Microstructural evolution and compressive strength enhancement of mortar containing spent coffee ground biochar as a sustainable filler

Jidsucha Darayen[1,*], *Chanikarn* Vukthong[1], *Chanachai* Thongchom[2] *and Sutha* Khaodhiar[3]

[1]Chemical Engineering, Faculty of Engineering, Thammasat School of Engineering, Thammasat University, Thailand
[2]Civil Engineering, Faculty of Engineering, Thammasat School of Engineering, Thammasat University, Thailand
[3]Department of Environmental and Sustainable Engineering, Faculty of Engineering, Chulalongkorn University

Abstract. This research investigates the influence of spent coffee ground biochar (SCGBC) on the mechanical and microstructural properties of cement mortar as part of sustainable construction practices. Mortar specimens were prepared with various SCGBC contents (0, 1, 2, 3, and 5 wt% of cement) and tested for compressive strength (7, 14, and 28 days). Phase composition and hydration characteristics were examined using XRD, SEM-EDS. The 1 wt% SCGBC sample revealed the highest compressive strength (15.03 tons at 28 days), approximately 6% higher than the control. The enhancement is attributed to the micro-filler and nucleation effects of biochar, which promote denser C–S–H gel formation and stronger interfacial transition zones (ITZ). XRD patterns confirmed typical hydrated phases—portlandite, calcite, quartz, and gypsum—with decreasing portlandite intensity as SCGBC increased, indicating mild pozzolanic reactions. SEM-EDS analysis revealed reduced porosity and higher Ca/Si ratios at 1 wt%, while excessive biochar (≥3 wt%) caused pore coalescence and particle agglomeration, resulting in strength loss. These findings demonstrate that coffee-waste-derived biochar can be effectively utilized as a green additive for improving mechanical performance and reducing the environmental impact of cement-based materials.

KEYWORDS: Biochar mortar, Spent coffee ground, Compressive strength, Sustainable construction materials, Microstructure

1 Introduction

The manufacture of cement-based materials remains a substantial source of human-induced CO_2 emissions, primarily because of the energy-intensive clinker manufacturing process [1]. This environmental concern has prompted extensive efforts to develop more sustainable cementitious systems by incorporating alternative materials. In particular, the utilization of waste-derived resources is considered a promising strategy to simultaneously reduce environmental impact and maintain desirable mechanical properties [2]. Biochar, a carbon-rich material produced through the thermochemical conversion of biomass under oxygen-restricted conditions, has attracted increasing attention for such applications [3]. Its physicochemical characteristics, such as a well-developed porous structure and large specific surface area [4], and reactive surface functionalities, enable it to interact effectively with cement hydration processes. These features may contribute to improved microstructural development through mechanisms such as pore refinement and enhanced nucleation of hydration products [5, 6].
Among potential biomass sources, spent coffee grounds (SCG) represent a widely available organic waste with limited reuse pathways and are commonly disposed of in landfills [7]. Transforming SCG into biochar and incorporating it into cementitious matrices offers a viable approach for waste valorization while supporting circular economy principles.

*Corresponding Author: djidsuch@engr.tu.ac.th

Previous studies suggest that incorporating biochar can modify hydration behaviour and internal moisture regulation; however, its performance is strongly influenced by factors such as dosage, surface chemistry, and particle morphology. In particular, the transition between beneficial and detrimental effects remains insufficiently understood for SCG-derived biochar systems [8].

This study therefore focuses on assessing the impact of SCG-derived biochar on the microstructure and compressive strength of cement mortar through the application of advanced characterization techniques, including XRD, SEM, and EDS, are employed to elucidate the underlying mechanisms governing performance.

2 Materials and Methods

2.1 Materials

The primary binder used in this study was Ordinary Portland cement (Type I). Spent coffee grounds (SCG) were sourced from local cafés and then oven-dried at 105 °C for 24 h to ensure complete moisture removal. The dried biomass was subsequently pyrolyzed at 400 °C for 2 h under oxygen-limited conditions to produce biochar (SCGBC). Natural river sand (fineness modulus = 2.6) was employed as the fine aggregate component. All mixtures were prepared using potable tap water.

2.2 Mix Proportions

Mortar specimens were formulated with fixed water-to-cement (w/c) and sand-to-cement (s/c) ratios of 0.50 and 2.75, respectively. SCG-derived biochar was introduced as a partial additive at dosages of 0, 1, 2, 3, and 5 wt% relative to the cement content. The constituents were uniformly blended to ensure adequate dispersion, followed by casting into cubic molds (50 × 50 × 50 mm).

