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Procedia Structural Integrity 78 (2026) 1871–1878

Structural Integrity
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XX ANIDIS Conference

A Review on the Application of Biochar as a Self-Sensing and Self-Healing Additive in the Cementitious Composites

Amandeep Singh Sidhu[a], Flora Faleschini[b,]*, Michele Secco[c]

[a,b]*Department of Civil, Environmental and Architectural Engineering, University of Padova, Via Marzolo 9, Padova 35131, Italy*
[c]*Department of Cultural Heritage: Archaeology and History of Art, Cinema and Music, Piazza Capitaniato, 7, Padova 35139, Italy*

Abstract

The biochar (BC) has seen usage in a diverse number of applications such as soil amendment, asphalt mix additive, waste water filtration and cementitious composites. These applications have also been continuously expanding through ongoing research efforts. In recent years, its use in cementitious composites has gained attention, particularly as a partial replacement for cement content to improve its strength and durability performance by enhancing its internal microstructure. More recently, biochar is being tested for certain novel implementations in the cementitious systems, particularly imparting self-sensing and self-repair properties to them. The research is being conducted to evaluate the potential of biochar in increasing the electrical conductivity of cementitious mixes, which could enable real-time structural health monitoring. Additionally, some studies have utilised biochar itself or as a carrier material for delivering self-healing bacteria and with other agents to repair any cracks formed during the lifetime of the cementitious material. While these innovative applications have shown promise, they are still in the initial phases of development. The present study aims to provide the state-of-the-art advancements in this field, which would offer insights into the underlying mechanisms and processes involved when BC is used for self-sensing and self-repair application in cementitious mixes, thereby guiding future research efforts.

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Keywords: Biochar; Self-Sensing cementitious composites; Self-Healing cementitious composites; Electrical conductivity

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* Corresponding author.
E-mail address: flora.faleschini@unipd.it

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10.1016/j.prostr.2025.12.238

1. Self-sensing cementitious material

1.1. Introduction

Incorporating self-sensing capability into buildings allows for real-time health monitoring with the capability to estimate external loads (through the piezoelectric effect) in addition to detecting crack generation and contaminant ingress (Cosoli et al., 2023). These techniques would be essential in future for enhancing the resilience of the built environment, as the structures would have the inherent ability to monitor and manage themselves by sensing early signs of damage and enabling pre-emptive measures to prevent failure (Cosoli et al., 2024; Shilar et al., 2024). To achieve this aim of self-sensing capability the widely used construction materials such as mortar and concrete needs to be conductive in nature, however, cementitious composites are known to have high electrical resistance typically in the range of $10^{3\sim7}$ kΩ·m, thus acting similar to an insulator (Park et al., 2023), which makes them unsuitable for any application of the self-sensing category. To overcome this limitation certain additives are added such as graphene conductive sheets (Kashif Ur Rehman et al., 2018), conductive fibres (Tian et al., 2024; Zhao et al., 2024), conductive powdered materials (Tian et al., 2024), carbon nano tubes (Tian et al., 2024) etc. which can increase the electrical conductivity through contact conduction, ionic conduction or tunnelling effect (Han et al., 2015; Kanagasundaram and Solaiyan, 2023). Figure 1 shows the typical working of the smart sensing cementitious materials.

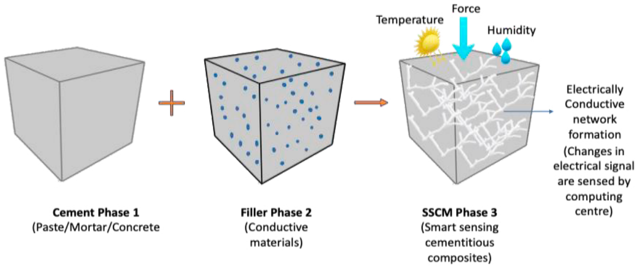

Figure 1. Smart sensing cementitious material development process (Adapted from Kanagasundaram and Solaiyan (2023))

