

Self-sensing response of cementitious sensors with wood-based biochar and liquid MWCNTs

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ABSTRACT: The development of piezoresistive sensors for internal deformation detection and damage assessment in building maintenance is garnering significant attention. Traditional piezoresistive sensors using multi-walled carbon nanotubes (MWCNTs) are limited by their high cost. This study aimed to commercialize cement composite sensors incorporating biochar as a cost-effective alternative. Additionally, biochar was surface-modified with ferric chloride (FeCl_3) aqueous solution to evaluate its potential for sensor applications and compatibility with MWCNTs. Mechanical property analysis confirmed that specimens with biochar exhibited higher average compressive strength. Electrical property analysis was conducted to assess the role of biochar as a sensor, focusing on strain recovery capability through repeated compression tests. Using an LCR meter, the fractional change in resistance (FCR) was analyzed, demonstrating the applicability of surface-modified biochar for sensing applications. A comparison of vertical strain and FCR values revealed that specimens incorporating both biochar and MWCNTs exhibited superior performance in terms of strain recovery capability and sensitivity. These findings suggest that further research on biochar-based sensors is necessary to explore their full potential.

1 INTRODUCTION

Recent years have seen rapid climate change, leading to severe environmental and economic challenges worldwide [1-2]. Carbon dioxide (CO_2), the primary greenhouse gas, is massively emitted from fossil fuel combustion, industrial activities, and the construction industry [3]. According to a McKinsey report, the construction sector accounts for approximately 25% of global greenhouse gas emissions, with cement production—the primary component of concrete—contributing about 8% of these emissions. Furthermore, the IPCC report warns that global surface temperatures have already risen by 1.1°C between 2011 and 2020 and are likely to reach 1.5°C between 2021 and 2040. In this context, carbon capture and storage (CCS) technology is emerging as a key solution to reducing CO_2 emissions [4]. Among CCS materials, biochar has gained significant attention [5]. Biochar is a carbon-rich, porous material produced by pyrolyzing biomass under limited oxygen conditions [6]. While traditionally used as a soil amendment, recent studies reveal its potential for a range of industrial applications [7]. Notably, incorporating biochar into concrete can maintain the physical performance of construction materials while sequestering carbon, thereby reducing the carbon footprint and improving mechanical properties such as compressive strength,

durability, and thermal characteristics [8]. This positions biochar as a pivotal material for transitioning to a sustainable construction industry.

Biochar consists of various chemical elements, including carbon, hydrogen, oxygen, and nitrogen, with its carbon content varying depending on feedstock composition and pyrolysis conditions [9]. Biochar produced under low-temperature, high-pressure conditions contains higher carbon content. As pyrolysis temperature increases, volatile components are removed, leaving a higher carbon residue, enabling biochar to capture and sequester CO₂ [10-12]. Preliminary studies on using biochar as a cement substitute showed that replacing 2–5% of cement with biochar enhanced concrete's compressive, tensile, and flexural strengths. As the substitution rate increased, biochar's carbon sequestration capacity also rose, capturing approximately 2.5 kg of CO₂ per kilogram of biochar. This was attributed to biochar's porous structure, which increased CO₂ absorption rates to 2.5–3%. The study proposed an optimal substitution rate of 2–3%, striking a balance between maintaining the physical properties of concrete and maximizing its carbon sequestration capacity [13]. These findings underscore biochar's dual environmental and mechanical benefits as a sustainable construction material. Concrete is widely used in infrastructure, including high-rise buildings, bridges, and dams, due to its durability, cost-effectiveness, and ease of use. However, it is prone to damage from loads, cracking, aging, water ingress, temperature fluctuations, and fires [14-16]. To prevent such issues and extend the lifespan of structures, real-time monitoring technologies are critical for assessing structural health and preventing accidents. With increasing global incidents of structural failures, interest in structural monitoring technologies has surged [17].

Structural health monitoring (SHM) is an essential technology that employs sensors to collect real-time data on stresses and deformations within structures. This data enables evaluations of structural stability and condition, optimizing maintenance strategies [18]. Recent research focuses on fabricating strain-sensing sensors by incorporating conductive materials into cement composites. Self-Sensing Cement Composites (SSCCs) exemplify this technology, using conductive materials to detect cracks, damage, and deformation through electrical signals. Carbon nanomaterials, with their diverse structures, exhibit excellent electrical, mechanical, and chemical properties, making them valuable for various sensor applications [19-20]. CNTs, graphene, and graphene oxide (GO) are commonly used to develop strain-sensing cement composites [21]. Studies have shown that increasing CNT concentrations decreases electrical resistivity, improves conductivity, and significantly enhances compressive and flexural strengths while reducing microcrack formation within composites [22]. By uniformly dispersing CNTs, cement composites demonstrate improved mechanical properties and durability, highlighting their potential for smart structural applications [23]. However, the high cost and tendency for CNT agglomeration limit their practicality. To address these issues, researchers are exploring cost-effective alternatives like carbon black (CB), steel fibers, and ground granulated blast furnace slag (GGBFS) for use in cement composite sensors [24].

