes. Then, superplasticizer and water were gradually added for 3 minutes. A flow test was conducted for fresh mixtures using the flow table test. Then, short, smooth steel fibers were manually added into the mixture and further mixed for 2 minutes. The mixtures were cast into the compressive molds (50x50x50 mm^3), the flexural molds (40x40x160 mm^3). For measuring the electrical resistance of specimens, four stainless steel wire meshes were embedded into flexural molds with a distance between meshes of 20 mm. All specimens were vibrated to remove the air bubbles, covered with plastic sheets, and stored at room temperature for 2 days. After demolding, the samples are cured in hot water (60 ˚C) for 3 days.

2.3. Test setup

The workability of fresh mixtures was tested using a mini cone with a 50 mm diameter and 100 mm height. The compressive and flexural strengths were conducted using the ADVANTEST 9 system with 3000 kN capacity (Controls - Italy). The loading rate is controlled at 0.5 MPa/s. Besides, the volume weight of SHPCs was calculated from the weight of specimens with sizes of 50x50x50 mm^3. The electrical resistance of specimens was measured using a Gwinstek GDM 9060 machine with a two-probe measurement method.

The electrical resistivity (ρ) of SHPCs was calculated from measured resistance (R) according to Eq. (1).

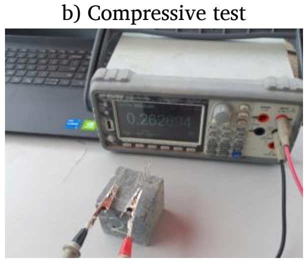
$\rho = R. A/L$ (1)

where A and L are the cross-sectional area and the gauge length measurement, respectively.

a) Flow test

b) Compressive test

c) Flexural test



d) The electrical resistance measurement test

Figure 2. Test setups.

3. Test results and discussion

3.1. The workability, the compressive strength, and the flexural strength of SHPCs containing graphite and steel fibers

Table 2 summarises the flow value, volume weight, compressive strength, and flexural strength of different SHPCs containing different contents of graphite and steel fibers. Figures 3 and 4 show the fracture images of SHPCs containing different graphite and fiber content under compression and flexural load, respectively. Figure 5 illustrates the cross-section of SHPCs containing graphite with and without steel fibers after the test. Figure 6 compares the compressive and flexural strengths of SHPCs.

The addition of graphite clearly decreased the compressive strength and flexural strength of SHPCs. The compressive and flexural strengths of G0F2 without graphite were 89.9 and 16.9 MPa, respectively. The addition of steel fibers generally little influence on the compressive strength of SHPCs. As the fiber volume content increased from 0 to 1.0 vol %, the flexural strength increased from 13.7 to 14.7 MPa. However, the addition of 5 % graphite and 2 vol % steel fibers decreased both the compressive (62.8 MPa) and the flexural strengths (12.3 MPa) of SHPCs. The flow value of G0F2, G5F0, G5F0.5, G5F1, and G5F2 was 200, 160, 165, 155, and 140 mm, respectively. Thus, the decrease in compressive and flexural strengths of G5F2 would be due to a decrease in the flowability of the fresh matrix, which would increase the void in the composite during preparation. The flowability of cementitious composites mainly depended on the free water in the composites [17]. As the graphite and steel fiber contents increased, the free water decreased owing to the water absorbed on the surface of the materials. Thus, G5F2 with higher graphite and fiber contents produced a lower flowability and resulted in a lower compressive strength.

The volume weight of SHPCs varied from 2216 to 2363 kg/m^3. As the fiber volume content increased from 0.5 to 2 vol %, the volume weight of SHPCs increased from 2216 to 2318 kg/m^3. The volume weight of steel fibers (around 7850 kg/m^3) was significantly higher than that of concrete. Thus, as the addition of fiber volume content increased, the volume weight of SHPCs increased.

The flexural strength per compressive stress ratio of smart high-performance concrete containing steel fiber and graphite was varied from 18.7 to 20.1 %. It is different from conventional concrete, which is 12 % according to TCVN 3118:2022 [18]. The combination of an SHPC matrix and dispersed steel fibers creates a synergistic effect. The strong, dense SHPC matrix provides an excellent bond for the steel fibers, allowing them to engage more effectively in resisting tensile stresses. This improved bond efficiency maximizes the contribution of fibers to flexural strength.

