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# Mixture of biochar as a green additive in cement-based materials for carbon dioxide sequestration

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## Abstract

Cement production for concrete is one of the main reasons why the building industry contributes significantly to carbon dioxide emissions. This paper investigates an innovative approach to utilizing CO<sub>2</sub> by incorporating mixed biochar in mortar. Various dosages (0%, 3%, 5%, and 10%) of mixed biochar were explored to assess their impact on the structural properties and environmental sustainability. In this study, mixed biochar was prepared using the pyrolysis method, in which biomasses (rice husk and sawdust) were heated in the absence of oxygen for 2 h in a muffle furnace at the heating rate of 10 °C/min to 550 °C with a 2-h holding time. The replacement of biochar was done with cement in a mortar mixture for casting the cubes followed by putting them in the carbonation chamber for 28 days curing. After that, the cured samples were tested for mechanical strength, porosity, density, and water absorption. X-ray diffraction (XRD) and thermo-gravimetric analysis (TGA) showed that biochar supplementation promoted cement hydration products. Field emission scanning electron microscope (FESEM) analysis showed that several cement hydrates such as C-S-H, Ca(OH)<sub>2</sub>, and CaCO<sub>3</sub> were formed with different doses of biochar and increased mechanical strength. Addition of 10 wt. % biochar increased the compressive strength of the composite by 24.2% than the control respectively, and successfully promoted the CO<sub>2</sub> sequestration with 6% CO<sub>2</sub> uptake after 28 days of accelerated CO<sub>2</sub> curing. The present research has shown the benefits of optimally integrating mixed biochar with cement in the development of low-carbon, sustainable cementitious materials that have the potential to convert building materials like concrete in the future.

**Keywords** Carbon dioxide, Biochar, Mechanical properties, Mortar, Concrete

## Introduction

Cement is a crucial construction material used worldwide in building infrastructure because of its unique benefits, in construction industries as compared to the other construction materials (Wu et al. 2022). It is the most

demanding and easily available construction material, due to its low cost and high strength. But the industries that make cement, are a big source of carbon pollution. Reducing carbon dioxide emissions from cement is a major challenge because cement factories are among the main contributors to carbon dioxide emissions when they transform limestone into clinker through a chemical process. The construction and building industries together are majorly responsible for the generation of around 39% of carbon footprints (www.outlookindia.com. 2024). Every year, each person in India utilizes an average of 2.3 metric tons of cement. In India, the cement manufacturing industry releases 149 million metric tons

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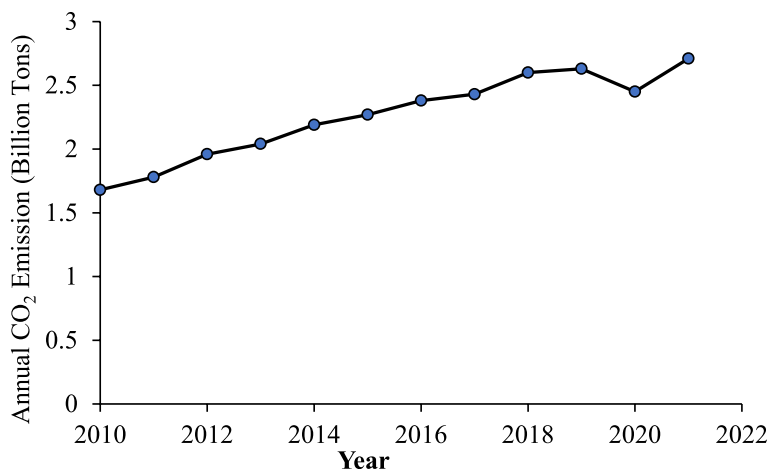
of carbon dioxide into the atmosphere, as per 2021 data (Ribeiro et al. 2022; Bhandari et al. 2023). Overall, the cement industry has contributed 8% of total CO<sub>2</sub> emissions globally (Liang et al. 2020). Various International agencies have set a goal to achieve zero carbon emissions by 2050.

Carbon dioxide is a greenhouse anthropogenic gas, which urgently needs to be captured, stored, and reduced. Researchers suggested that if the demand for cement goes down, it could lead to a reduction in the pollution produced during its manufacturing. They investigated the possibility of blending it with various waste materials such as silica fume, biochar, fly ash, free lime, slag, and many more, which helps in lowering carbon dioxide emissions. These materials not only lower the carbon dioxide emission produced by cement but also improve the cement's durability and performance. Using eco-friendly materials for constructing buildings, like biochar, has a minimal impact on the environment in terms of carbon emissions (Yaashikaa et al. 2020; Nighot and Kumar 2023). The use of biochar is one of the most economical and affordable methods for carbon dioxide sequestration. The process of carbonation curing can generate a hydration product, which then transforms into stable carbonate (Gupta et al. 2018; Liu et al. 2022) biochar can speed up the carbonation process due to its improved pore structure, biochar has great chemical stability and low thermal conductivity because of this it is a suitable building material, the pores structure of biochar contributes to its less thermal conductivity enhance the insulation of structure and it also helps to reduce the amount of energy needed to heat and cool the structure (Wang et al. 2020). Additionally incorporating biochar as a cement additive not only reduces carbon footprint but also has the potential to encourage the recycling of waste and to greatly reduce the land

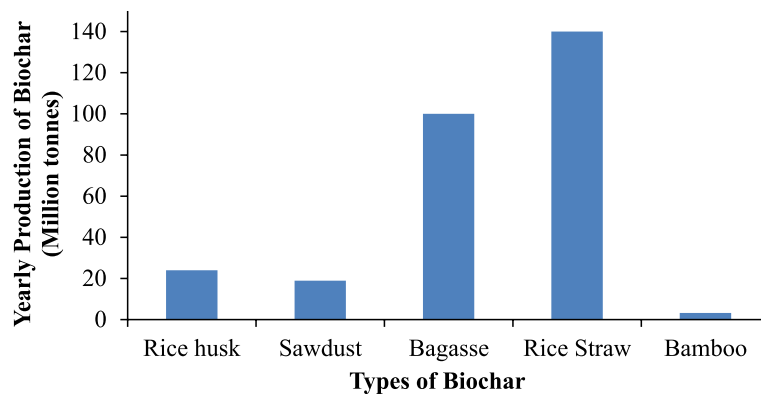
needed for waste disposal (Mohamad et al. 2022; Song et al. 2023; Suarez-Riera et al. 2020). Figure 1 shows the annual CO<sub>2</sub> evolution in India due to industries (Ritchie et al. 2020).

Biochar is a carbon-rich sustainable material, obtained by the pyrolysis of biomass at a moderate temperature (550 °C) in the presence of limited or no oxygen in a muffle furnace. Figure 2 shows year year-wise generation of biochar in India (Rahman et al. 2017; Munagala et al. 2022). After pyrolysis, all the volatile matter that was present in biomass will evaporate and only black carbon-rich solid matter is left, which is known as biochar. It possesses the ability to reduce the impact of climate change by capturing and storing carbon dioxide (Rahman et al. 2017).

