Paper ID: CE 0200

Hardened and Microstructural Characteristics of a Biochar-Cement Mortar Composite

M. H. Khan[1], M. H. R. Sobuz[2*], M. K. I. Kabbo[3]

[1] Department of Building Engineering and Construction Management, KUET, Bangladesh (mahmudurhossainkhan@gmail.com)
[2*] Department of Building Engineering and Construction Management, KUET, Bangladesh (habib@becm.kuet.ac.bd)
[3]Department of Building Engineering and Construction Management, KUET, Bangladesh (kabbo@becm.kuet.ac.bd)

Abstract

The increasing rate of carbon dioxide (CO_2) emissions has emerged as one of the most pressing problems facing the globe today. Regulation and reducing CO_2 emissions have prompted as pressing concerns in response to the expanding carbon footprint of the construction sector. The utilization of biochar as a carbon-sequestering component in cement mortar is the main focus of this study. This study aims to examine the effects of biochar on the fresh, hardened, and microstructural properties of cement mortar and its carbon sequestration efficiency. A control group and eight additional mix batches were used to include biochar (BC) into mortar samples at 1%, 3%, 5%, and 8% by weight of cement, utilizing two fixed temperatures (300°C and 500°C) throughout the BC preparation process. The results demonstrated that adding BC improved the cement mortar's workability and compressive strength. SEM analysis of biochar-cement mortar composites indicates the presence of mesopores and micropores. Carbon sequestration is aided by biochar because of its large number of pores. The pores of the biochar-infused mortar capture CO_2. Carbon sequestration significantly reduces the environmental impact of cement mortar. The study concludes that biochar has promising potential as a sustainable alternative component of cement mortar.

Keywords: *Mortar; Biochar; Workability; Strength; Sustainability.*

1 Introduction

The construction sector significantly impacts the environment as one of the top energy and resource consumers. One of the most severe environmental dangers in recent years is rising CO_2 emissions. Urbanization was responsible for the persistent increase in daily CO_2 emissions. For urbanization, Portland cement is one of the most widely used building materials due to its affordability and accessibility to basic materials. However, producing Portland cement is a resource-intensive and energy-intensive process. According to reports, each ton of cement needs about 1.5 tons of raw materials, and one ton of carbon dioxide is discharged into the atmosphere during manufacturing, contributing to about 7% of the world's anthropogenic greenhouse gas emissions (Worrell et al., 2001). The sequestration of stable carbon in the material itself without impacting the performance of the host matrix is one way to lower the net emissions associated with cement-based materials (Gupta et al., 2018). A substance that sequesters carbon and improves cement composite performance may reduce emissions and increase civil infrastructure serviceability. Biochar's high surface area and affinity for nonpolar molecules make it a potential CO_2 adsorbent. The potential of BC implementation demonstrated that it could reduce 1.8 Gt CO_2 equivalent per year or 12% of anthropogenic emissions (Woolf et al., 2010). Biochar (BC) offers a solution to improve waste recycling and minimize the need for garbage disposal space. It involves the transformation of agricultural waste, food leftovers, and wood scraps into biochar, which can be used to produce building materials. For every ton of dry feedstock, this process has the potential to significantly decrease greenhouse gas (GHG) emissions by around 870 kilograms of CO_2 equivalent. Approximately 62–66% of this emission reduction is achieved through biomass carbon capture and storage capabilities used in BC production (Roberts et al., 2010). Moreover, BC contributes to the enhanced recycling of wood waste, which is currently utilized for composting, as fuel for cogeneration plants, or disposed of in landfills. This shift towards utilizing wood waste for BC production will be better for the environment. Traditional practices, such as burning wood as fuel, can lead to respiratory diseases due to the airborne release of sawdust and wood chips. By converting sawdust into stable BC without oxygen and incorporating it into construction materials, landfill waste is reduced, and wood processing companies can derive value from their waste products.