Research on biochar-incorporated cement composites has evaluated electrical resistivity, compressive strength, and hydration heat, demonstrating performance comparable to or exceeding that of traditional carbon-based sensors. These findings suggest biochar's viability as a conductive material for sensors, supporting its use in sustainable construction and long-term monitoring technologies [25]. With sustainability and environmental concerns becoming critical in the construction industry, biochar's exceptional carbon sequestration and physical properties position it as a promising alternative to traditional construction materials. Its electrical conductivity and porous structure make biochar suitable for fabricating strain-sensing sensors. Furthermore, biochar offers a practical, economical alternative to CNTs, addressing their high cost and agglomeration issues while contributing to SHM advancements [26]. This study explores the feasibility of using biochar as a conductive material in cement composite-based sensors, aiming to overcome CNT limitations and enhance sensor performance.

2 EXPERIMENTAL PROGRAM

2.1 Raw materials

2.1.1 Cement

In this experiment, ordinary Portland cement (OPC) with a density of 3.14 g/cm^3 and a fine-ness of $3,750 \text{ cm}^2/\text{g}$, supplied by domestic company 'H,' was used. The cement complies with the Korean standard KS L 5201. The chemical properties of the cement are presented in Table 1.

2.1.2 Biochar

Biochar exists in various forms, including rice husk, sawdust, wood, and rice straw. In this experiment, wood-based biochar, pyrolyzed at approximately 450°C and identified as having the highest carbon content among biochar types, was used based on prior research (Han and Choi, 2023). Additionally, following previous studies (Gupta et al., 2021), the biochar content was set to 3% of the cement's mass ratio. To prepare the sensors incorporating biochar, a roll mill operating at 250–350 RPM was used to grind the biochar for over 30 minutes, matching the particle size of cement. Figure 1(a) illustrates the biochar after grinding.

Due to its high carbon content, biochar was anticipated to impart electrical conductivity to the cement composite. To maximize its conductive performance, the ground biochar was immersed in an iron chloride solution ($\text{pH} < 2.0$) to enhance conductivity within the composite.

2.1.3 Multi-Walled Carbon Nanotubes (MWCNTs)

To compare the performance of cement composite sensors incorporating biochar with those incorporating MWCNTs, a high-concentration liquid-phase MWCNTs solution (2% by weight of cement, TNM8, Chengdu Organic Chemicals Co., Ltd., China) was used. Additionally, a polycarboxylate-based high-performance superplasticizer was added to enhance the strength of the cement composite. The dissociated anionic particles from the superplasticizer adsorbed onto the surfaces of the cement and MWCNTs particles, generating repulsive forces between the anions, thereby facilitating dispersion.

2.1.4 Steel fiber

To consider the applicability of sensors within buildings, steel fibers were incorporated as both reinforcement and conductive materials due to their high toughness and conductivity. Steel fibers, which are short and thin wire-like fragments, are distributed within the concrete to prevent cracking and improve mechanical properties, thereby enhancing the strength of the concrete. The physical properties of the steel fibers are presented in Table 2, and their shape is shown in Figure 1(b).

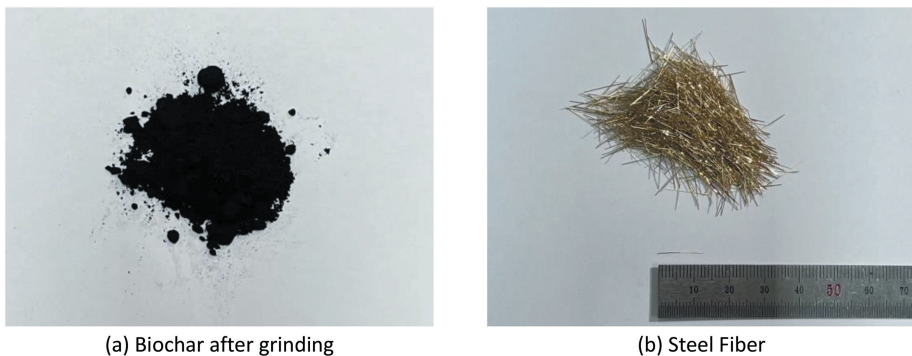


Figure 1. Images of Biochar and Steel Fiber.