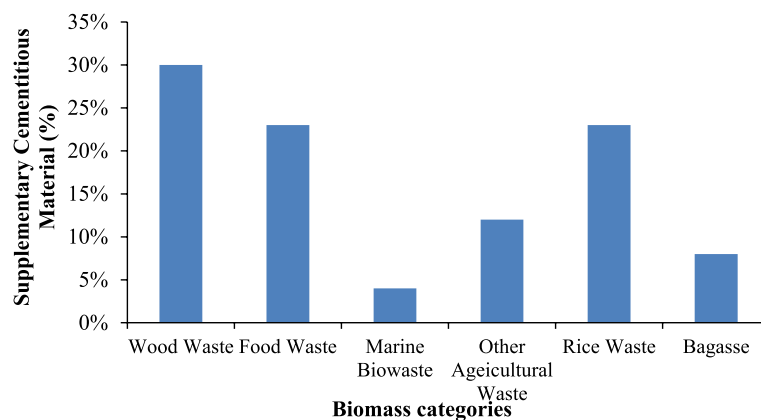
Biochar has gained a lot of popularity in recent years among researchers because of its properties like its large surface area, high porosity, and stability, which make it a versatile material suitable for various uses. Biochar not only boosts the carbon-capturing ability but also enhances the mechanical characteristics of cement by speeding up the process of hydration (Sinha et al. 2023; Lin et al. 2023). It contributes to enhancing the mechanical strength (both flexural and compressive), physical characteristics, and water absorption of cement. The inclusion of biochar in cement improves the hydration procedure of the cementitious composite. Figure 3 shows the utilization of different types of biomasses as supplementary cementitious material (Liang et al. 2023; Aman et al. 2022; Ali et al. 2023). Table 1 represents the % CO<sub>2</sub> uptake of different types of biomasses. A compact internal structure and increased compressive strength are achieved by gradually utilizing the absorption of biochar by water in the curing process of the cementitious product (Agarwal et al. 2023; Mensah et al. 2021).



**Fig. 1** Annual CO<sub>2</sub> emission in India due to industries (Ritchie et al. 2020)



**Fig. 2** Yearly production of different biochar in India (Rahman et al. 2017)



**Fig. 3** Utilising different types of biomasses as additional cementitious ingredients (Liang et al. 2023)

**Table 1** Table 1% CO<sub>2</sub> uptake of different types of biomasses

| Types of biochar                  | % CO <sub>2</sub> uptake | References               |
|-----------------------------------|--------------------------|--------------------------|
| Wood sawdust                      | 5–6.5                    | (Gupta 2021)             |
| Unwashed hull of processed peanut | 5–7                      | (Gupta et al. 2021)      |
| Mixed wood sawdust                | 5.80–3.08                | (Gupta et al. 2018)      |
| Wood waste                        | 5.9                      | (Chen et al. 2022a)      |
| Mixes woods                       | 2                        | (Nair et al. 2020)       |
| Peanut shell                      | 3                        | (Gupta and Kashani 2021) |
| Maize                             | 2                        | (Gupta et al. 2018)      |
| Straw                             | 4                        | (Gupta and Kashani 2021) |

It was projected that the fracture resistance and bending capacity of the biochar-based cement composite may be increased because particles might absorb cracking force in the cementitious composite (Liang et al. 2023).

Little and late research has been done on the effectiveness of biochar in cementitious materials for sequestering

carbon. There is still significant debate about the complementary effectiveness of biochar cement-based materials for sequestering carbon, particularly the relative contribution of different methods. Therefore, more comprehensive research is needed to understand how cement-based materials and biochar work together to sequester carbon. Future studies should also address the issue of corrosion caused by carbonation at later stages. Subsequent investigations ought to concentrate on the pragmatic utilization of materials derived from biochar cement. With attributes including low combustion, low thermal conductivity, and minimizing weight without degrading the mechanical performance of cement-based composites.

Most of the researchers have studied carbonation curing in cementitious material with individual biochar such as rice husk, sawdust, wheat, and pine needle; however, the addition of different compositions of biochar has not yet been studied. The performance impact of replacing mixed biochar with cement-based products that have undergone carbonation curing remains unclear as of yet. In the present study, biochar

**Table 2** The constituents of ordinary Portland cement (OPC-43) (Agarwal et al. 2023)

| Constituents                   | Weight (%) |
|--------------------------------|------------|
| CaO                            | 61.15      |
| SiO <sub>2</sub>               | 22.03      |
| Al <sub>2</sub> O <sub>3</sub> | 5.911      |
| Fe <sub>2</sub> O <sub>3</sub> | 2.30       |
| SO <sub>3</sub>                | 2.17       |
| MgO                            | 3.21       |
| Na <sub>2</sub> O              | 0.50       |
| K <sub>2</sub> O               | 0.18       |
| MnO                            | 0.13       |
| P <sub>2</sub> O <sub>5</sub>  | 0.041      |
| LOI                            | 0.079      |

**Table 3** Cement specification according to IS 8112–1989 (2013)

| Parameter  | Test value | Recommendation as per IS 8112–1989 |
|--|------------|------------------------------------|
| Ratio of lime to silica, alumina, and iron oxide (ratio) | 0.87       | 1.02 (max.)<br>0.66 (min.)         |
| Ratio of alumina to iron oxide (%)                       | 1.58       | 0.66 (min.)                        |
| Insoluble residue (%)                                    | 1.05       | 4.0 (max.)                         |
| Magnesia (%)   | 2.40       | 6.0 (max.)                         |
| Total sulfur content (%)                                 | 1.10       | 3.5 (max.)                         |

was prepared through the process of pyrolysis at 550 °C within the limited supply of oxygen using a mixture of rice husk and saw dust biomasses. The obtained mixed biochar was then incorporated in the cement mortar and characterized using XRD, FESEM, and CO<sub>2</sub> uptake was calculated using thermogravimetric analysis (TGA).

## Material and methods

### Materials

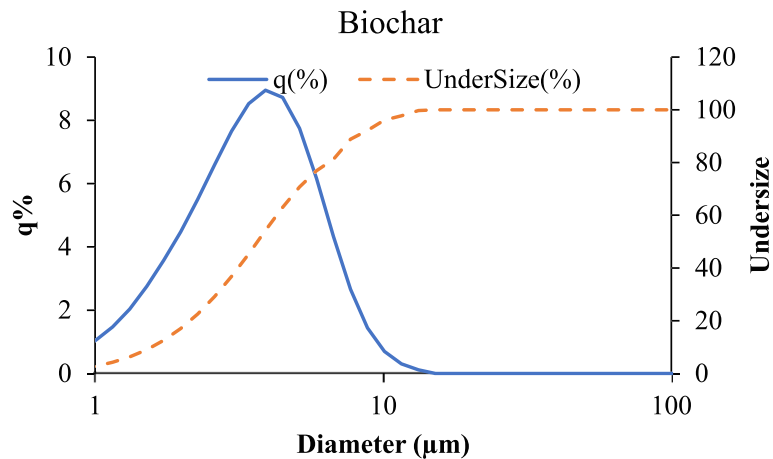
This experimental program contained a test on mortar-based material cubes which is incorporated by biochar at various percentages. Biochar is a mixture of 50% of rice husk and 50% of sawdust. Rice husk was collected from the rice mill, and sawdust was collected from the plywood industry at the Roorkee's local market, Uttarakhand, India. Standard sand (Grade III) is used to assess the quality of cement. Cement (Ordinary Portland cement) of grade 43 was purchased from the Roorkee's local market, Uttarakhand, India. The standard chemical composition of ordinary Portland cement (OPC-43) is given in Tables 2 and 3.