The use of BC as a construction material for buildings and roads has garnered significant scientific interest in recent years. Akhtar and Sarmah (2018) assessed the durability and water absorption of concrete containing biochar at a replacement rate of 0.1% of the total cement content. Despite the fact that water absorption was not significantly different compared to that of the control, biochar generated from rice husk and sludge from a paper mill both improved the split-tensile and early-age (7-day strength) compressive strengths of concrete. Khushnood et al. (2016) investigated the mechanical parameters, namely the modulus of rupture and fracture energy, in cement paste using biochar generated from hazelnut shells and peanut shells, respectively. The study observed that adding biochar particles at a weight ratio of 1% to the cement paste resulted in an increase in the modulus of rupture and fracture energy. The experimentation conducted in the study suggests that the inclusion of biochar particles within the cement paste causes the formation of multiple branching fractures that propagate along intricate paths. Consequently, a higher amount of energy is required for crack propagation in the biochar cement paste compared to the standard paste. This phenomenon can be attributed to the angular shape of the biochar particles, which enables them to resist fracture propagation effectively. As a result, the biochar cement paste exhibited a higher modulus of rupture. Gupta et al. (2017) went through the primary elements, such as the preparation process, the physical qualities, and the chemical properties of biochar, which make it appropriate for use as a carbon sequestering component in cement mortar. Zeidabadi et al. (2018) investigated the efficacy of two different BC (rice husk biochar and bagasse biochar) produced at the same 700 °C pyrolysis temperature. The authors observed changes in the mechanical characteristics of two biochar-added concretes formulated using the same procedure and weight %. Based on the findings of this experiment, it was observed that the feedstock material that is used has a considerable impact on the development of bonding within the cementitious matrix.

However, there is still a lack of studies that focus on using biochar from wood sawdust in cement mortar composites as an addition. This study investigated the strength and microstructural properties of cement mortar affected by biochar. Biochar from two different temperatures (300°C and 500°C) was added at different dosages: 1%, 3%, 5%, and 8% by weight of cement.

This paper presents a significant achievement by demonstrating the extraordinary potential of biochar as a carbon-sequestering component in cement mortar. This innovative approach improves the material's workability and compressive strength and significantly reduces its environmental imprint. In doing so, the paper contributes to the expanding corpus of research on biochar-integrated building materials. This emerging field has the potential to usher in carbon neutrality and sustainability in the construction industry, representing significant progress toward a more environmentally conscious future.

2 Materials

The utilization of Ordinary Portland Cement (OPC) is widespread worldwide, making it one of the most prevalent cement forms. In this investigation, OPC of type I (CEM I/52.5N) was chosen as a locally available material following ASTM C150/C150M-17 guidelines. Sylhet sand was collected and used as a fine aggregate in the mortar mix. The sand's relative density, known as specific gravity, and fineness modulus (FM) was ascertained using ASTM C128-15a and ASTM C144-18a, respectively. Table 1 presents the physical properties of the fine aggregate. The sieve analysis of the fine aggregate, conducted in accordance with the requirements of the ASTM C136-19 standard, revealed that it naturally exhibited a higher degree of gradational consistency. Polycarboxylate ethers-based superplasticizer, conforming to ASTM C494-19, achieved sufficient workability during mixing. The biomass utilized in this study consisted of mixed wood sawdust that was collected from a nearby wood milling facility. It was dry before the combustion of the material. Subsequently, the biomass underwent a pyrolysis procedure, transforming into biochar. The elemental composition of the biomass, in the form of biochar, after the pyrolysis process is displayed in Table 2.

Table 1. Physical Properties of Fine Aggregate

Properties	OPC	Fine Aggregate
Fineness Modulus	-	3.20
Specific Gravity	3.15	2.72
Moisture Content	-	4.3%
Unit Weight	1440 kg/m^3	1687 kg/m^3

Table 2. Elemental Composition of BC 300 & BC 500

	C	O	Mg	H	K	Ca	N
BC 300	59.30	25.21	0.25	3.1	0.41	0.24	0.47
BC 500	82.24	7.25	0.43	2.65	0.43	0.61	0.42

3 Experimental Program

3.1 Mix Design

A total of nine different mix designs were developed to investigate the fresh characteristics and qualities of the hardened cement mortar composite containing biochar. The mortar compositions followed the weight proportions of 1:2.75:0.40 for cement, sand, and water, as specified in ASTM C270-19a. Table 3 displays the specific constituent proportions for mortar samples with varying BC 300 and BC 500 dosages. Notably, in the experimental set-up, all mixtures utilized the exact proportions of cement, sand, and water.