Biochar (BC) is one such material which can provide self-sensing capacity to cementitious materials (Kang et al., 2024). Presently, BC is used in various applications such as soil improvement (Yang et al., 2019), asphalt modification (Rondón-Quintana et al., 2022) and cementitious composites (Akinyemi and Adesina, 2020) etc. These applications of BC derive benefits from its inherent properties such as porous nature, high surface area, fine size and presence of certain functional groups (Yang et al., 2019; Akinyemi and Adesina, 2020; Guo et al., 2020; Ma et al., 2022; Rondón-Quintana et al., 2022). The application of BC in the cementitious composites has been of particular interest due to its ability to improve the performance of the mix by partially replacing cement, in addition to reducing the carbon footprint of the cement. Further expanding on these initial studies, there have been ongoing efforts to use another aspect of the BC in the cementitious composites, i.e., its ability to increase the conductivity of the cement-based material. This novel application of the BC is a direct result of its high carbon content. Cementitious materials have an inherently low conductivity as previously discussed, therefore mostly categorised as a semi-conductor to sub-insulator (Hou et al., 2017). BC presence in cementitious material offers it an enhanced electrical conductivity, which can help in developing self-sensing capability and real-time structural health monitoring. Self-sensing or piezoresistive composites are known for their low electrical resistance, which assists in real-time monitoring of the stress and strain development in them (Monteiro et al., 2017), therefore, BC is a viable option to develop self-sensing cementitious material based on same principle.

1.2. Biochar application in self-sensing cementitious composites

Kamaluddin et al. (2020) experimented with 5%, 10%, 15% BC content by cement weight to modify the electrical resistivity of the cement paste and found 5% BC mix to be optimal, which was able to reduce the electrical resistance to a value of 16.8 MΩ after 168 hrs. of curing. Haque et al. (2021a), in a preliminary study, tested the impact of stearic acid-treated BC (to improve hydrophobicity) on electrical conductivity. The authors found the conductivity increased in the range of 17.7-22.5% for up to 10% BC content in cementitious composite (Refer Figure 2). Extending the findings of this study, Haque et al. (2021b) further employed varying amounts of treated hydrophobic BC (0-15% of cement) in cement mortar and paste to evaluate the electrical conductivity and its self-sensing ability. The authors were successfully able to demonstrate reduction in the electrical resistance by 22.9-28.6% for different curing periods of 7-56 days. The authors also found a strong linear relationship between stress and functional change in resistivity (FCR) in the 15% biochar-based mix ($R^2 = 0.9964$), indicating a highly consistent self-sensing behaviour. In contrast, the reference mix exhibited a sporadic and less predictable relationship between the same parameters (Refer Figure 3). Thus, the authors confirmed that BC can be employed as a cheap alternative to other high cost nano-carbon materials to use in self-sensing cement mixes. In a similar study by Jeong et al. (2022), the authors modified the BC using melamine as a functional group and found the electrical conductivity to be increased by almost 10^8 times with 0.1% BC content; however, any further BC content didn't contribute much change in conductivity. The conductivity achieved by the functionalised BC was above the value which is typically achieved through the use of 1% graphene nano plates (GNPs), as per the author's observation, which can help replace these expensive carbon fillers with a cheaper alternative of melamine functionalised BC.

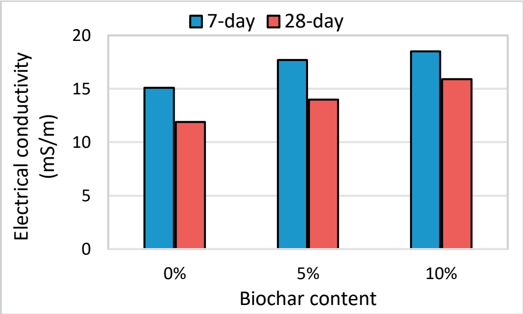

Figure 2. Comparison of electrical conductivity of BC mixes (Data from Haque et al. (2021a))

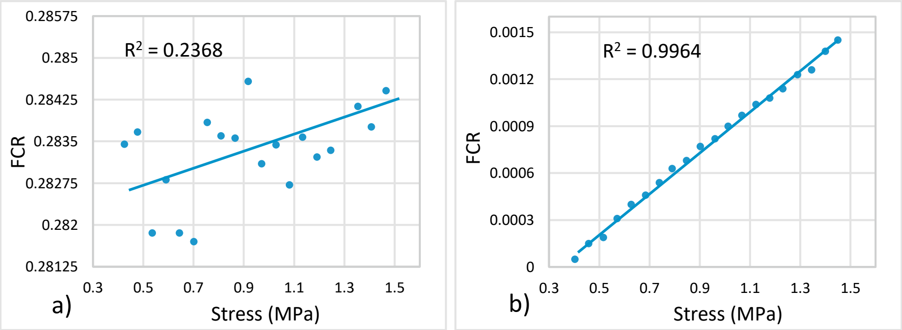

Figure 3. Fraction resistivity change (FCR) (a) with 0% SHCP (i.e., control batch) and (b) with 15% SHCP as partial replacement of cement (Adapted from Haque et al. (2021b))

