DRIVING SUSTAINABLE CONSTRUCTION: ADVANCING BIOCHAR-BLENDED COMPOSITES TO REDUCE SAND DEPENDENCY AND LOWER CARBON FOOTPRINTS

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ABSTRACT: Rapid urbanization and increasing infrastructure demands have driven a surge in the use of natural construction materials—particularly sand—causing significant environmental degradation from excessive extraction. This study explores the use of biochar, derived from waste biomass, as a sustainable partial substitute for sand in mortar composites. Wood-based biochar was incorporated into mortar mixes at varying replacement levels (2–40% by sand weight). Tests evaluated workability, density, mechanical strength, and durability, including water absorption and fire resistance. Water-to-cement ratios were adjusted to maintain workability in biochar-modified mixes. Results revealed that biochar addition enhanced composite performance, with optimal dosages achieving improved compressive strength after 28 days—57.32 MPa at 2% wood biochar—alongside reduced density and acceptable durability. These findings demonstrate the potential of biochar-blended mortar as an eco-friendly, lightweight alternative to conventional sand-based materials, supporting circular economy principles and advancing low-carbon construction practices.

1. INTRODUCTION

The growth of population, economy, and living standards of modern civilizations are driving up consumption of building materials including cement, sand, and coarse aggregate (Kanthi, 2014). Another pressing issue is the depletion of river sand exacerbated by the excessive extraction of river sand due to the construction industry's rapid expansion, which has also increased the detrimental effects of climate change by riverbank erosion, loss of biodiversity, depletion of water table, and even the subsidence of bridge piers like vital infrastructures (Li et al., 2011; Noufal E. and Manju, 2016) River sand is a non-renewable natural resource and hence it is crucial to find and employ alternate sources to replace river sand and address the scarcity of construction sand (Zhang et al., 2023).

One promising green, sustainable and significant technique to manage the wood wastes is the conversion of wood waste into biochar (Gupta and Kua, 2017), as the biochar is produced under absence or limited oxygen condition with minimal CO_2 emissions compared to the combustion of wood (Rajapaksha et al., 2016). A potential alternative can be the use of biochar in lightweight mortar as it has porous structure and lower density that hold potential for the thermal and energy efficiency of the building construction (Gupta and Kua, 2017; Praneeth et al., 2021). Biochar has the potential to lower the avoidable CO_2 emissions that result from soil emissions and the disposal or decomposition of organic waste (Akhtar and Sarmah, 2018).

Maljaee et al. (2022) found that, the functioning of cement mortar remains unharmed by replacing up to 60% of the coarse sand with olive stone wastes (OBS). Wang et al. (2020) used biochar as a substitute for river sand and observed that the' compressive strength of the composites was enhanced by 8.9% with the addition of 1 wt.% biochar. Biochar was employed by Praneeth et al. (2021) as a filler material to replace sand, accounting for 10-40% of the overall weight, and determined that biochar may be used in place of sand in mortars to increase toughness, reduce the density, and thermal conductivity of cement-based mortars. Chen et al. (2022) observed that using biochar in place of recycled aggregate boosted cement hydration by internal curing of biochar-regulated release of water.

Previous research on biochar-based cement composites has primarily focused on mechanical properties and thermal conductivity, leaving durability aspects largely unexplored. Critical parameters such as water absorption and fire resistance—essential for long-term performance—have received limited attention when sand is replaced with biochar. This study addresses this gap by investigating the durability of biochar-incorporated mortar composites to assess their resistance to moisture and high-temperature conditions. The overarching goal is to develop lightweight composites with sufficient structural strength while reducing energy consumption during production. By leveraging waste-derived biochar, this research not only enhances material performance but also promotes resource efficiency, circular economy principles, and low-carbon construction practices.