2.3 Curing and Testing

After 24 h, the specimens were removed from the molds and subjected to water curing at 30 ± 2 °C until testing at 7, 14, and 28 days. The compressive strength measurements were determined using a universal testing machine (UH-200A, Shimadzu). Microstructural characterization was carried out on fractured surfaces obtained after mechanical testing.

2.4 Characterization

The phase composition of hydration products was determined using X-ray diffraction (Rigaku) with Cu-K_α radiation in the 2θ range of 10–90º. Scanning electron microscopy (SEM) was employed to assess morphological and microstructural features at 10 kV, and elemental analysis was performed using energy-dispersive X-ray spectroscopy (EDS) attached to the SEM system (Hitachi SU3500 equipped with a Horiba X-maxN detector).

3 Results and Discussion

3.1 Compressive Strength

The change in compressive strength of mortar (Figure 1) as a function of curing time at different SCGBC dosages is shown. An increase in compressive strength with curing age is observed for all mixtures, suggesting the ongoing progression of cement hydration. However, the extent of strength development is strongly influenced by the biochar content. The mortar incorporating 1 wt% SCGBC consistently demonstrates superior compressive strength at all curing ages, reaching 15.03 tons at 28 days, which is marginally higher than that of the control sample (14.95 tons). This enhancement suggests that a low dosage of SCGBC effectively improves the mechanical performance of the cementitious matrix. In contrast, further increasing the SCGBC content results in a gradual decline in strength. The mixtures containing 2 wt% and 3 wt% SCGBC show moderate compressive strengths of 11.70 and 10.46 tons, respectively, while a more pronounced reduction is observed at 5 wt% (9.26 tons). This behavior can be attributed to the dual role of SCGBC within the system. At low dosage, the fine biochar particles enhance particle packing and facilitate the formation of hydration phases, primarily calcium silicate hydrate (C–S–H), leading to enhanced microstructural densification and cohesion. [9, 10]. In addition, the intrinsic porosity of biochar may enable temporary water retention, which supports continued hydration and contributes to matrix densification.
However, at higher dosages, the dispersion of SCGBC becomes less uniform, promoting particle agglomeration and the formation of additional pore structures. These defects disrupt the continuity of the cement matrix and reduce the effective load-bearing area, ultimately resulting in decreased compressive strength. Therefore, the mechanical performance is governed by a balance between microstructural refinement at low SCGBC content and porosity-induced weakening at higher incorporation levels.

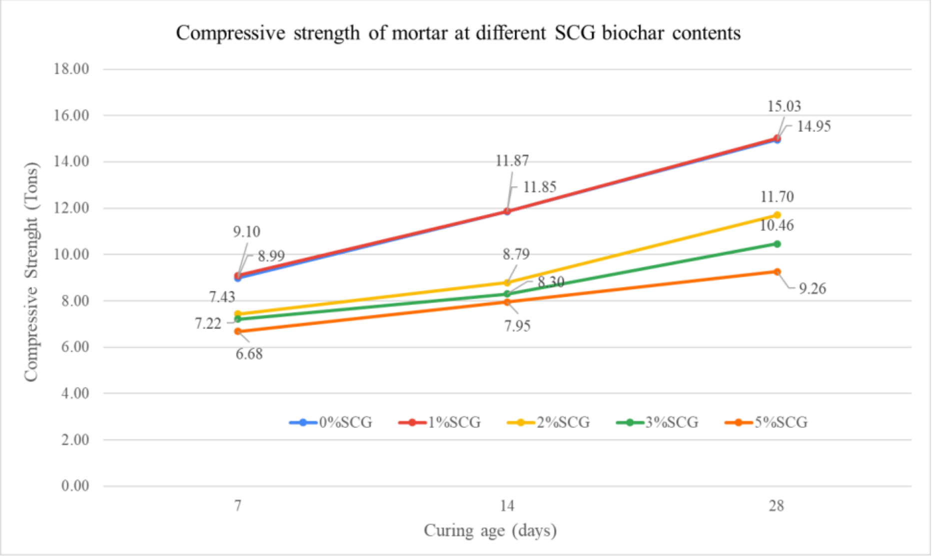

Figure 1. Compressive strength of mortar at different SCG biochar contents.