To increase the cementitious materials' conductivity, there have been attempts to combine BC with other conductive materials. To exploit the carbon component present in BC it was used in conjunction with other nano carbon material byKang et al. (2024), where the authors set up an experiment consisting of Digital Image Correlation (DIC) test, four-probe resistivity test, non-contact resistivity test and piezoresistive test. The results of the resistivity test confirmed the BC's ability to reduce the electrical resistance when used at 4.5% and 9% in the mix, under continuous monitoring for 72 hrs. The rate of resistivity change in the cement paste was linked to the evolution of the hydration reaction and was divided into five stages over a 24-hour period. The highest rate of resistivity decrease occurred during the fourth stage (10–17 hrs.), where the hydration process was driven by nucleation and growth and led to a significant consumption of ions in the pore solution, resulting in the hardening of the mix. The 4.5% BC contributed to a decrease in resistivity by 23.1% in cement paste at 35-day testing, through the tunnelling and contact conduction phenomenon, therefore confirming its suitability for application in self-sensing cement composite. In another study, the authors used a small amount of BC (0.05% by vol. of mortar), in combination with 0.5% carbon fibres, enabling high sensitivity in strain measurement, which can be effectively exploited to provide self-sensing capabilities (Cosoli et al., 2023). Zhang et al. (2025) synthesised iron-rich BC using a 1:1 mixture of iron sludge and glucosamine sludge, which was heated up to 800 °C. The authors found that the electrical resistivity of the cement paste decreased by 28.81–48.42% as the biochar content increased from 0% to 10%. Ahmed et al. (2024), in an attempt to increase the carbon content of the BC, which would better support the electrical conductivity when used in cementitious composites, blended rice husk and coal in a ratio of 3:1 to produce BC. The synthesised BC achieved a high carbon content of 74.91%, which resulted in increased electrical conductivity from the reference value of 4.5 mS/m to 7.5 mS/m, for a 15% BC mix at 28 days of curing. The change in sensitivity for self-sensing applications also yielded positive results, as the BC mixes exhibited a linear correlation with a high R^2 (0.99) which was significantly better than the reference mix, with R^2 value of 0.29.

2. Self-healing composite materials

2.1. Introduction

Self-healing of cementitious materials refers to their ability to repair cracks that form during the service period without any external intervention (Sahmaran et al., 2013; Li et al., 2018). Such cement mixes will be essential for future applications, as they offer increased durability and sustainability, along with reduced overall maintenance costs and enhanced safety (Jefferson et al., 2018; Panza Uguzzoni et al., 2023). While autogenous healing can allow for repairs in the finer-sized cracks (50-60 microns), the use of self-healing additive materials helps in repairing even wider cracks (Gupta, 2022). These self-healing techniques also have the potential to replace traditional manual repair methods i.e., use of sprays or injections of chemical sealants, which have several limitations such as material compatibility issues like volume instability, mismatched thermal expansion coefficients, delamination and long-term degradation of the repaired areas (Kessler and White, 2001; De Muynck et al., 2008; X. Wang et al., 2019). To achieve self-repair in cementitious composites, several strategies have been explored in recent years that allow for inherent self-healing through continued hydration reactions or through the incorporation of self-healing agents such as epoxy (Perez et al., 2015), polyurethane (Anglani et al., 2022), methyl methacrylate (Van Tittelboom et al., 2011), bacteria-induced healing (Chen et al., 2016), superabsorbent polymers (C. Wang et al., 2019) etc. These methods function in various ways such as reaction of polymer with the functionalised silica in the cement matrix (Perez et al., 2015), filling cracks by calcite formation (Li et al., 2024), expansion of the SAP to seal any cracking/openings in contact with moisture (Chindasiriphan et al., 2020), or through late hydration of the unreacted cement particles when it comes in contact with moisture (Wu et al., 2012). These techniques counteract cracking that occurs during the service life of the cementitious composite, thereby enhancing durability and extending structural lifespan. Among the various self-healing techniques discussed previously, biological approaches, such as the use of bacteria, have recently gained attention (Seifan and Berenjian, 2020). Immobilising bacteria in carrier support materials has been shown to improve their survivability in cementitious composites, as high pH of the pore solution of the cement acts against the survivability of bacteria spores if added directly (Wang et al., 2015; Singh and Gupta, 2020), therefore, it becomes important to provide external support to the bacteria for enhancing its self-healing performance (Khaliq and Ehsan, 2016).