2. MATERIALS AND METHODS

2.1 Raw Materials, Mix Proportions and Curing

The raw materials used for the study comprise Type II Ordinary Portland cement (OPC), manufactured sand passing through 4.75 mm, forest wood biochar, and tap water. The water absorption of the oven-dried sand was observed as 1.6%. The saturated surface dry (SSD) sand was employed in this study. The biochar size of ≤2 mm was used as a replacement for sand. Different mixes of cube mortar composites were made with the dimensions of 50 × 50 × 50 mm^3. The cement-to-sand ratio was 50:50, and the water-to-cement ratio (w/c) was adjusted to five ratios (0.35, 0.42, 0.45, 0.55, and 0.58) for various mixes to maintain the workability of the composites. Sand was replaced by biochar at dosages of 2%, 5%, 10%, 20%, and 40% by weight percentages of sand and the mortar samples were designated as control, BC2%, BC5%, BC10%, BC20% and BC40% based on the biochar percentages. The compressive strength was tested for all the mixtures. Mortars that met the minimum compressive strength requirement of ≥17.2 MPa, as specified in ASTM C270 - 19a´1 (ASTM C270 - 19a´1, 2019) were selected for subsequent testing. Based on the compressive strength results, the control mix and the mortars containing higher percentages of biochar (BC5%, BC10%, and BC20%) were selected for further density and durability evaluations. The mortar cubes were cured in a curing room with a temperature of 20 ± 2 ℃ and a relative humidity of 95% until the day of testing.

2.2 Experimental Methods

2.2.1 Unconfined compressive strength

The compressive strength of mortar-composites was determined in accordance with ASTM C109/C109M − 21 (2021). The mortar samples were prepared with the dimensions of 50 x 50 x 50 mm^3 and cured in a curing room for 28 days. The compressive strength test was performed by using an Instron compression testing machine with a capacity of 200 kN. The electronic vernier calliper was used to measure the dimensions of the mortar samples. The test load rate was 1.5 kN/s.

2.2.2 Wet and dry density

The wet and dry densities of 50 × 50 × 50 mm3 mortar samples were measured after 28 days of curing. The wet density was measured by weighing the 28-day samples to get the wet mass after removing them from the curing room. The dry density was determined by oven-drying the samples at 110 ℃ for at least 24 hours until a constant mass was achieved. Then the dry mass of samples was measured. Both wet and dry densities were determined by using the following equation (Eq. 1):

[1] $\rho = m/v$

where, ρ = the dry density of the sample, kg/m^3
m = the dry mass of the sample, kg
and, v = the volume of the sample, m^3

2.2.3 Water absorption

The water absorption test of cement-based materials was performed to find out the water absorption capacity of the composites according to ASTM C642 − 21 (2021). The 50 × 50 × 50 mm^3 mortar composites of different mixes were prepared and cured for 28 days following the oven drying at 105 ± 5 ◦C for 48 h to attain a constant mass. Afterwards, the samples were weighed to determine the dry mass (A). Then the samples were immersed in water for 48 h and a constant wet mass (B) was recorded. The following equation (Eq. 2) was used to calculate the water absorption of each mortar mix.

[2] Water absorption (%) = (B-A)/A*100

2.2.4 Fire resistance

According to ASTM E 119-20 (2020), the fire resistance of different mixes of cement-based composites was conducted. To decrease the vapour pressure of capillary water, the 28-day cured mortar cubes were oven-dried for 24 h at 110 ◦C. Subsequently, the target temperatures were set to 200 ℃ and 600 ℃ in an electrical muffle furnace with a heating rate of 7◦C/min to reach the desired temperature. The samples were heated for 2 hours at the target temperatures. Then, the samples were transferred to ambient laboratory conditions to cool, sealed for storage, and 24 hours after removal from the furnace, the mass loss and compressive strength were determined. The mass loss was determined by weighing the samples after oven-drying and after heating at targeted temperatures, and the following equation (Eq. 3) was used to measure the relative residual compressive strength (RRCS) of the fire-tested mortar composites.

[3] RRCS [%] = $(F_{c,t}/F_{c,28}) \times 100$

Where, $F_{c,t}$ = the compressive strength of heated samples
and $F_{c,28}$ = the compressive strength of nonheated samples at 28 days

3. RESULT AND DISCUSSION

3.1 Workability

The workability of the mixes was evaluated using the flow table test. The flow values are presented in Figure 1. The amount of water added to the mixture was increased with increasing biochar content to maintain workability within a reasonable range. The flow varies from 162 mm to 188 mm across different mortar composites. From this, it is observed that the flow value decreases with an increase in the dosages of biochar in the mortar mix despite adding more water in the biochar-based mixes. According to Gupta et al. (2018b), the decrease of workability may be associated with the higher water absorption of biochar which decreases the water content of the mix.