## Mix proportions and sample preparation

### Preparation of biochar

A carbon-enriched biomaterial known as biochar is created when biomass is burned in a procedure known as pyrolysis. In pyrolysis, biomass (such as crop and forestry wastes, manure, and municipal and industrial wastes) is heated at temperatures higher than 400 °C in the presence of limited or no oxygen. As previously reported by Ghani et al. (Ghani et al. 2013) pyrolysis at 500–550 °C leads to the decomposition of hemicellulose and cellulose, which are the major source of sugars harmful to the hydration of cement. Also, Parihar et al. (Parihar et al. 2017) demonstrated that pyrolysis at 500–550 °C can eliminate the generation of alcohol, phenol, and methylene groups, which are detrimental to the physical stability of cementitious matrix. Pyrolysis temperature variance studied by Chen et al. (Chen et al. 2022b) also showed that 500–550 °C is the most efficient temperature for pyrolysis. In this study, rice husk and sawdust were used for making biochar. The rice husk and sawdust were dried at 60 °C without any pre-treatment (washing) until a constant weight was achieved. A mixture of 500 g of sawdust biomass and 500 g of rice husk biomass were heated at a temperature of 550 °C with a heating rate of 10 °C/min and 2 h of holding time in a muffle furnace in a limited oxygen environment condition. A normal programmable heating furnace was used during the pyrolysis of the biochar it does not influence any properties of the biochar. Consistent quality of biochar was obtained by maintaining the same heating rate (10 °C/min), holding time (2 h), and oxygen-free environment in the furnace. A grinder mixer was used to grind the biochar into very fine particles.

A crucial component of biochar “design” that has gotten far less study attention is particle size. Given that smaller biochar particles would inevitably have more physical contact with soil particles, it is anticipated that particle size will have a significant impact on interactions between soil and biochar (Sigua et al. 2014). According to Chen et al. (Chen et al. 2017), biochar with a greater ash concentration that is produced from smaller feedstock particles generally has liming effects that are amplified. Additionally, there is proof that biochar containing finer particles can improve the sorption of organic compounds and nutrients (Xie et al. 2015). Biochar's capacity to absorb and exchange nutritional ions is mostly determined by its micro-porosity, surface areas, and exterior surface areas; so, biochar with smaller particle sizes may have better nutrient availability for plants. RHB and SDB mixed biochar particle size is shown in Fig. 4.



**Fig. 4** Particle size of biochar

**Preparation of biochar-based mortar cubes**

In this experiment, the sample cubes were prepared, by mixing mortar paste with biochar (rice husk and sawdust). In the mortar mixture, Ordinary Portland cement (OPC) was replaced by 0%, 3%, 5%, and 10% of different dosages of mixture biochar (rice husk and sawdust). As reported by Gupta et. al., a 3% dosage of biochar provided an optimum strengthening of specimens, followed by a 5% dosage. In comparison, a 1% dosage of biochar had a relatively minor effect on compressive strength. To make the paste, a biochar-based mortar mixture was mixed with water. 50 mm × 50 mm × 50 mm molds were used for making the cube samples. The prepared sample was filled into the molds, and by using a vibration table all the cubes were compacted and kept for 24 h. After 24 h of drying, casted cubes were de-molded and placed in a carbonation chamber for 28 days for carbon curing as shown in Fig. 5. After 7 and 28 days, the incorporated biochar-based mortar sample cubes were taken out from the carbonation chamber and tested.

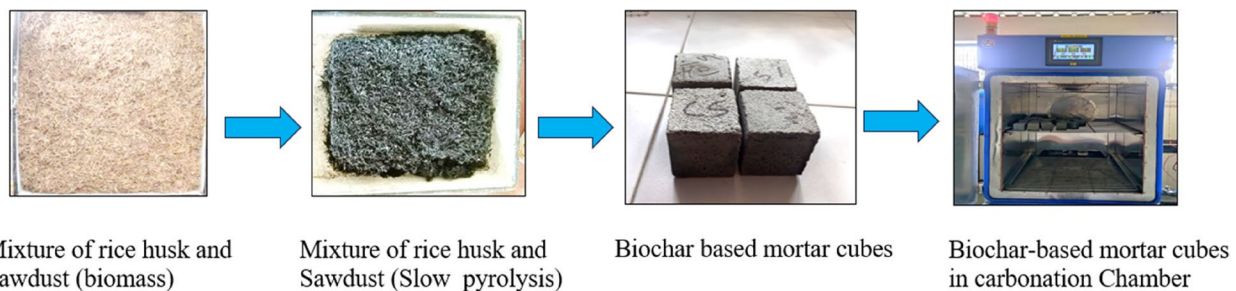
**Test methods**

**Phenolphthalein test**

To determine the carbonation depth in carbonated biochar-based mortar cubes traditional phenolphthalein test is used. Cubes of various dosages of biochar-based mortar were prepared and placed in a carbonation chamber for 28 days. Phenolphthalein indicator was sprayed on the broken surface of concrete and left for 5 to 10 min. This technique records the difference in color between concrete that is completely carbonated, moderately carbonated, and non-carbonated. Phenolphthalein is a commonly used chemical compound used as a pH indicator. It becomes pink in basic solutions (non-carbonated) and remains colorless in acidic ones (carbonated).

**Mechanical strength**

The mechanical strength test was done in accordance with the standard method (IS 4031–1988 Part 6, 1988). The compressive strength of cement is the property of cement which specifies how much load it can withstand



**Fig. 5** Experimental setup for incorporating biochar into a cement-based sample

when cement is made into hardened mass mixing with standard sand and water. The compressive strength of casted mortar paste cubes was 50 mm × 50 mm × 50 mm in size, in addition to a mix of biochar (rice husk and sawdust) of 0%, 3%, 5%, and 10% were evaluated. The compressive strength of the cubes was tested by CTM (compressive testing machine) by the force applied to the cross-section area of the cube. It is given in Eq. (1):

$$\text{Compressive strength} = \frac{\text{Load}}{\text{Cross sectional area}} \quad (1)$$

#### Porosity

After performing the compressive test, the crushed samples were placed in Acetone chemical and covered by paraffin wax parafilm for 24 h to determine the wet weight (A) of the samples. After 24 h, the samples were taken out from the Acetone chemical and placed in the oven for drying at 50 °C for 24 h. The dry weight of the samples was determined (B). The porosity of the biochar-based mortar cubes is determined by the Eq. (2).

$$\text{Porosity \%} = \frac{A - B}{A} \times 100 \quad (2)$$

#### Density

The density of the mortar incorporated with mixed biochar was done in accordance with ASTM C642–13 (1997). The cubes were taken out from the carbonation chamber after days of carbon dioxide curing. Determine the mass of the cubes (M) and also determine the volume of the cubes (V). After that, the density of the cubes is calculated by using Eq. (3).

$$\text{Density} = \frac{M}{V} \quad (3)$$

#### Water absorption

The water absorption of the mortar incorporated with mixed biochar was done in accordance with ASTM C642–13 (1997). The cured biochar-based mortar specimen was placed in an oven and dried at a certain temperature (100 °C–110 °C) for 24 h. After 24 h, the specimens were taken out from the oven, and the dry weight (A) of each sample was determined. All the specimens were placed in water for the next 24 h. After 24 h, the samples were taken out of the water, and each sample surface was cleaned with dry cotton clothes. The wet weight (B) of each specimen was determined.