Bacterial cementitious composites previously researched have identified several support mediums for the bacteria such as alganite and chitosan gel (Wang et al., 2015, 2018), silica gels (De Belie and De Muynck, 2008), light weight aggregates (Wiktor and Jonkers, 2011) etc. However, these materials can have certain limitations, such as loss in mechanical strength of the mix (Wang et al., 2015), high cost (Wiktor and Jonkers, 2011), low scalability (Feng et al., 2022), poor long-term durability (Wiktor and Jonkers, 2011) etc. To support bacterial survivability in the cement mixes BC usage has been regarded as a viable option. BC as immobilizing medium for self-healing bacteria addresses the abovementioned limitations and offers a cost-effective (Zhang et al., 2024), environmentally friendly (Woolf et al., 2010), carbon negative (Gupta et al., 2018) solution for the self-healing of concrete.

2.2. BC application in self-repair cementitious composites

Kua et al. (2019) compared the efficiency of 1% BC (with macro-pores of 10-20 µm) as a bacterial immobilisation medium with other approaches, i.e., superabsorbent polymers (SAPs) and combinations of fibres, for self-repairing concrete. The bacterial immobilized BC proved to be more effective than the other methods, particularly for repairing wider cracks (500 µm and 800 µm). The presence of BC also reduced permeability and enabled better recovery of sorptivity properties after repeated damage–healing cycles. Fu et al. (2024), also conducted experiments along similar lines by using BC as a medium for CO_2 capture, along with superabsorbent polymers (SAPs) and ammonia solution ($NH_3 \cdot H_2O$) to accelerate carbonation. A novel coarse aggregate in the form of pellets (4 mm dia. × 4-5 mm ht.) was developed and termed as Carbonation-Activated Aggregate (CAA). Among all the tested mixes, the mix containing 5% CAA exhibited the best performance, achieving the highest healing percentage after the testing period, thus showing the supportive role of BC in the self-healing cementitious mix.

Gupta et al. (2018) immobilised Bacillus sphaericus in 2% BC (by cement mass) and observed a higher sealing ratio after repair, under the application of 50% and 70% of the peak load. The BC based mix showed a compressive strength recovery exceeding 100% compared to the regular (non-healing) mix. In a similar study with fibre reinforced mortar mix, Gupta (2022), compared the self-healing performance of different carrier media i.e., superabsorbent polymers (SAP) and biochar (BC), for bacterial immobilisation, along with the incorporation of fibres in both systems. The study found that BC-based bacterial mixes achieved a reduction in water penetration by 25-27% and 12-13%, depending on the type of fibre used. In contrast, the reference mix showed no significant improvement. The compressive strength regains showed that repaired samples were just 2-8% value lower than the undamaged samples at 28 days for the 60%σ and 80%σ; however, when the damage was beyond the 80%σ, the BC resulted in undesired weak zones in the mix. The SEM micrographs showed that in BC based mixes, both finer and wider cracks were filled with the deposited calcite crystals. The BC immobilised bacteria was also used by Anoop and Palanisamy (2025) in the mortar mix in form of powder. The results favoured the use of BC against the direct introduction of lyophilised bacterial spores in the mix because it was successful in filling a wide crack of size 0.8 mm at 56 days when submerged in rainwater conditions due to the high dissolved oxygen content in rainwater, compared to the other methods used in the study. Under a similar testing method, Lin et al. (2025a) used simulated seawater (5% Na_2SO_4) for curing mortar containing BC and a crystalline healing admixture. The authors found that while BC did not significantly influence the healing process when used with the crystalline admixture, it contributed to the formation of more complex crack patterns, resulting in higher energy absorption. Anoop et al. (2024), used "Bacillus safensis CG1" and "Bacillus cereus DKBovi-5" bacterial species, immobilised in BC and stored at 4 °C. These bacterial mixes healed cracks up to 0.888 mm within 56 days, while cracks smaller than 0.2 mm were fully healed in 28 days. The mix with BC immobilised bacteria also exhibited the smallest average pore size of 3.086 nm. Ultrasonic pulse velocity testing showed healing improvements of 30.31% for the "BC + Bacillus cereus DKBovi-5" mix and 16.12% for the "BC + Bacillus safensis CG1" mix after 56 days. The role of BC-immobilised bacteria was further explored in conjunction with carbon fibres in mortar by Zhang et al. (2024). The study found that unmodified BC and carbon fibres exhibited a synergistic effect with internal curing provided by BC and crack-bridging by carbon fibres. This combination achieved healing rates of 41.21% at 28 days and 43.05% at 90 days. Moreover, the mix containing BC immobilized bacteria achieved a complete crack healing by 90 days, which was attributed to the microbially induced calcium carbonate precipitation (MICP) process. Figure 4 depicts the crack healing rate from the study.