Table 3. Mix Proportion (kg/m^3)

	Mortar Mix	**Mix Description**	**Cement (kg/m^3)**	**Sand (kg/m^3)**	**Water (kg/m^3)**	**Biochar (kg/m^3)**	**Super-plasticizer Dosage (wt.% of cement)**
Control	Control	Control mortar without biochar	202.3	610.6	81	-	0.57
When BC 300 will be added	M1T300	Addition of 1 wt.% BC at 300℃	202.3	610.6	81	2	0.58
	M2T300	Addition of 3 wt.% BC at 300℃	202.3	610.6	81	5.6	0.58
	M3T300	Addition of 5 wt.% BC at 300℃	202.3	610.6	81	9.4	0.63
	M4T300	Addition of 8 wt.% BC at 300℃	202.3	610.6	81	16	0.69
When BC 500 will be added	M1T500	Addition of 1 wt.% BC at 500℃	202.3	610.6	81	2	0.60
	M2T500	Addition of 3 wt.% BC at 500℃	202.3	610.6	81	5.6	0.62
	M3T500	Addition of 5 wt.% BC at 500℃	202.3	610.6	81	9.4	0.68
	M4T500	Addition of 8 wt.% BC at 500℃	202.3	610.6	81	16	0.73

3.2 Biochar Preparation

Locally obtained mixed wood sawdust was used in the production of BC. Before putting the sawdust through the pyrolysis process, it was first completely dried out. The pyrolysis was performed in a muffle furnace, shown in Figure 1, at two distinct temperatures: 300℃ and 500℃. When the pyrolysis process was finished, the resulting char could undergo a cooling process before being placed in an airtight container. The amount of BC that could be produced at temperatures of 300℃ and 500℃ was roughly 40 and 25 percent, respectively shown in Figure 2. The ASTM C109/C109M-20a- code was followed throughout the mortar casting process.

Figure 1: Pyrolysis process of biomass in a muffle furnace

Figure 2: Pyrolysis process of biomass before and after

3.3 Test Set-Up Instrumentation

The mortar was meticulously prepared following standardized procedures. To ensure the molds for the cube and cylinder samples remained free from any adhesive properties, they were thoroughly cleaned and lightly coated with a layer of grease. Subsequently, the molds were carefully positioned on a level surface. A depiction of the sample preparation and curing process can be observed in Figure 3. The flow table test was performed in line with the ASTM C1437-20, ensuring adherence to standardized procedures for assessing the flow characteristics of the biochar cement mortar composite. Similarly, the compressive strength test of the biochar cement mortar composite was carried out following the guidelines outlined in ASTM C109-20a, ensuring accurate and consistent measurements of the material's compressive strength properties. Figure 4 depicts the test set-up for the flow table and compressive strength measurements.

Figure 3: Preparing and curing of samples

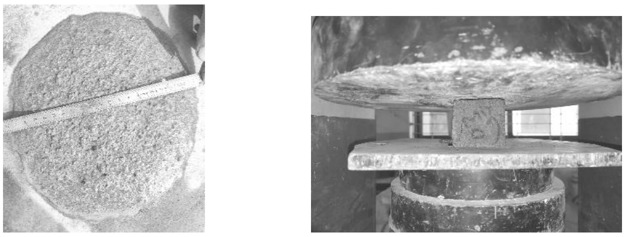

Figure 4: Flow table and Compressive strength test set-up

4 Results and Discussion

4.1 Flowability: Flow Table Test Results

The percentage flow of all biochar-incorporated fresh mortar compositions is illustrated in Figure 5. According to the findings from experiments, incorporating BC decreases the percentage flow of fresh mortar linearly. Figure 5 also displays the fresh density of mortar mixes on the right Y-axis as a visual depiction of the behavior of fresh density. Regarding BC300 and BC500, the percentage flow rate of fresh mortar decreased from 5.51-20.87% and 9.05-26.38% compared to the control mix. However, integrating 1% biochar had no significant impact on fresh density, but adding higher percentages of biochar decreased fresh density considerably. From the findings of Gupta et al. (2017), porous biochar particles absorb a significant amount of water, decreasing the flowability of fresh mortar. Mota-Panizio et al. (2023) observed a comparable type of temperature effect. According to the author, water absorption increased with respect to the incineration temperature at which biochar was manufactured.