Water absorption is calculated by Eq. (4)

$$\text{WaterAbsorption} = \frac{B - A}{A} * 100 \quad (4)$$

#### XRD (X-ray powder diffraction) analysis

X-ray powder diffraction (Make: Rigaku, Japan and Model: D-Max 2200) is a recognized methodology in cement chemistry that gives detailed information about the mineralogical composition and crystallographic structure of the crystalline materials. An entire spectrum of diffraction angles concerning the corresponding incident angle is used to identify the material. The system was operated under a Ni filter at room temperature, with an optimized diffraction angle range of 5°–80° (20).

#### FESEM (field emission scanning electron microscope) analysis

FESEM is a technique for visualizing minute topography and elemental characteristics on the surface of whole or fractioned objects. Electrons are accelerated in a strong electrical field gradient after being liberated from a field emission source. Electronic lenses focus the original electrons from the electron beam to create narrow, secondary electrons that are related to the object's surface structure. A detector catches the secondary electrons and generates an electrical signal. This signal is amplified and transformed into either a video scan image that can be viewed on a monitor or a digital image that can be saved and analyzed.

#### Thermogravimetric differential thermal (TG/DTA) analysis

Thermo-gravimetric/differential thermal analysis involves two different techniques TG (thermo-gravimetric) and DTA (differential thermal analysis). TGA measures the thermal stability and in DTA, the temperature change occurs during heating concerning inert material under identical conditions. It evaluates sample weight changes due to oxidation, decomposition, and any other physical or chemical processes that cause weight gain or loss. The analysis of biochar-based mortar samples was carried out with the help of Thermogravimetric analysis (Make and Model: LINSEIS and STAPT 1600). The sample was heated from 50 to 1000 °C at a temperature range of 20 °C/min. in the presence of a nitrogen atmosphere.

Based on the obtained curve the cement hydration product has been determined by using Eq. (5):

% CH Product:

$$CH_{dx} = 4.11 * dx_{(400-500^{\circ}C)} \quad (5)$$

where CH<sub>dx</sub> is the percentage of calcium hydroxide and dx mass loss of decarboxylation.

% CaCO<sub>3</sub> Product:

The percentage of  $\text{CaCO}_3$  is determined from the Eq. (6).

$$\% \text{CaCO}_3 = \% \text{CO}_2 \text{ uptake} \times 100/44 \quad (6)$$

$\text{CO}_2$  uptake % is calculated from TGA curves, i.e., Weight loss % between 500 and 800 °C

## Results and discussion

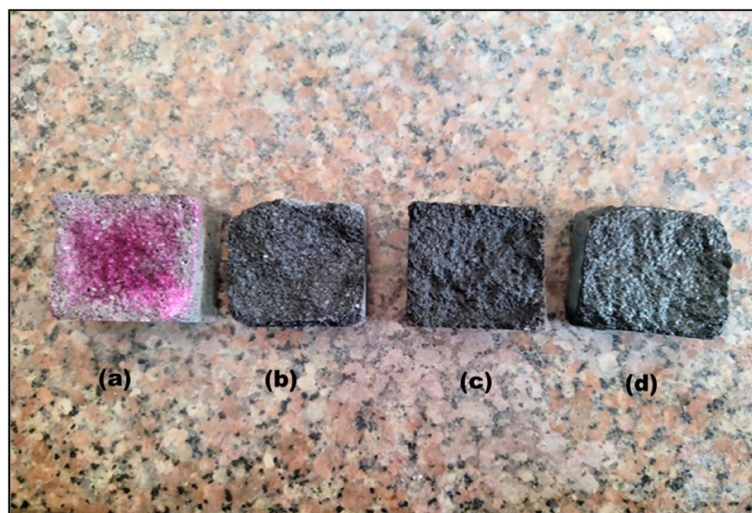
### Phenolphthalein test

Figure 6 shows the phenolphthalein test of the control sample and biochar-based mortar sample after 28 days of carbonation. As compared to the control sample (cube: a) biochar-based mortar sample (cube: b, c, d) is more carbonated because the presence of biochar provides more space for  $\text{CO}_2$  to react with hydrated compounds. It is especially helpful since it provides a visual representation

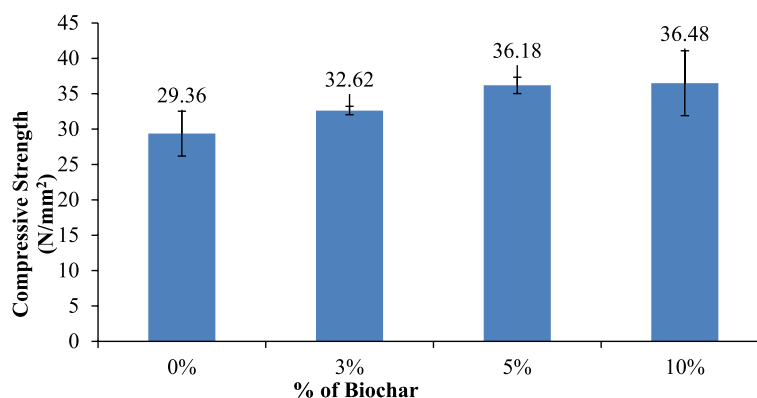
of a continuous carbonation front. The colorless area shows the carbonated area of the cube and the pink color shows, the area which is not carbonated.