While the previously mentioned studies focused on self-healing in cementitious composites using bacteria immobilised in BC, Vafaei and Ghahremaninezhad (2024) directly investigated the self-healing potential of BC itself. The study yielded favourable results, highlighting that BC can act as a self-healing agent due to its water retention capacity, which supports healing through the hydration of unreacted cement particles and calcium carbonate deposition facilitated by CO_2 ingress through formed cracks (Refer Figure 5). However, when the BC immobilised bacteria in fly ash based geopolymer mix was tested against direct bacteria introduction in the mix, Doctolero et al. (2020) suggested that while BC immobilized bacteria did not reach the same effect as direct bacteria introduction, the maximum improvement was achieved by using an optimal BC content of about 0.3-04 g/ml.

To test for any advantage from incorporating BC in a mix already using a proprietary healing agent, “PENENTRON crystalline admixture”, Lin et al. (2025b) used 2% and 5% BC in the cement mix. The BC mixes were able to fill the cracks completely after 56 days; however, for such results, the sample should be exposed to wet dry cycle curing conditions to allow for the CO_2 exposure. The study found that the incorporation of BC had no negative impact on the healing behaviour of the crystalline admixture. In fact, 5% BC led to a more complex cracking pattern due to improved ductility, which was also completely sealed after 56 days of healing due to additional nucleation sites provided by the BC particles to form mostly $CaCO_3$ and some $Ca(OH)_2$ and CSH gel.

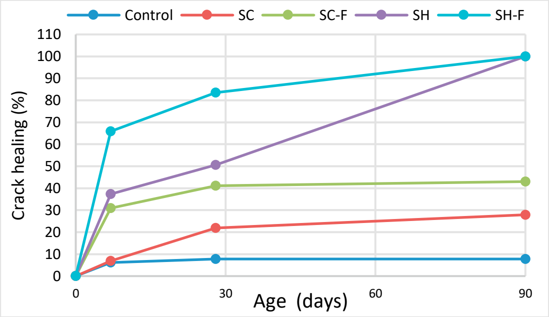

Figure 4. Crack healing rate of specimen (Adapted from Zhang et al. (2024)) (SC – Only biochar; SC-F –[Biochar + Carbon fiber]; SH – [Biochar + bacteria]; SH-F – [Carbon fiber + healing agent])

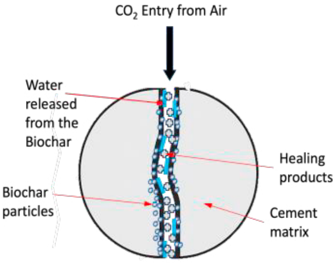

Figure 5. Self-healing schematic for BC based cement mix (Adapted form Vafaei and Ghahremaninezhad (2024))

Conclusions

The present study provides insights into the application of the BC as an additive in the self-sensing cementitious composites and the role of BC as an immobilising medium for the bacteria and its usage in combination with other materials for cementitious mixes self-healing. Based on the data presented following conclusions can be drawn:

- BC has an ability to reduce the electrical resistivity of the cementitious composites due to its high carbon content.
- The cementitious mixes have been found to provide a consistent fractional resistivity change with a high coefficient of determination (R^2) when BC is present in the mix, thereby providing evidence of the self-sensing ability of such mixes.
- The BC can contribute to the process of self-healing in cementitious mixes through various modes i.e., (a) Highly porous structure of BC act a support for bacterial hybrid-healing system (b) BC provides a place for nucleation site for production of CSH gel and $CaCO_3$ thus improving crack healing efficiency (c) High water holding and release capacity of BC offer ability to heal cracks by reacting with unreacted cement particles during later stages.
- BC when used as a support for bacterial immobilisation in self-healing, is able to fill wider cracks than bacterial spores that are directly introduced into the mix.
- The principal component observed to be involved in the crack healing process is the $CaCO_3$ crystal, however small amount of CSH gel and $Ca(OH)_2$ may also be present.
- The use of BC in cementitious mixes provides a viable, low-cost and environmentally friendly approach for the development of self-sensing and self-repairing materials. However, future research should be carried out to scale its application for larger structures and assess its long-term performance under real-world conditions.

Acknowledgement

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022)

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