3.2. The electrical conductivity of SHPCs with different graphite and fiber contents

Figure 5 shows the effects of polarization on the electrical resistivity of SHPCs containing steel fiber and graphite. The electrical resistivity at initial and stable points was determined and summarized in Table 3. As can be seen in Figure 7, the electrical resistivity of SHPCs containing graphite with/without steel fibers increased according to time and had a stable value after 15 to 20 minutes. Nguyen et al. and Le et al. [8], [19] also reported that the electrical resistivity of high-performance concretes containing steel fibers was stable after around 20 minutes after applying a DC current. This is owing to the polarization effects, as application of a DC to two embedded electrodes in the samples. When a DC is applied, ions within the pore solution of the concrete begin to migrate toward the opposite electrode, causing ion accumulation at the interface between the electrode and the concrete matrix. This leads to the formation of an electrical double layer, which increases contact resistance at the electrode surface. This polarization effect causes the measured electrical resistivity to gradually increase over time. Eventually, the system reaches a dynamic equilibrium, typically after 15 to 20 minutes, and the electrical resistivity stabilizes.

The value of the electrical resistivity of SHPC was higher than the electrical resistivity of SHPC composites because of the two-probe measurement method. The measured electrical resistance using this method included both the electrical resistance of the composite and the electrical resistance of the contact between the composites and the electrodes [1]. However, this method is simple and easy to apply for evaluating the sensing ability of SHPCs under external loads [8], [20], [21]. A four-probe method would be used to determine the electrical resistivity of the SHPC composite.

a) G5F0

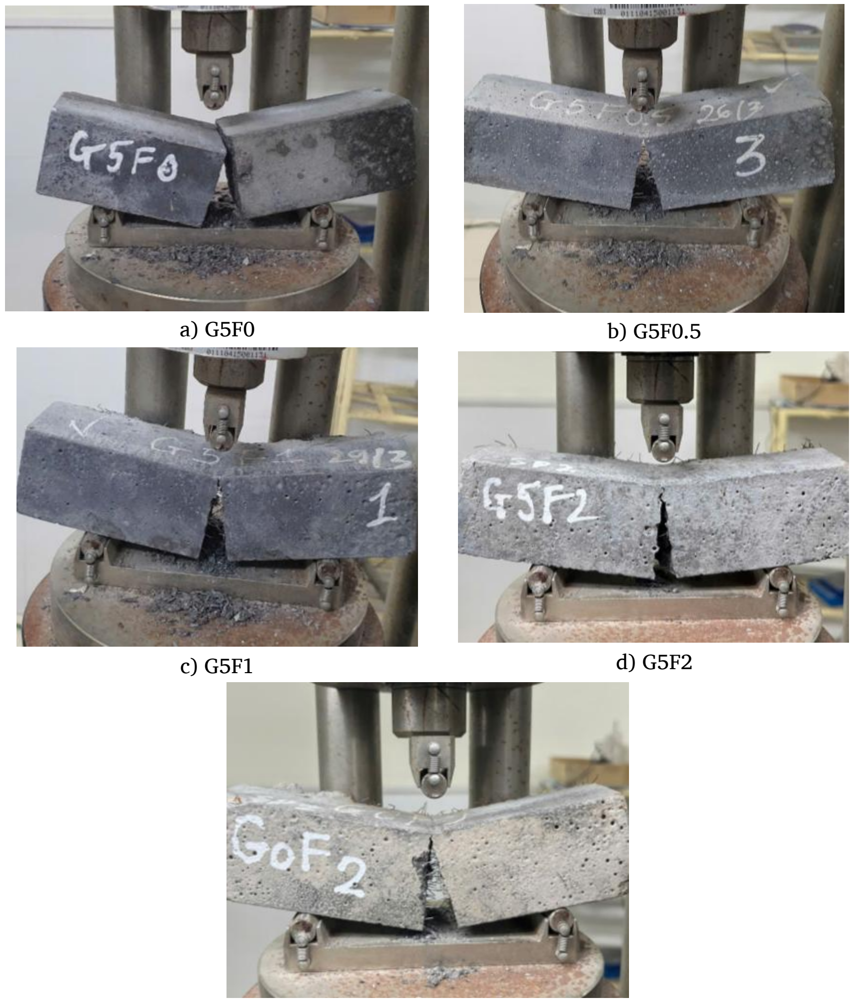
b) G5F0.5

c) G5F1

d) G5F2

e) G0F2

Figure 3. Fracture images of SHPCs under compression.