### Mechanical strength of biochar-based mortar cubes

The data presented in Fig. 7 shows the effect of biochar as a replacement of cement in mortar strength with different dosages (0%, 3%, 5%, and 10%), after 28 days of carbon curing. The strength of cement slurries mixed with different dosages of biochar increases as the biochar wt. % increases from 0 to 10%. Compared to the control sample after 28 days of carbonation, at 3 wt. %, and 5 wt. %, and 10 wt. % the compressive strength increased by 11%, 23.2%, and 24.2% respectively. The increase in compressive strength can be credited to the significant production of calcite in biochar cement composites. The transformation from Calcium hydroxide to Calcium carbonate occurs as a result of carbonation during the solidification



**Fig. 6** Phenolphthalein test of carbonated biochar-based mortar cubes

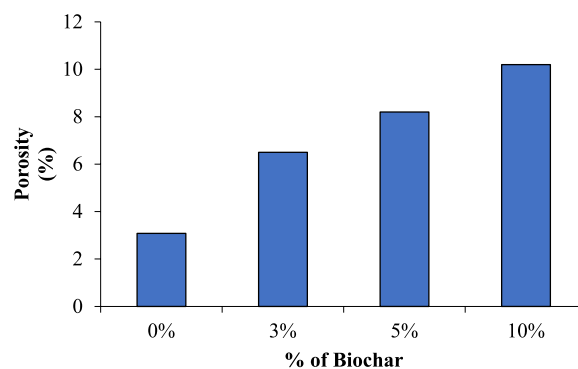


**Fig. 7** Compressive strength of biochar-based mortar cubes

of CO<sub>2</sub>. Biochar made from wood and food waste has been shown to increase strength because of its higher absorption capacity. This lowers the binder ratio and creates a denser microstructure. This improved strength is also thought to be a result of the biochar's capacity to refine the microstructure and plug pores. In addition, all mortar mixtures including biochar became stronger with time, suggesting that the hydration process would not be negatively impacted. In order to produce their separate biochar, Wadud et al. (Javed et al. 2022) carried out extensive studies utilizing five different bio-based feedstocks: rice husk, bagasse, coconut husk, wheat husk, and peanut husk. After that, different proportions of cement were substituted with these biochars. Their results showed that the greatest improvement in compressive strength, a noteworthy 18% gain, was seen in concrete mortars containing a 2% weight addition of bagasse biochar. According to the study, biochar variations that contained more amorphous silica were more successful in increasing compressive strength. According to Gupta et al. (Dixit et al. 2019), adding various sizes of biochar to ultra-high-performance concrete (UHPC) resulted in a small drop in strength, with larger biochar particles producing more noticeable reductions. This is because smaller biochar particles have a larger pore-filling capacity and are more reactive. The study conducted by Chen et al. (Wang et al. 2020) about the temperature at which biochar pyrolyzes revealed no noteworthy variations in the strength of carbon-cured concrete blocks when the biochar was treated at 500 °C or 700 °C. On the other hand, adding 1% biochar to Portland cement resulted in a 10% strength improvement, which was explained by the biochar speeding up the hydration reaction during carbon dioxide curing. Because biochar is a brittle material, higher dosages of it weaken the material and increase the risk of fissures. For improved compression strength results, Kua et al. (Gupta and Kua 2018) advise moist curing composites and pre-soaking biochar. Because the pre-soaked biochar acts as an internal curing agent in the composite and adds more water for hydration, the compression strength of the material is increased. Because of its porous structure, which permits it to retain water, biochar can act as an internal curing agent.

#### Porosity of biochar-based mortar cubes

The data presented in Fig. 8 shows the effect of biochar as a replacement of cement in a mortar with different dosages (0%, 3%, 5%, and 10%) after 28 days of carbon curing on the porosity of the samples. As biochar dosage increases in cement paste cubes, the porosity of the biochar-based mortar paste cubes is increased as compared to the control sample. The reason may be attributed to the porous nature of biochar, which results in an increase



**Fig. 8** Porosity of biochar-based mortar cubes

in sample porosity. After 28 days of curing, as compared to the control sample, the porosity of 3 wt. %, 5 wt. %, and 10 wt. % biochar-based mortar cubes, increased by 52%, 62%, and 69%. In biochar-based mortar cubes, the porosity increases as biochar dosage increases because the total porosity increases in the cement matrix and biochar.

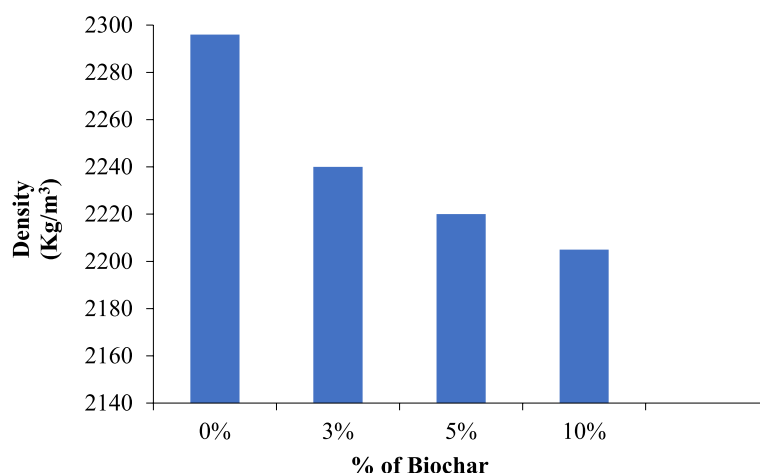
#### Density of biochar-based mortar cubes

The density of the cement paste containing biochar (rice husk and sawdust biochar) was determined as per ASTM C642-97, after 28 days in Fig. 9. As biochar increases in mortar paste, the density of the biochar-based mortar cubes is reduced as compared to the control specimen. In cases of 3%, 5%, and 10 wt. % of biochar, there is a significant decrease in density by 2.5%, 3.3%, and 3.9% when compared to the control specimen. Small air holes that take up space in the cement matrix are comparable to biochar pores. The porosity of the biomass biochar increases as the amount of biochar increases. The density of biochar-based mortar cubes decreases due to the effective porosity increases as shown in Fig. 7.

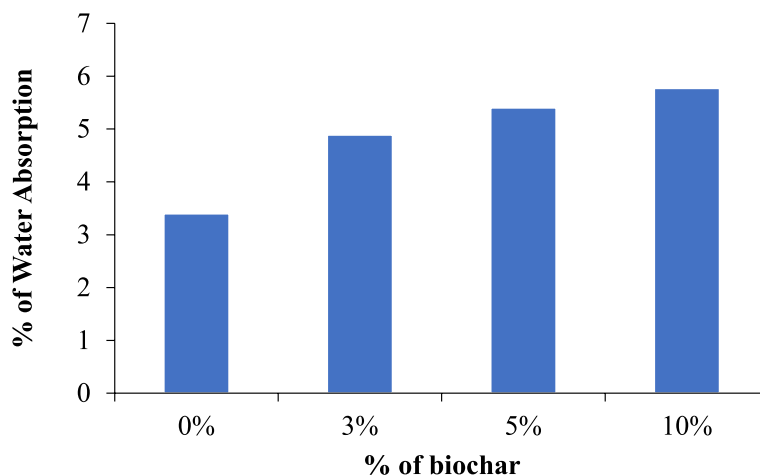
#### Water absorption of biochar-based mortar cubes

As per ASTM C642-97 (1997), the water absorption of mortar paste containing biochar was evaluated in Fig. 10 following a 28-day carbonation curing period. As compared to the control sample, the water absorption increases with an increased amount of biochar (0, 3, 5, and 10 wt. %), in the mortar mixture. After 28 days of carbonation, the water absorption at 0, 3, 5, and 10 wt. % increased by 43%, 59%, and 69% respectively. This is because the density of the mortar cube changes as the amount of biochar increases, and the pores in the biochar act as tiny air pockets that take up space in the cement matrix. The quantity of empty pores in cement did, however, rise as the biochar level did. Consequently, the incorporation of biochar influences important pore structure characteristics in mortars, like water absorption





**Fig. 9** Density of biochar-based mortar cubes



**Fig. 10** Water absorption of biochar-based mortar cubes

and apparent porosity, which significantly influence the durability and strength of cement composites. The results meet ASTM C1403-15 (2015) requirements.