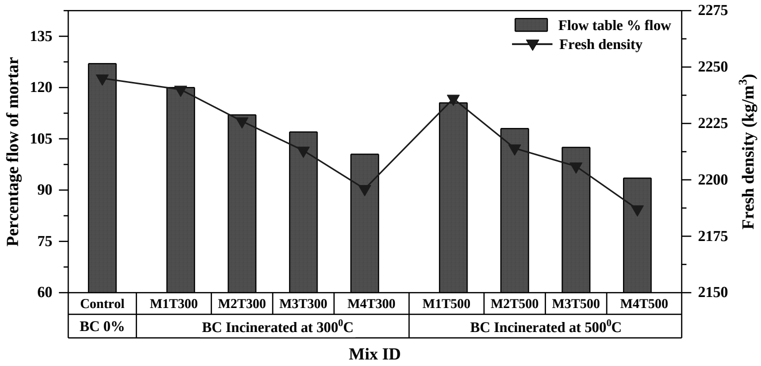

Figure 5: Flow rate of mortar mixes

4.2 Compressive Strength Test Results

Figure 6 illustrates the variation of compressive strengths with error bars at 7 and 28 days. In accordance with the findings of the tests, the mix with 1% BC ignited at both 300 and 500 degrees outperformed all specimens in terms of compressive strength at 7 and 28 days. However, compressive strengths significantly decreased with the further inclusion of more than 1% biochar.

Akhtar and Sarmah (2018) observed consistent outcomes concerning the improvement of compressive strength in different biochar-mortar composites. Their study specifically examined the impact of BC derived from paper mills (PP) and rice husk (RH) on concrete. The findings indicated that adding BC at a concentration of 0.1% significantly enhanced compressive strength, with PP biochar demonstrating a 10% increase and RH biochar exhibiting a 6% increase. Likewise, Ahmad et al. (2015) obtained similar findings while investigating the influence of bamboo biochar on cement composites. Their study demonstrated that adding 0.08% biochar led to a significant 30% increase in compressive strength compared to the control mix. These parallel findings emphasize the consistently positive impact of biochar additives on enhancing the compressive strength of various cement composites.

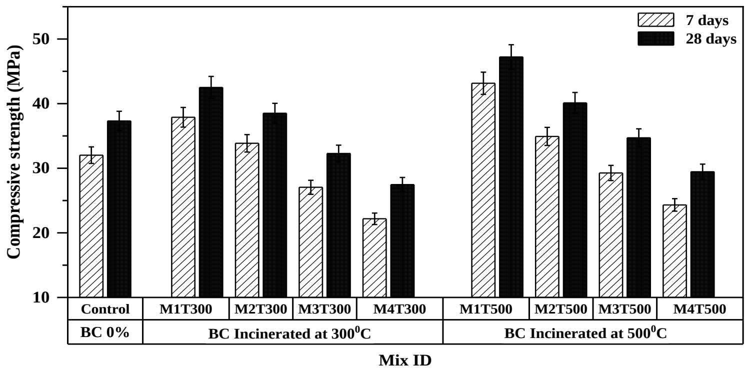

Figure 6: Compressive strength of all BC-mortar composites at 7 and 28 days

4.3 Scanning Electron Microscopy (SEM) Test Results

SEM test was carried out to examine the microstructural characteristics of BC particles and evaluate their dispersion in cement mortar composites. Figure 7 (a) illustrates the SEM image of the control cement mortar composite, which showed a typical microstructure with no BC particles. The surface of the material was reasonably smooth, and there were not many pores or cracks that could be seen. Figure 7 (b) demonstrates the production of BC in a cement mortar composite at 10 microns. BC in cement mortar composites contains a wide range of meso- and micro-pores that help in carbon sequestration. From analyzing Figure 7 (b), it can be said that this 8% wt. of BC500 forms a considerable fraction of voids compared to the control.

Similar types of voids were discovered in the SEM test that Gupta et al. (2018) carried out. It was shown that a large proportion of voids were produced at a specific dose of biochar compared to the control.