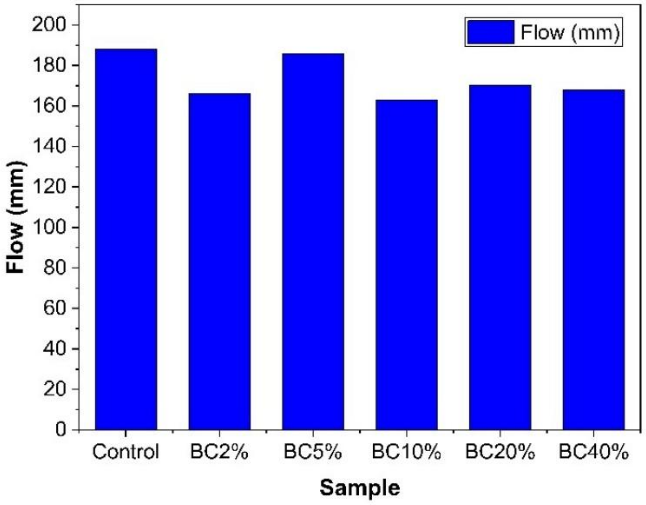

Figure 1: Flow test results

3.2 Compressive Strength

The compressive strength test of control and biochar-added mortar composites were performed after 3, 7, 14 and 28 days cured mortar composites, and the result is shown in Figure 2. The obtained result shows that the compressive strength increases with the increasing of curing days for all the mixes but a substantial decrease of compressive strength of mortars observed with the inclusion of biochar. The highest strength of 71.43 MPa seen for the control sample without having biochar. The highest reduction of strength was observed in the 40% sand replacement by biochar which exhibits a strength of 2.7 MPa. The lowest decrease of strength of approximately 14%, 5%, 7% and 20% in 3, 7, 14 and 28d test respectively was found in 2% biochar-based mortar showing a strength of 57.3 MPa respective to control. These observations of gradual reduction of compressive strength when the biochar is added to the cement mix are compatible with the earlier studies (Maljaee et al., 2022; Praneeth et al., 2021). The possible cause of the decrease of strength after adding biochar in mixes could be due to the water absorption of biochar. The water added to the mixture during the mixing of ingredients was intended to be applied for the hydration of cement was absorbed by biochar causes incomplete cement hydration leading to the declination of strength (Rupasinghe et al., 2025). A further reason of strength loss might be associated with the use of additional water to maintain the workability of mixture after incorporating biochar, which can be released by biochar with the curing time and thus generating more voids and eventually reducing the strength of composites (Muthukrishnan et al., 2019). The high porosity of biochar comprises the low density and thus inclusion of higher amount of biochar results the decrease of strength (Rupasinghe et al., 2025).

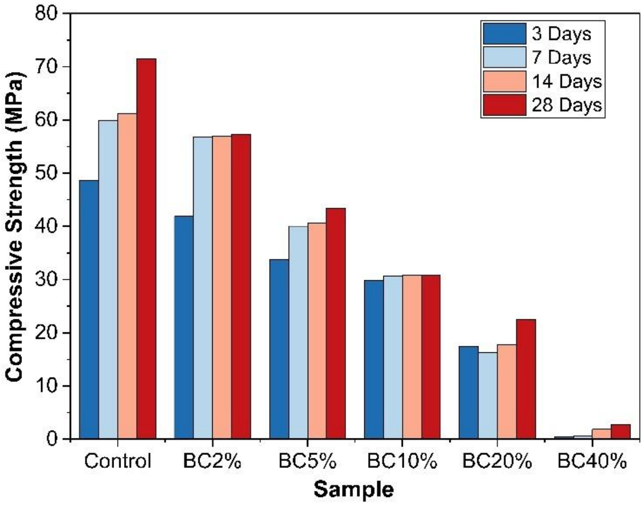

Figure 2: Compressive strength results of mortar composites

3.3 Density

Wet and oven-dry densities were measured for both control and biochar-incorporated mortar composites, as shown in Figure 3. The results indicate that oven-dry density is consistently lower than wet density, and both decrease progressively with higher biochar content. Compared to the control mix, wet density dropped by approximately 7%, 13%, and 30% for 5%, 10%, and 20% biochar replacement, respectively. A similar trend was observed for dry density. These findings align with previous studies: Praneeth et al. (2021) reported 5% and 10% reductions in dry density for 10% and 20% biochar replacement, while Rupasinghe et al. (2025) observed decreases of 5%, 7%, 12%, and 15% for 5%, 10%, 15%, and 20% biochar dosages. Other researchers, including Singh et al. (2025), Sikora et al. (2022), and Cuthbertson et al. (2019), have also documented similar trends. The reduction in density is primarily attributed to the high porosity and low density of biochar particles (Rupasinghe et al., 2025; Singh et al., 2025). Figure 4 illustrates the correlation between density and compressive strength, showing that strength decreases as composite’s density declines.