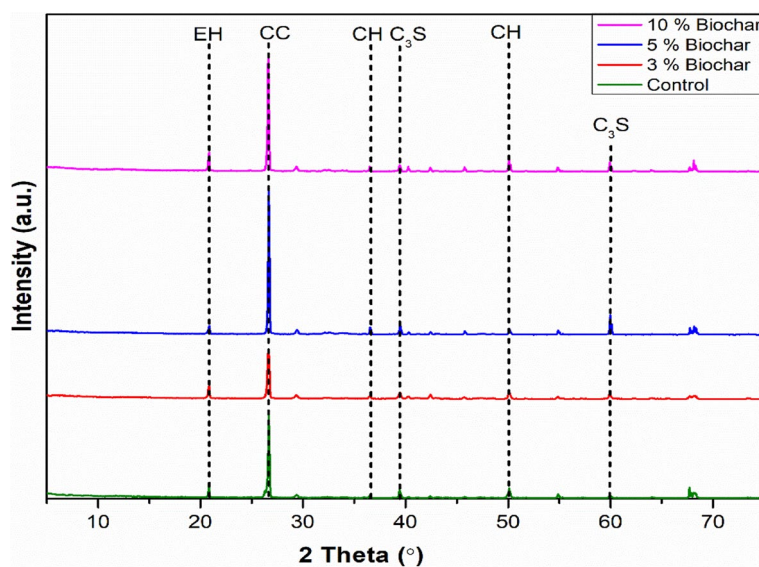
#### XRD analysis of biochar-based mortar cubes

Figure 11 depicts the XRD patterns of a carbonated cement paste containing biochar at 28 days. Hydration products, including calcite ( $\text{CaCO}_3$ ) and calcium hydroxide (CH), are seen at  $2\theta = 29.40^\circ$  and  $18^\circ$ ,  $35^\circ$  respectively. Calcite peak increased with increasing biochar dosage in cement paste. Simultaneously, the CH peak decreased as biochar dosage increased. After 28 days in carbonated samples, the calcite intensity was enhanced. After 28 days, the biochar's pores filled with water, which quickly combined with  $\text{CO}_2$  to generate carbonic acid. The carbonic acid then reacted with calcium hydroxide to form calcite. The biochar replacement of cement in mortar paste increased the amount

of calcium carbonate in the mixture. This suggests that the addition of  $\text{CO}_2$ -saturated biochar to cement paste results in a larger fraction of calcium carbonate being produced. Based on the CH and calcite intensities seen in the XRD spectra, it is possible to conclude that calcium carbonate is the result of the carbonization of biochar and cement paste, which is a component of the calcium hydroxide generated during hydration. The results obtained suggest that the inclusion of biochar in the cement-based material significantly enhances the cement's hydration degree.

#### TG/DTA analysis of biochar-based mortar cubes

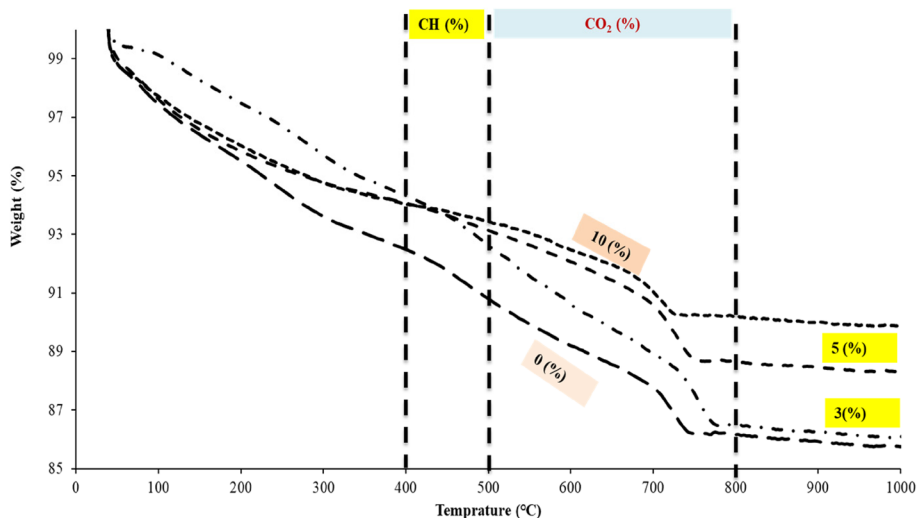
After 28 days, carbonated samples were subjected to TGA analysis to ascertain the hydration and carbonated products in the cementitious materials. Three notable weight losses were observed at various temperature ranges as shown in Fig. 12. Dehydration of C-S-H between  $105^\circ\text{C}$



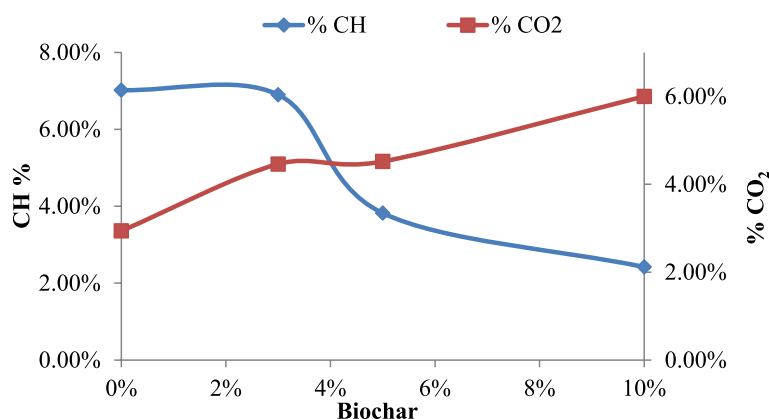
**Fig. 11** XRD graph of carbonated biochar-based mortar sample. EH—Ettringite, CC—calcium carbonate, CH—calcium hydroxide, C<sub>3</sub>S—tricalcium silicate

and 150 °C is the cause of the initial weight loss. The second is brought on by the calcium hydroxide hydration product breaking down, which is further identified by Eq. (5) and is at the dihydroxylation temperature between 400 °C and 500 °C. Because of carbonated products, the third weight loss (in percentage) was seen between 500 °C and 800 °C. The carbonation of calcium hydroxide results in calcite breakdown, which was represented by mass loss in the 500–800 °C range. Equation (6) was used to determine the percentage of CaCO<sub>3</sub> and % of CO<sub>2</sub> uptake. At 10 wt. % of biochar the CO<sub>2</sub> uptake was maximum,

which was 6%. % CH and %CO<sub>2</sub> uptake w.r.t to biochar % of biochar-based mortar sample were shown in Fig. 13. As biochar increases, % uptake of CO<sub>2</sub> increases, corresponding to calcium hydroxide decreases. It means that the calcium carbonate is higher due to consumption of calcium hydroxide from 7.02 to 2.42% corresponding to 0% to 10%. Due to the porous structure and presence of basic functional groups biochar is being considered as an effective CO<sub>2</sub> adsorbent (Lahijani et al. 2018; Chia et al. 2015). The mechanism of CO<sub>2</sub> adsorption is dependent on physical and chemical adsorption. Specifically,