a) G5F0 b) G5F0.5

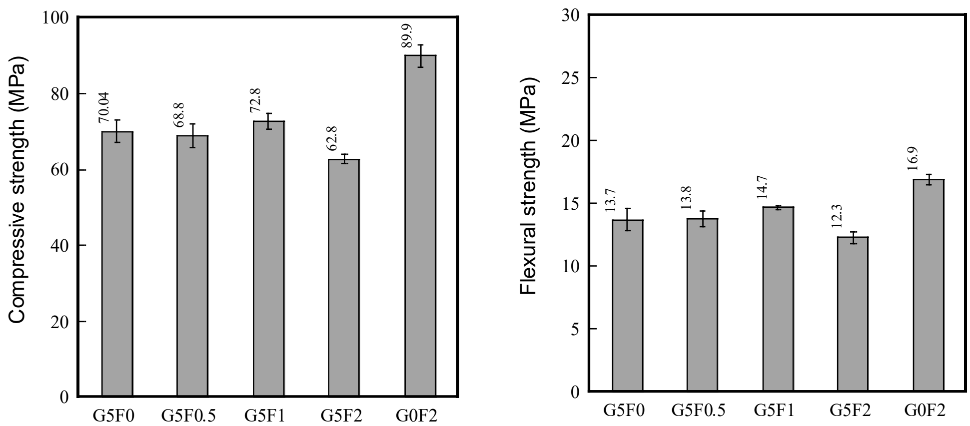
c) G5F1 d) G5F2

e) G0F2

Figure 4. Fracture images of SHPCs under flexural loads.

a) G5F0 b) G5F2

Figure 5. Cross-section of SHPCs containing graphite with/without steel fibers.



a) Compressive strength

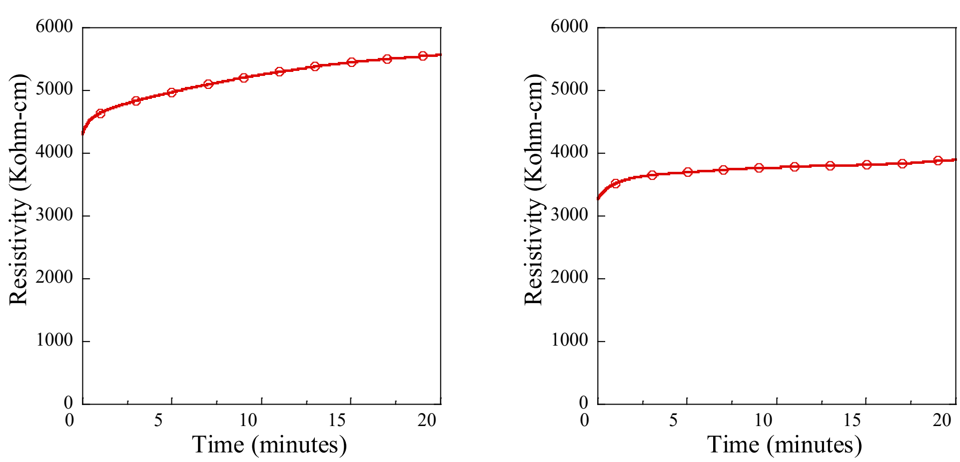
b) Flexural strength

Figure 6. Effects of graphite on the mechanical properties of SHPCs.

Table 2. The mechanical properties of SHPCs containing steel fibers and graphite.

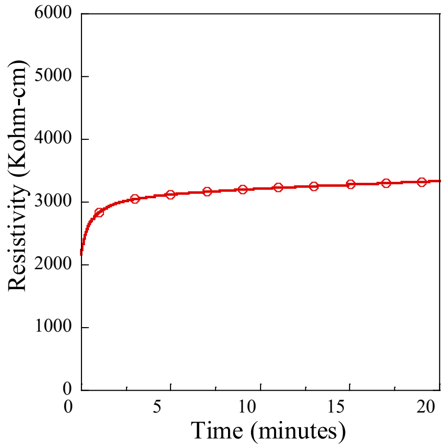
Mechanical properties	Specimen	G0F2	G5F0	G5F0.5	G5F1	G5F2
Flow value (mm)		200	160	165	155	140
Volume weight (kg/m^3)		2363	2216	2256	2272	2318
Compressive strength (MPa)	SP1	89.9	72.15	72.69	72.33	64.7
	SP2	93.5	65.8	64.97	75.64	61.49
	SP3	86.5	72.17	68.73	70.46	62.3
	Average	**89.9**	**70.04**	**68.80**	**72.8**	**62.8**
	STDV	2.8	3.00	3.15	2.14	1.36
Flexural strength (MPa)	SP1	17.6	14.66	14.69	14.64	12.85
	SP2	16.6	12.49	13.16	14.86	12.1
	SP3	16.7	13.82	13.5	14.45	11.8
	Average	**16.9**	**13.7**	**13.8**	**14.7**	**12.3**
	STDV	0.4	0.89	0.66	0.17	0.44