3.2 XRD Analysis

The compressive strength trend corresponds closely with the XRD results, which revealed intensified C–S–H peaks at 1 wt% SCGBC [11], indicating enhanced hydration and gel formation responsible for matrix densification [12, 13]. The progressive decline in strength at SCGBC contents above 3 wt% corresponds to a reduction in hydration product development and the presence of residual carbon phases, indicating that excessive biochar incorporation interferes with the normal hydration process [14, 15]. Thus, the mechanical performance and microstructural evolution observed are strongly governed by the balance between hydration promotion and porosity development influenced by the SCGBC dosage.

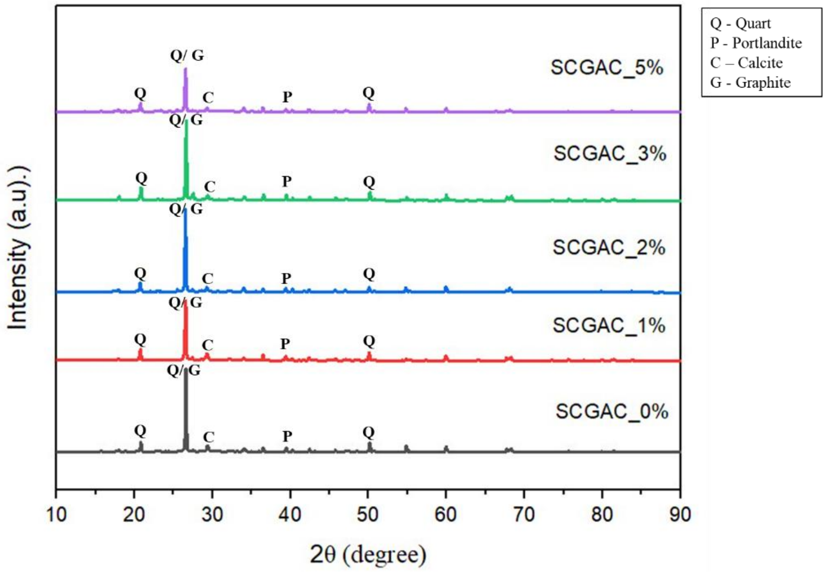

Figure 2. XRD patterns of mortar samples containing different SCGBC contents.

XRD patterns (Figure 2) show dominant peaks corresponding to quartz (Q), calcite (C), portlandite (P), and gypsum (G). The intensity of portlandite peaks decreases slightly as SCGBC content increases, confirming partial consumption of $Ca(OH)_2$ through a mild pozzolanic reaction with amorphous carbonaceous silica from the biochar. No additional crystalline phases were observed, indicating that the fundamental hydration pathway of the cement matrix remains largely unaffected. The combined microstructural densification and secondary C–S–H formation explain the enhanced strength at low SCGBC contents.

3.3 SEM-EDS Microstructural Observations

The SEM–EDS analysis (Figure 3) clearly demonstrates the microstructural and compositional evolution of mortar with increasing SCGBC content. The control sample (0% SCGBC) displays a relatively porous surface with weak particle bonding and visible voids, corresponding to a Ca/Si ratio of 2.18. Upon adding 1 wt% SCGBC, the morphology becomes significantly denser, with compact C–S–H gel formation and well-bonded matrix regions, reflected by an increased Ca/Si ratio of 2.42, suggesting enhanced hydration and gel development.