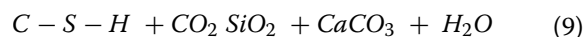
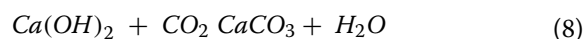
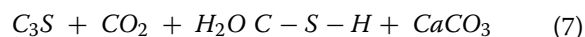


**Fig. 12** TGA of carbonated biochar-based mortar sample



**Fig. 13** % CH and %CO<sub>2</sub> uptake of biochar-based mortar sample

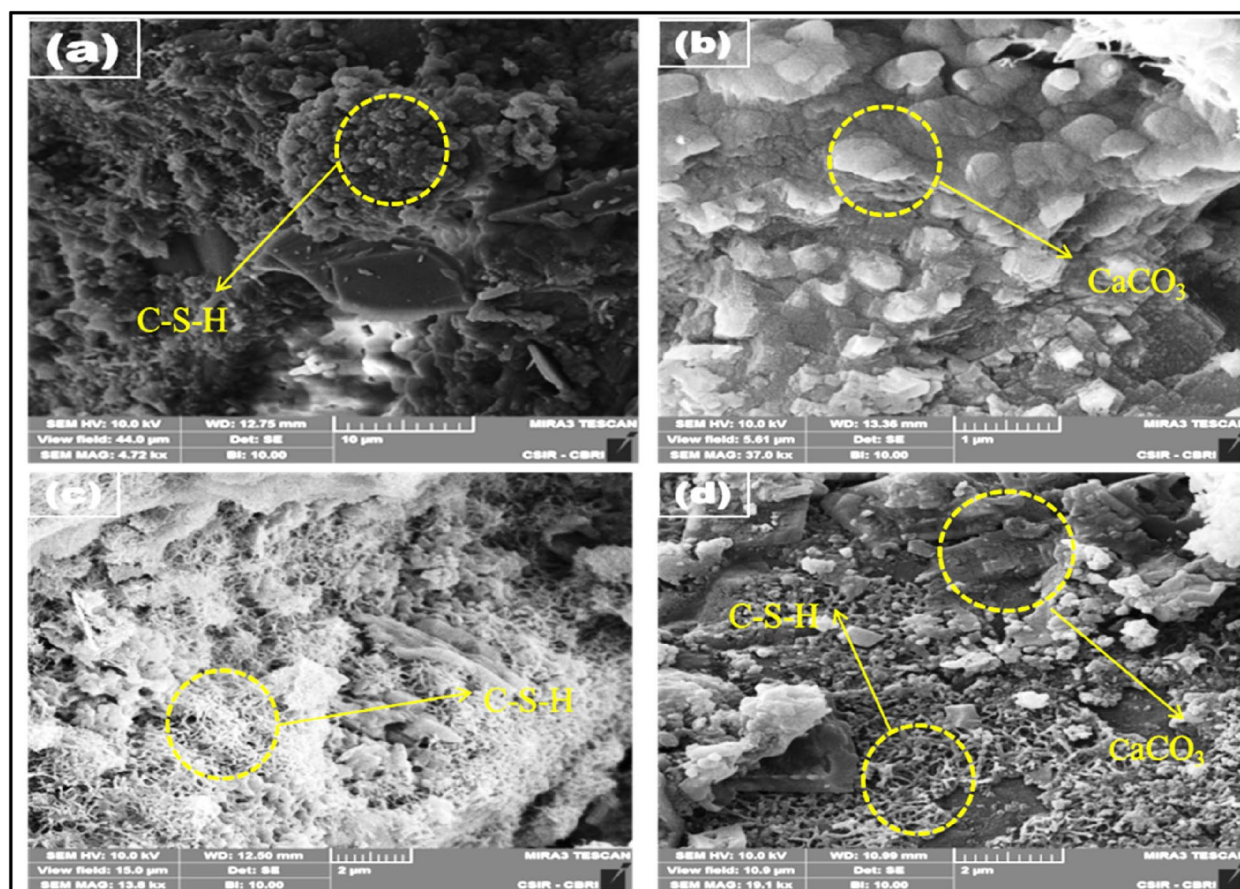
the physisorption of CO<sub>2</sub> between biochar and surface functional groups depends mostly on surface area and pore structure, whereas chemisorption relies primarily on the Lewis acid–base interaction (Serafin et al. 2017). Due to overlapping adsorption forces and potential fields from nearby pore walls, narrow micropores are closer to the dynamic diameter of CO<sub>2</sub> molecules and have a higher attraction to CO<sub>2</sub>. This is why biochar's CO<sub>2</sub> capture capability is dependent on micropores less than 1 nm in diameter (Li et al. 2022). Micropores act as the packing space for CO<sub>2</sub> adsorption, mesopores facilitate mass transfer at the gas–solid interface, and macropores improve CO<sub>2</sub> diffusion to lessen pressure drop (Shen and Fan 2013). According to Angin et al. (Angin 2013), micropores had a smaller effect on adsorption capacity at high temperatures, and as temperatures rose beyond 500 °C, biochar's pore volume and micropores shrank (Walton et al. 2006; Guo et al. 2022). It was explained by the fact that, at high temperatures, the process of pore enlargement and adjacent pores coalescing with a decrease in pore volume takes precedence over micropores. Biochar's ability to adsorb CO<sub>2</sub> can be improved by raising the surface's alkalinity, which modifies the functional groups on the surface to improve the interaction with CO<sub>2</sub>, or by lowering the O and H content of the biochar, which contributes to its high hydrophobicity and low polarity. According to Zhang et al. (2022); Gomes et al. (2021 and Kamal et al. (2020), cementitious composites which include concrete, mortar, and bricks are thought to be the CO<sub>2</sub> reservoir used in the carbonation process to capture carbon dioxide (Praneeth et al. 2020). The main mechanism is that the reaction between calcium hydroxide and absorbed carbon dioxide produces stable precipitation of calcium carbonate (Li et al. 2022), resulting in desirable CO<sub>2</sub> capture. In general, the CO<sub>2</sub> sequestration is achieved via the following equations (Eqs. (7, 8, 9)):



Studies by Chen et al. (Chen et al. 2022b) and Zhang et al. (Zhang et al. 2022) in the past decade have focused on the optimization of concrete mixtures to reduce the ecological footprint by applying different supplementary cementitious materials. The application of biochar has gained attention due to its larger surface area and porous structure. Several researchers (Gupta et al. (Gupta et al. 2020); Dixit et al. (Dixit and Verma 2021), Praneeth et al. (Praneeth et al. 2020); Zhang et al. (Zhang et al. 2022)) reported that the main advantage of biochar in improving carbon sequestration was that the porous structure of biochar provided reaction site for the formation of calcium carbonate.