STDV: standard deviation.

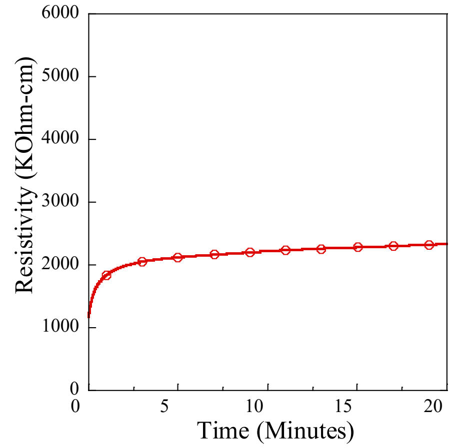


a) G5F0

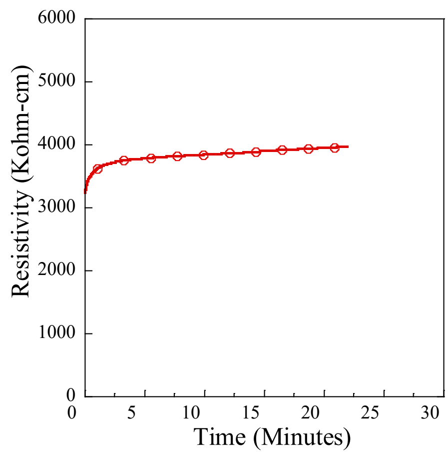
b) G5F0.5



c) G5F1



d) G5F2



e) G0F2

Figure 7. Polarization effect on the initial electrical resistivity of SHPCs.

Table 3. The electrical resistivity of SHPCs using the two-probe DC measurement method.

No.	Initial electrical resistivity (kΩ-cm)	Stable electrical resistivity (kΩ-cm)
G0F2	3233.2	3968.8
G5F0	4301.7	5678.8
G5F0.5	3274.8	3917.4
G5F1	2228.0	3369.1
G5F2	1116.2	2110.4

4. Conclusions

The study investigated the effects of graphite and steel fiber contents on the workability, compressive strength, flexural strength, and electrical resistivity properties of SHPCs. The following conclusions have been drawn, as below:

As the graphite content increased from 0 (G0F2) to 5 % (G5F2), the compressive and flexural strengths notably decreased from 89.9 to 62.8 MPa and 16.9 to 12.3 MPa, respectively. Besides, the electrical resistivity of SHPCs (measured by two-probe DC measurement method) decreased from 3968.8 to 2110.4 kΩ-cm, i.e., the electrical conductivity significantly increased.

The SHPCs containing 5 % graphite and 1 vol % steel fibers produced the highest compressive strength (72.8 MPa) and flexural strength (14.7 MPa) in comparison with SHPCs containing 5 % graphite and other steel fiber contents. As the fiber volume content increased from 0 to 2 vol %, the volume weight increased from 2216 to 2363 kg/m^3. The SHPC containing 5 % graphite and 2 vol % steel fibers produced the highest conductivity.

The flexural strength per compressive strength of SHPCs was around 18.7 to 20.1 %.

The polarization effects on the electrical resistivity measurement of SHPCs containing steel fiber and graphite were varied from 15 to 20 minutes. After polarization time, the electrical resistivity of SHPCs was stable.

The SHPCs containing graphite and steel fibers produced a well-conductive network in SHPCs and resulted in high electrical conductivity. These findings produced optimized SHPC mix designs, which will facilitate their broader application in advanced civil infrastructure for effective structural health monitoring and the development of smart cities.

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Author Contributions

Duong Tuan Trung – Data Analysis, Investigation, draft version preparation; Le Huy Viet - Methodology, draft version preparation, Manuscript Writing, Verification, and supervision.

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