2.2 Mix proportion

The mix proportions for the fabrication of the control specimen (OPC), biochar, Fe-loaded biochar, and MWCNTs & Fe-loaded biochar-incorporated cement composite sensors are

Table 1. The chemical composition of cement.

Chemical compositions	SiO ₂	Al ₂ O ₃	CaO	MgO	SO ₂	Fe ₂ O ₃
OPC (wt.%)	21.7	5.5	62.4	1.7	2.5	2.4

Table 2. The mechanical properties of Steel Fiber.

Specific gravity (kg/cm ³)	Length (mm)	Diameter (μm)	Tensile strength (MPa)	Elastic modulus (GPa)
7.85	13	200	2650	205

shown in Table 3, and the specimens were prepared following the standard mixing procedure. First, the cement, silica sand, 1% by mass steel fibers, and biochar were dry-mixed. A polycarboxylate-based high-performance superplasticizer, equivalent to 1% of the cement mass, was uniformly mixed with water, followed by the addition of 2% by mass MWCNTs to produce the sensors. The prepared specimens were cured under standard conditions and subsequently subjected to the curing process.

Table 3. Mix proportions of Biochar-cement composites.

Mixture	Cement (kg/m ³)	Water (kg/m ³)	Biochar (kg/m ³)	Silica sand (kg/m ³)	Liquid MWCNTs (kg/m ³)	S-F (kg/m ³)	S-P (kg/m ³)
OPC (control)	1250	375	0	500	0	78.5	12.5
BCCC	1212.5	375	37.5	500	0	78.5	12.1
FBCC	1212.5	375	37.5	500	0	78.5	12.1
FCCC	1187.5	375	37.5	500	25	78.5	11.8

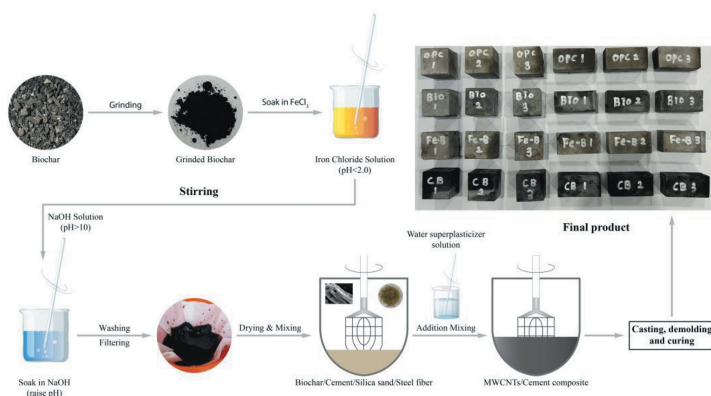


Figure 2. Preparation process of Biochar-cementitious sensors.

2.3 Experimental method

Compression strength specimens and sensor specimens were fabricated with dimensions of 50×50×50 mm³ and 40×40×80 mm³, respectively (Figure 2). Compression strength tests were conducted according to ASTM C109M standards, with a loading rate of 800 N/s.

To evaluate the piezoresistive performance of cement composite sensors incorporating biochar, electrical resistance measurements were performed using an LCR meter. The four-probe method, which eliminates electrode resistance and contact resistance, was used for these measurements. The LCR meter applies an AC signal to the specimen and measures the resulting impedance, which combines resistance (R), inductive reactance (L), and capacitive reactance (C) as described in Equation 1. To calculate piezoresistance, the resistivity (ρ_{AC}) was determined using Equation 2, where A is the cross-sectional area of the specimen (16 cm²) and L is the distance between electrodes (15 cm). The change in resistivity (ΔP_{AC}) was calculated using Equation 3 and expressed as the “Fractional Change in Resistivity” (FCR). Measurements were performed at a fixed frequency of 1 kHz and voltage of 1 V.