#### FESEM analysis of biochar-based mortar cubes

The morphology of the carbonated biochar incorporated mortar paste sample after 28 days is shown in Fig. 14a–d. The FESEM study shows the hydration products, like CH, C-S-H, and calcite morphologies, among others. Calcium silicate hydrate (C-S-H) is the primary binder component. Nevertheless, C-S-H binds the particles of biochar to the cement paste and enhances strength only when it is integrated into the cement matrix. Figure 14 b–d shows the growth of hydration products in the biochar pores. Incorporation of biochar in the mortar samples and 28 days of carbonation curing has led to increase or enhancement in the hydration products such as crystalline calcium



**Fig. 14** FESEM images of **a** carbonated mortar cubes, **b, c,** and **d** carbonated biochar mortar-based cubes

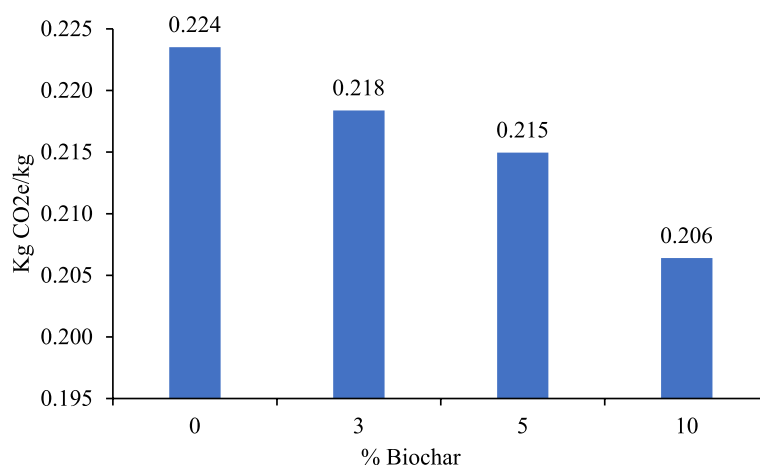
hydroxide (CH), ettringite crystals (AFt), and calcium-silicate-hydrate (C-S-H) in contrast to control samples (Dixit and Verma 2021). Greater hydration products increase the strength of the cement containing biochar and improve the pore structure, decreasing the porosity and the volume of macropores. Moreover, the micro filler effect of biochar fills the voids and cracks showing enhancement in the effectiveness of samples. According to Goldman et al. (1994), the paste is strengthened more by the inert carbon black micro-filler than by the pozzolanic activity. Moreover, because biochar is hydrophilic, adding it lowers the effective water-to-cement ratio. Calcite is a reactive material that modifies the mineralogy of wet cement pastes by influencing the distribution of lime, alumina, and sulfate. Formation of calcite in the biochar-incorporated system of mortar leads to an increase in the strength of the samples as the calcium hydroxide reacts with the  $\text{CO}_2$  present and results in the formation of calcium carbonate. As the amount of biochar increased up to 10 wt.%, a denser structure of calcite and hydration products was found. These results

showed that  $\text{CO}_2$ -cured biochar-based mortar cubes are compatible with cement paste.

#### **$\text{CO}_2$ emissions**

The literature values for corresponding  $\text{CO}_2$  emission equivalent values for OPC (Turner and Collins 2013), water (Crawford et al. 2019), and fine aggregates (Crawford et al. 2019) were taken. In this study, carbon emissions caused by the transportation and processing of rice and sawdust are considered since the industry burns these biomasses as fuel. For RHB and SDB, the  $\text{CO}_2$  emissions were calculated according to the method described by references (Alnahhal et al. 2018). RH and SD were collected from the local area of Roorkee, Uttarakhand, India. The distance between the site and the laboratory where the casting and testing were done is roughly 10 km.

Control and mixed biochar incorporated mortar were used to calculate the  $\text{ECO}_2\text{e/kg}$  by using Eq. (10) (Selvaranjan et al. 2021).



**Fig. 15** Embodied carbon of different biochar percentages blended in cement mortar

$$ECO_{2e} = \sum CO_{2i} \times miEq \quad (10)$$

$CO_{2i}$  is the embodied carbon emission factor, and  $mi$  corresponds to the mass of mortar ingredient  $i$  per kg of mortar.

Mortar with RHB and SDB in 3, 5, and 10% proportions as a replacement for cement was evaluated for their environmental efficacy. Compared to control mortar, RHB and SDB mortars contribute less greenhouse gas emissions, making them environmentally friendly. The derived results are illustrated in Fig. 15. RHB and SDB incorporation into mortar clearly affects the difference obtained for  $ECO_{2e}$  for different mortars. The  $ECO_{2e}$  of blended mortar is 2.3%, 3.8%, and 7.7% less than that of the control mortar at 3%, 5%, and 10% of OPC replaced with RHB and SDB.

## Conclusion

This study investigated the impact of SDB and RHB replacement with cement in mortar mixture on improving mechanical, physical, and environmental sustainability. The biochar prepared from rice husk and sawdust was incorporated into mortar-based as a replacement of cement with different dosages and cured under a  $CO_2$  environment. After 28 days of carbonation curing mechanical and mineralogical studies were conducted with the following conclusion:

1. As compared to the control sample, the replacement of 3, 5, and 10 wt. % of biochar in mortar mixture increased the compressive strength by 11%, 23.2%, and 24.2% in 28 days.

2. With replacement of 3, 5, and 10 wt.% of biochar with cement in mortar mixture affects its physical properties such as water absorption increases by 43%, 59%, and 69%, density decreases by 4.79%, 8.87%, and 10.65% and porosity increases by 52%, 62%, and 69%, as compared to the control sample.
3. TGA analysis of carbonated samples shows, that 10% of biochar incorporated in mortar mixture reduces the formation of calcium hydroxide by 65% and increases the formation of calcite product. XRD analysis of the carbonated sample shows higher calcite and C-S-H formation.

Therefore, to improve the properties of composites based on cement and promote carbon dioxide sequestration, waste rice husk biochar and sawdust biochar and  $CO_2$  curing should be synergistically integrated. In the future, this approach could be employed to manufacture construction materials in a more environmentally friendly and economically valuable manner.

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## Authors' contributions

SK analysed and interpreted the results. Drafted the Manuscript. SS analysed and interpreted the results. Drafted the Manuscript. RA interpreted the results and was a major contributor in writing the manuscript. NSN analysed and interpreted the results. RK supervised the experiments and drafted the Manuscript. HM drafted and revised the Manuscript. SNB supervised the experiments and drafted the Manuscript. All authors have read and approved the final manuscript.

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**Availability of data and materials**

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

**Declarations****Ethics approval and consent to participate**

Not applicable.

**Consent for publication**

The authors give consent for publication.

**Competing interests**

The authors declare that they have no competing interests.

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