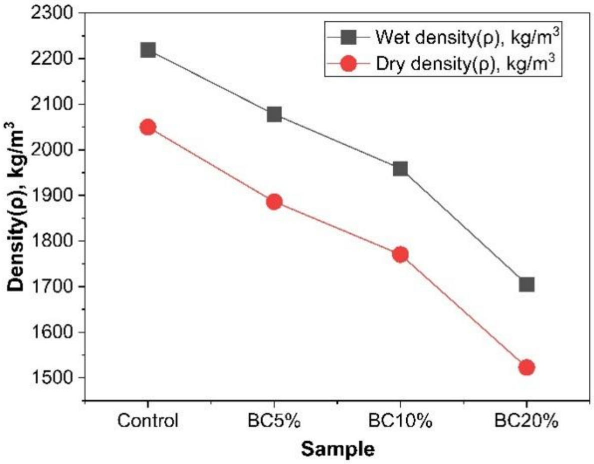

Figure 3: Density of mortar composites

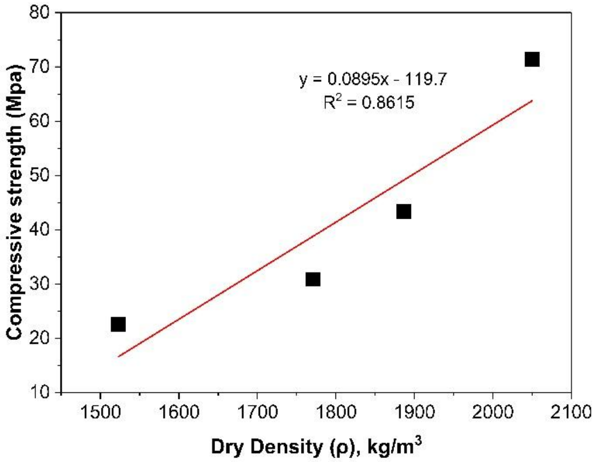

Figure 4: Correlation between strength and dry density of mortar composites

3.4 Water absorption

The water absorption test results for mortar composites are presented in Figure 5. The results show that water absorption increases with increasing percentages of biochar relative to the control sample. The absorption is observed as 10%, 14%, 15% and 20% for control, BC5%, BC10% and BC20% respectively. The examined result is comparable with the findings of earlier research on water absorption of biochar-based cementitious composites (Gupta et al., 2018a; Praneeth et al., 2021). The water absorption of biochar-based mortar materials depends on the water absorption capacity and particle size of biochar. The porosity of biochar influences the water absorption properties of biochar (Praneeth et al., 2021). Therefore, the porosity of mortar and biochar together ultimately contributes to the porosity of composites and thus higher absorption of water can result in the decrease in compressive strength of biochar-based mortar composites (Rupasinghe et al., 2025).

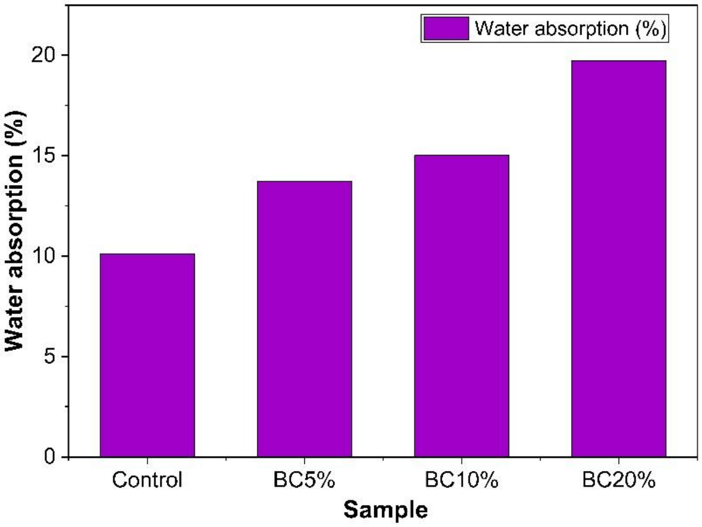

Figure 5: Water absorption results of mortar composites

3.5 Fire Resistance

The fire resistance of control and biochar-incorporated mortar composites was evaluated after heat treatment at 200℃ and 600℃. The resistance of mortar composites was studied by examining the residual mass (%) and relative residual compressive strength (RRCS) after experiencing high temperature action, and the obtained results are presented in Figure 6 and Figure 7, respectively. Figure 6 depicts that, after experiencing the heat treatment all of the mortar mixes lose mass compared to the mass of samples at the room temperature. The mass loss is less than 1% for samples that experienced 200℃ of heating and is approximately 5-8% for the samples heated at 600℃.