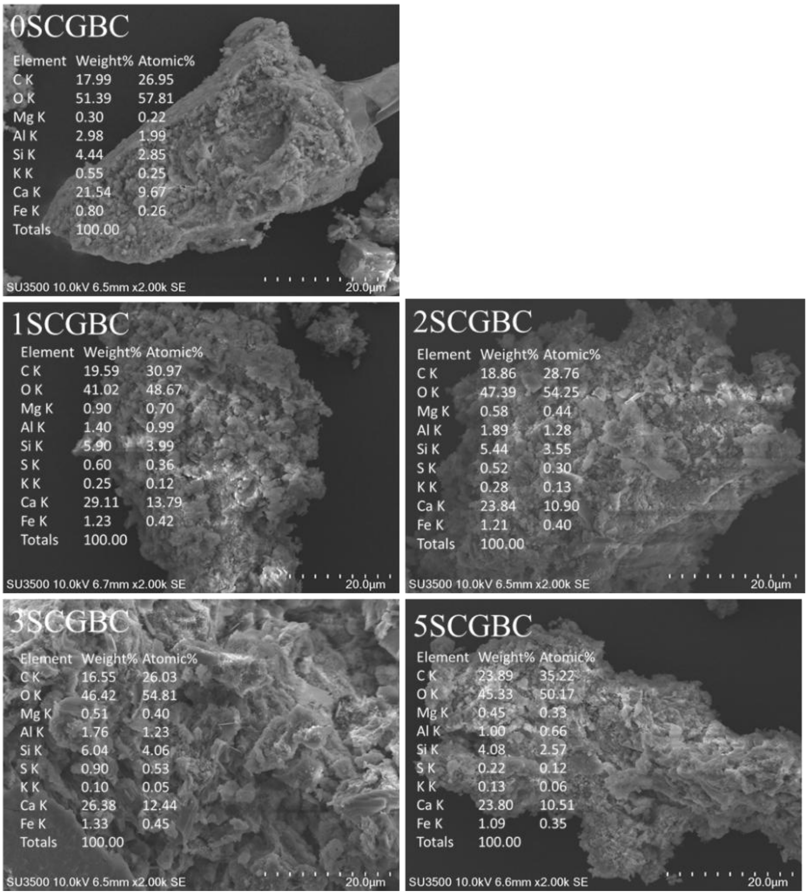

Figure 3. SEM/EDX micrographs of mortar samples with varying SCGBC (0-5%) contents.

At 2–3 wt%, partial agglomeration of biochar particles and localized microcracks begin to appear, slightly reducing matrix uniformity. In the 5 wt% SCGBC sample, a heterogeneous and porous structure dominated by carbon-rich clusters (up to 23.9 wt% C) is evident, indicating incomplete hydration and the presence of unreacted phases. These SEM–EDS findings align closely with the compressive strength results, confirming that the optimal 1 wt% SCGBC dosage promotes matrix densification through improved hydration, whereas higher contents introduce excessive carbon and porosity, weakening the overall mechanical performance.

3.4 Mechanistic Interpretation

At the optimal dosage of 1 wt%, SCGBC functions synergistically as a micro-filler, nucleation center, and internal curing agent. The incorporation of fine SCGBC particles enhances packing efficiency within the cementitious matrix, contributing to a more compact and refined microstructure. In addition, the biochar surface enhances the formation of key binding phases, including C–S–H, by facilitating favorable conditions for early-stage reactions. The inherent porosity of SCGBC further supports internal moisture regulation, enabling gradual water release that sustains hydration over extended curing periods and improves overall matrix integrity. However, when the SCGBC content exceeds 3 wt%, the hydrophobic nature of biochar particles leads to agglomeration, disrupting the matrix continuity and creating interconnected pores. This increased total porosity reduces the effective load-bearing area, counteracting the initial microstructural benefits. Thus, the mechanical performance is governed by a balance between hydration enhancement at low dosages and porosity-induced weakening at higher additions.

4 Conclusion

The findings indicate that spent coffee ground biochar (SCGBC) can serve as a sustainable additive in cementitious materials, offering improvements in both mechanical performance and environmental impact. The findings indicate that an optimal dosage of 1 wt% yields the highest compressive strength, which is associated with enhanced microstructural densification. Microstructural analyses using XRD and SEM/EDS reveal that low SCGBC incorporation promotes the development of hydrated phases, particularly C–S–H, thereby improving matrix densification and cohesion. In contrast, increasing SCGBC content beyond 3 wt% leads to particle agglomeration and the formation of additional pores, which disrupt matrix continuity and reduce mechanical strength. Overall, SCG biochar contributes dual benefits: mechanical enhancement of mortar and valorization of waste biomass, aligning with the principles of circular construction and carbon reduction. Future research will focus on evaluating durability properties—including permeability, carbonation resistance, and long-term shrinkage—to further substantiate SCGBC's applicability in sustainable infrastructure development.

The authors gratefully acknowledge the support provided by the Faculty of Engineering, Thammasat School of Engineering, Thammasat University. Financial support for this work was provided by the National Research Council of Thailand (NRCT) under Contract No. N42A680234 and the Thammasat University Research Fund under Contract No. TUFT028/2568.