To assess the deformation recovery performance and sensitivity of the sensors, repeated compression tests were conducted using a universal testing machine (UTM). Repeated loading was applied at 10%, 30%, 50%, 70%, and 90% of the measured compressive strength. During the repeated loading process, strain values were recorded using a strain gauge connected to a TDS data logger, and resistivity was measured using the LCR meter. FCR values were then used to evaluate the strain-sensing capability of the sensors. As shown in Equation 4, the deformation sensing sensitivity of the sensors is determined by the Gauge Factor (GF), which is calculated based on the relationship between compressive stress, strain, and FCR.

$$Z = R + L + C \quad (1)$$

$$\rho_{AC} = \frac{R_{AC}A}{L} \quad (2)$$

$$FCR = \frac{\rho_{AC} - \rho_0}{\rho_0} \times 100\% = \frac{\Delta\rho_{AC}}{\rho_0} \quad (3)$$

$$GF = \frac{FCR}{\varepsilon} \quad (4)$$

3 EXPERIMENT RESULTS

3.1 Compressive strength

Figure 3 illustrates the compressive strength of the specimens. For specimens incorporating biochar, it is hypothesized that the wide surface area and porous structure of the biochar retained moisture during the early stages of curing, reducing the free water within the cement composite. This process likely facilitated densification and subsequently released moisture internally, contributing to increased strength. However, for specimens containing Fe-loaded biochar and MWCNTs, it is inferred that changes to the biochar surface medium interfered with the hydration process of the cement, resulting in slightly reduced compressive strength.

3.2 Repeated loading test

Figure 4 presents the graph of piezoresistive responses under cyclic compression. The control specimen (OPC) exhibited electrical properties due to the incorporation of conductive steel fibers, and the BCCC specimens demonstrated similar characteristics. The specimens with Fe-loaded biochar showed superior strain recovery capabilities compared to the control specimen; however, as the applied load exceeded 70%, the FCR values increased, leading to inconsistent piezoresistive performance. Specimens incorporating additional MWCNTs exhibited superior piezoresistive performance compared to other specimens.

Specimens incorporating additional MWCNTs exhibited superior piezoresistive performance compared to other specimens. However, when Fe-loaded biochar was mixed with MWCNTs, the results deviated slightly from previous findings. This difference is presumed to arise from the interaction between surface-modified biochar and MWCNTs, indicating the need for further investigation.

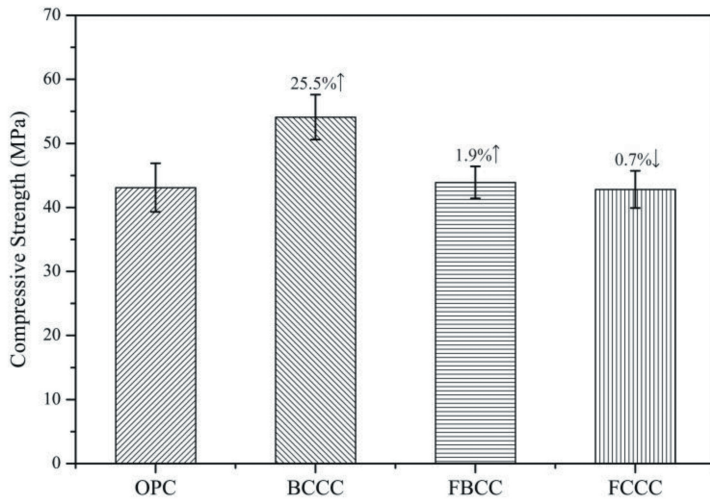


Figure 3. Compressive strength of Biochar based sensor.