Figure 7 shows that the RRCS (%) value increases for all the biochar-replaced mortar composites treated at 200℃, compared to the strength at room temperature. The strength increases to approximately 14%, 43% and 15% for BC5%, BC10% and BC20% respectively. The strength increment at 200℃ might be associated with the increase of the rate of hydration, growth of hydration products and the formation of denser internal structure that promotes the strength development (Shen et al., 2022). However, the strength decreased significantly for all the composites at 600℃. This strength decline might be due to the dehydration and decomposition of hydration products and the destruction of the internal structure of the composites at high temperature (Mensah et al., 2024; Navaratnam et al., 2021).

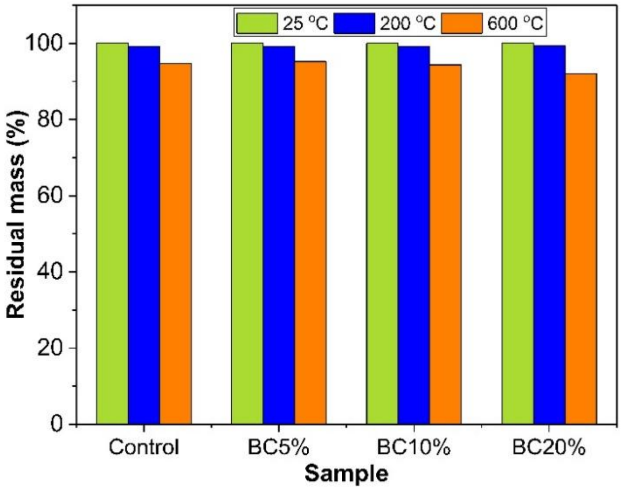

Figure 6: Residual mass (%) of mortar composites after fire test

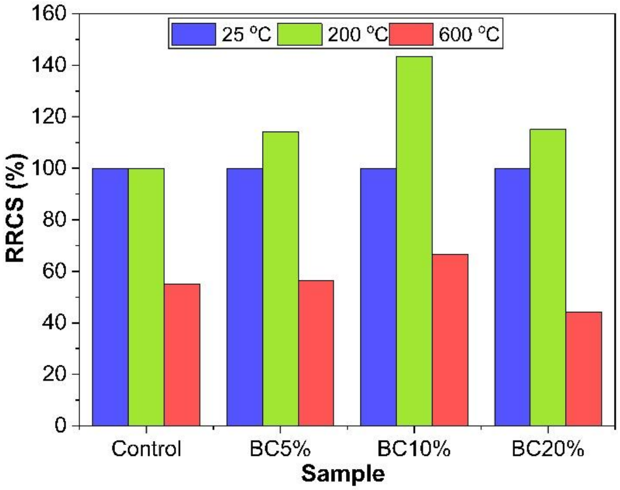

Figure 7: RRCS (%) of mortar composites after fire test

4. CONCLUSIONS

The implementation of biochar particles as an alternative for sand and their impact on the density, mechanical and durability characteristics of mortar composites were the main topics of this investigation. The present study reported that more energy-efficient, lightweight mortars could be produced by employing biochar as a sand substitute. The findings of this research work can be summarized as follows:

1. The workability results showed that the flow values ranged from 162 mm to 188 mm across mixes, with flow decreasing as biochar dosage increased. Wet density dropped by approximately 7%, 13%, and 30% for 5%, 10%, and 20% biochar incorporation, respectively, compared to the control. Similar reductions were observed in oven-dry density inclusion reduced strength relative to the control mix. The highest strength (57.3 MPa) occurred at 2% biochar, while the lowest (2.7 MPa) was recorded at 40% replacement.

2. Water absorption increased with biochar content: 10% (control), 14% (BC5%), 15% (BC10%), and 20% (BC20%). Higher porosity from biochar contributed to increased water intake.

3. Fire resistance tests were conducted on mortar composites at 200°C and 600°C to evaluate thermal performance. All mixes exhibited mass loss compared to their initial weight at room temperature (25°C), with less than 1% loss at 200°C and approximately 5–8% at 600°C. Interestingly, compressive strength increased after heating at 200°C—by about 14% for BC5%, 43% for BC10%, and 15% for BC20%—relative to their original strengths at 25°C. However, at 600°C, strength declined significantly for all mixes, indicating material degradation at higher temperatures.

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