References

1. L. Huang, G. Krigsvoll, F. Johansen, Y. Liu, and X. Zhang, "Carbon emission of global construction sector," Renewable and Sustainable Energy Reviews, vol. 81, pp. 1906-1916, 2018/01/01/ 2018, doi: https://doi.org/10.1016/j.rser.2017.06.001.
2. X. Li et al., "A systematic review of waste materials in cement-based composites for construction applications," Journal of Building Engineering, vol. 45, p. 103447, 2022/01/01/ 2022, doi: https://doi.org/10.1016/j.jobe.2021.103447.
3. M. Afshar and S. Mofatteh, "Biochar for a sustainable future: Environmentally friendly production and diverse applications," Results in Engineering, vol. 23, p. 102433, 2024/09/01/ 2024, doi: https://doi.org/10.1016/j.rineng.2024.102433.
4. W. Suliman, J. B. Harsh, N. I. Abu-Lail, A.-M. Fortuna, I. Dallmeyer, and M. Garcia-Pérez, "The role of biochar porosity and surface functionality in augmenting hydrologic properties of a sandy soil," Science of The Total Environment, vol. 574, pp. 139-147, 2017/01/01/ 2017, doi: https://doi.org/10.1016/j.scitotenv.2016.09.025.
5. R. d. K. G. Pereira, J. F. Natalli, A. R. G. de Azevedo, and M. T. Marvila, "Evaluation of the pozzolanic activity of biochar produced by low temperature pyrolysis of wood waste," Materials Chemistry and Physics, vol. 345, p. 131238, 2025/11/01/ 2025, doi: https://doi.org/10.1016/j.matchemphys.2025.131238.

6. W. Liu, S. Tan, L. Qing, and Y. Li, "Pozzolanic activity of biochar with high carbon content and its influence on comprehensive strength-emission performance of biochar-cement composite paste," Construction and Building Materials, vol. 478, p. 141427, 2025/06/06/ 2025, doi: https://doi.org/10.1016/j.conbuildmat.2025.141427.
7. D. N. Dari, L. F. da Silva, A. M. B. L. Júnior, I. S. Freitas, F. I. da Silva Aires, and J. C. S. dos Santos, "Spent coffee grounds: Insights and future prospects for bioenergy and circular economy applications," Green Technologies and Sustainability, vol. 3, no. 4, p. 100213, 2025/10/01/ 2025, doi: https://doi.org/10.1016/j.grets.2025.100213.
8. M. Stefani et al., "Transforming spent coffee grounds into sulfonated char: an eco-innovative method using a refined simultaneous sulfonation-carbonization process," Biomass Conversion and Biorefinery, 2025/09/01 2025, doi: 10.1007/s13399-025-06881-2.
9. A. Sičáková and M. Špak, "The Effect of a High Amount of Micro-Fillers on the Long-Term Properties of Concrete," (in eng), Materials (Basel), vol. 12, no. 20, Oct 18 2019, doi: 10.3390/ma12203421.
10. H. Liao, Y. Ju, H. Lyu, T. Liu, D. Han, and Y. Li, "Compressive strength development and microstructure evolution of mortars prepared using reactivated cementitious materials under carbonation curing," Developments in the Built Environment, vol. 18, p. 100397, 2024/04/01/ 2024, doi: https://doi.org/10.1016/j.dibe.2024.100397.
11. B. Li et al., "Wet carbonation of calcium silicate hydrate (C-S-H): Structural transformation and calcium carbonate crystallization pathways," Journal of Building Engineering, vol. 113, p. 114090, 2025/11/01/ 2025, doi: https://doi.org/10.1016/j.jobe.2025.114090.
12. Y. Yan, J. Tang, and G. Geng, "Exploring microstructure development of C-S-H gel in cement blends with starch-based polysaccharide additives," Case Studies in Construction Materials, vol. 19, p. e02589, 2023/12/01/ 2023, doi: https://doi.org/10.1016/j.cscm.2023.e02589.
13. X. M. Aretxabaleta, J. López-Zorrilla, I. Etxebarria, and H. Manzano, "Multi-step nucleation pathway of C-S-H during cement hydration from atomistic simulations," Nature Communications, vol. 14, no. 1, p. 7979, 2023/12/02 2023, doi: 10.1038/s41467-023-43500-y.
14. X. Yang and X.-Y. Wang, "Hydration-strength-durability-workability of biochar-cement binary blends," Journal of Building Engineering, vol. 42, p. 103064, 2021/10/01/ 2021, doi: https://doi.org/10.1016/j.jobe.2021.103064.
15. S. Xiao et al., "The influence of biochar addition on the mechanical performance, hydration mechanism, and carbonation capacity of Super Sulfated Cement," Construction and Building Materials, vol. 463, p. 140073, 2025/02/14/ 2025, doi: https://doi.org/10.1016/j.conbuildmat.2025.140073.