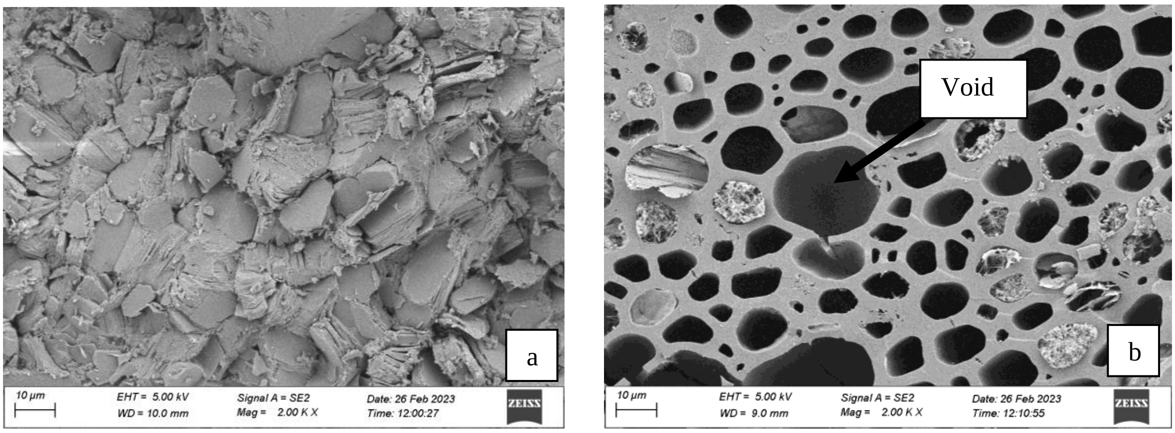

Figure 7: SEM micrograph of (a) Mortar (Control) (b) Mortar with 8 Wt.% BC500 (M4T500)

5 Conclusion

According to the research, biochar has the potential to be a sustainable and environmentally friendly component of cement mortar and may help lower carbon dioxide (CO_2) emissions from the construction sector. The study's results suggest that the construction industry should consider investigating the feasibility of integrating biochar into cement mortar mixtures as a viable approach to mitigate CO_2 emissions and enhance the mechanical characteristics of construction materials. This recommendation is based on the findings of the study. The optimal percentage of biochar and the temperature at which it is produced should be carefully considered to maximize its effectiveness. In general, the findings of this research provide a viable strategy for developing environmentally friendly and sustainable construction materials that might assist in mitigating the adverse effects that growing CO_2 emissions have on the environment. However, more research is required to determine the durability and long-term performance of biochar-cement mortar composites under a variety of environmental conditions.

References

Ahmad, S., Khushnood, R. A., Jagdale, P., Tulliani, J.-M., & Ferro, G. A. (2015). High performance self-consolidating cementitious composites by using micro carbonized bamboo particles. *Materials & Design*, *76*, 223-229.

Akhtar, A., & Sarmah, A. K. (2018). Novel biochar-concrete composites: Manufacturing, characterization and evaluation of the mechanical properties. *Science of the Total Environment*, *616*, 408-416.

Gupta, S., Kua, H. W., & Cynthia, S. Y. T. (2017). Use of biochar-coated polypropylene fibers for carbon sequestration and physical improvement of mortar. *Cement and Concrete Composites*, *83*, 171-187.

Gupta, S., Kua, H. W., & Dai Pang, S. (2018). Biochar-mortar composite: Manufacturing, evaluation of physical properties and economic viability. *Construction and Building Materials*, *167*, 874-889.

Khushnood, R. A., Ahmad, S., Restuccia, L., Spoto, C., Jagdale, P., Tulliani, J.-M., & Ferro, G. A. (2016). Carbonized nano/microparticles for enhanced mechanical properties and electromagnetic interference shielding of cementitious materials. *Frontiers of Structural and Civil Engineering*, *10*, 209-213.

Mota-Panizio, R., Carmo-Calado, L., Assis, A. C., Matos, V., Hermoso-Orzáez, M. J., Romano, P., Gonçalves, M., & Brito, P. (2023). Properties and Uses of Biochars Incorporated into Mortars. *Environments*, *10*(3), 47.

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental science & technology*, *44*(2), 827-833.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature communications*, *1*(1), 1-9.

Worrell, E., Price, L., Martin, N., Hendriks, C., & Meida, L. O. (2001). Carbon dioxide emissions from the global cement industry. *Annual review of energy and the environment*, *26*(1), 303-329.

Zeidabadi, Z. A., Bakhtiari, S., Abbaslou, H., & Ghanizadeh, A. R. (2018). Synthesis, characterization and evaluation of biochar from agricultural waste biomass for use in building materials. *Construction and Building Materials*, *181*, 301-308.