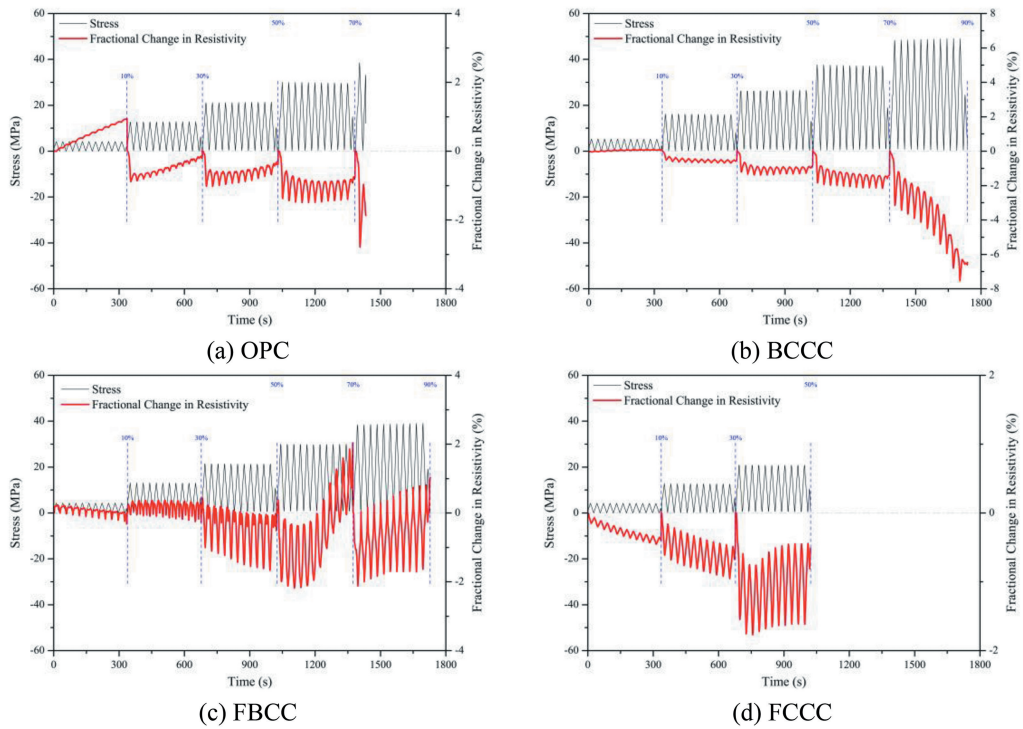


Figure 4. Self-sensing response of Biochar based sensors in repeated loading test.

In this experiment, the VCX-750 ultrasonic disperser from Sonics & Materials Inc. was used to disperse the MWCNTs. To prevent defects and overheating of the MWCNT surfaces during ultrasonic dispersion, the container was immersed in ice water to maintain a low temperature, as shown in Figure 2(a). The maximum amplitude under ultrasonic conditions was kept below 50%. The dispersion energy levels were set to 500J and 1000J, which had shown optimal results in previous studies[19], and the experiments were conducted accordingly. As illustrated in Figure 2(b), sensors were fabricated based on these conditions.

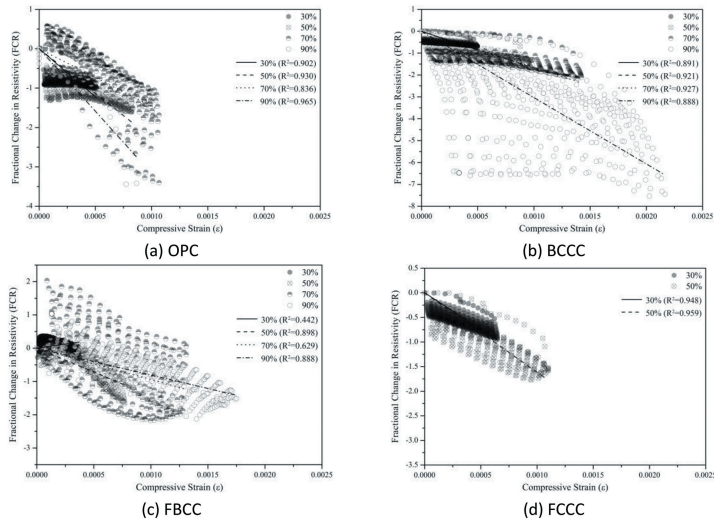


Figure 5. Relationship between FCR and compressive strain of Biochar based sensors.

4 CONCLUSIONS

In this study, biochar with carbon capture capability was immersed in an iron chloride solution to form metal (Fe) oxides, thereby imparting electrical conductivity. Through compressive strength tests, impedance measurements, and cyclic compression tests, the piezoresistive performance and strain-sensing capabilities of the sensors were evaluated. The findings of this study are summarized as follows.

1. The strength of the composite incorporating biochar was found to be higher than that of the reference specimen (OPC). This is attributed to the porous structure of the biochar, which retained initial moisture and reduced the free water within the cement composite, thereby strengthening the ITZ (Interfacial Transition Zone) region.
2. The composites incorporating OPC and biochar exhibited detectable electrical properties due to the conductive material, steel fibers; however, they showed inferior deformation recovery ability. In contrast, the mortar incorporating Fe-loaded biochar demonstrated excellent deformation recovery ability but showed inconsistent piezoresistive performance under loads exceeding 70%. Additionally, composites with the additional incorporation of MWCNTs exhibited superior deformation recovery ability, but their piezoresistive performance differed from previous studies involving MWCNTs. This discrepancy is attributed to the interaction between surface-modified biochar and MWCNTs, suggesting the need for further research.

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