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Effects of Partial Replacement of Cement with Biochar in Concrete for Carbon Sequestration

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ABSTRACT

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The cement industry accounts for approximately 8% of globally anthropogenic CO₂ emissions and requires sustainable solutions. The use of the commercially available BBQ coal biochar for partial cement replacement for carbon sequestration in concrete was studied. Five different concrete mix proportions were designed using a constant water-cement ratio of 0.7 and a concrete mix ratio of 1:2:4 with biochar at 0%, 5%, 10%, 15%, and 20% by the weight of Ordinary Portland Cement (OPC). The biochar had a carbon content of 32.20% and alkaline pH of 9.1. Physical, mechanical and thermal properties were determined at 7 and 28 days along with a theoretical carbon sequestration calculation. Results showed the bulk density and the compressive strength decreasing gradually with the increasing amount of biochar. But the 5% replacement mix (BCC-5) produced 28-day compressive strength of 21.03 N/mm², which is just 4.45% less than the control and above the minimum requirement for M20 grade. BCC-5 also exhibited good flexural strength and thermal resilience at 500C, and sequestered 17.73 g CO₂-equivalent/block. Hence, the dosage of 5% BBQ biochar is found to be the optimum, providing a compromise between structural strength and eco-friendly properties for sustainable building.

Introduction

Climate Change is one of the most urgent environmental problems of the 21st century. It is expressed as the increase in the global average temperature, changes in precipitation, and an increase in the frequency of extreme weather events, which all have a negative impact on the natural ecosystems and human settlements (Lehne & Preston, 2018). The Intergovernmental Panel on Climate Change (IPCC) has emphatically pointed out that these changes are mostly driven by human activities and

that a massive effort to decarbonize the economy is urgently needed (Masson-Delmotte et al., 2021). The burning of fossil fuels, deforestation and industrial production releases billions of tonnes of CO₂ and other Green House Gases (GHGs) per year (Andrew, 2019). The construction industry is key to the situation, with the production of cement being a single-sector emitter of carbon emissions, one of the greatest in the world (Habert et al., 2020).

Ordinary Portland Cement (OPC) is the most popular cement used for making concrete, the most commonly used construction material. The production of OPC is extremely energy and carbon intensive. Limestone is calcined into calcium oxide and carbon dioxide, releasing considerable amounts of CO₂ into the atmosphere, the main chemical reaction being the thermal decomposition of calcium carbonate (CaCO₃) to calcium oxide (CaO) and carbon dioxide (CO₂). The energy required for the production of conventional cement is not compatible with decarbonizing the world, as more fossil fuel energy is needed for traditional cement production. The cement sector is responsible for about 8% of all anthropogenic CO₂ emissions (Lehne & Preston, 2018) globally. This is accentuated by the extent of urbanization, with about 60% of the world's population expected to live in urban areas by 2030, while these cities use 60% to 80% of global energy and account for about 70% of all carbon emissions (Salvia et al., 2021). Therefore, it is necessary to make fundamental changes in the building sector to reach the climate goals, such as rethinking the production, use and disposal process of building materials (Andrew, 2019).

A one- way approach is to use alternative carbon-rich products in part of the cement. Biochar is a porous carbon-rich solid product of thermochemical conversion of any organic material in a limited oxygen atmosphere otherwise known as pyrolysis (Akinyemi & Adesina, 2020). During pyrolysis carbon is converted into a very stable and biologically and chemically recalcitrant form and can persist in material matrices for centuries to millennia (Lehmann et al., 2006). Using biochar in concrete then is a method to store carbon in a long-lived manner in the built environment and not as CO₂ in the atmosphere. Typically, the carbon content of biochar ranges from 30% to over 90%, varying with feedstock and pyrolysis conditions (Sohi et al., 2010). Biochar's porous structure and high specific surface area also have an internal curing effect to achieve complete hydration of the cement (Conte & Chaouche, 2019). Moreover, some biochars exhibit pozzolanic reactivity that promotes the formation of calcium silicate hydrate (C-S-H) phases, boosting the durability of the biochar over time (Maljae et al., 2021).

Commercially produced charcoal is sold as cooking fuel (BBQ coal) and is readily available, low cost, consistently produced biochar. It has a high content of fixed carbon, porous micro structure and chemical stability, therefore it is a promising biomass material for construction use in developing countries such as Pakistan (Usman et al., 2018). Although there are many available references on laboratory scale biochar, very little data can be found for the use of commercial BBQ coal in structural concrete.

The significance of this work lies in the combination of sustainable building, valorisation of waste and minimisation of climate change. This study proposes reducing the energy-intensive cement by partially substituting it with BBQ coal biochar and sequestering carbon in the built environment by taking a positive step. The study is relevant to the following United Nations Sustainable Development Goals: SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption), and SDG 13 (Climate Action). This study aims for the following: (i) to find the optimum ratio for replacing BBQ coal with biochar in the production of sustainable concrete, and (ii) to investigate the effect of the produced concrete with BBQ coal biochar on the physical, mechanical, durability and carbon sequestration properties of concrete.

Materials And Methods

Raw materials

Cement (binding material)

All concrete mixes were prepared with Ordinary Portland Cement (OPC) Type I according to ASTM C150 (ASTM, 2016). The cement was bought from a trusted supplier in the local market of Tandojam. Prior to use, the cement was tested for lumps and stored in airtight bags to avoid moisture absorption before use.

Fine aggregates

The locally available hill sand was used as fine aggregate. The sand had a fineness modulus ranging from 2.5 mm to 4 mm was used as fine aggregate. The sand was screened to remove any excess materials or large particles and was dried in the air prior to use.

Coarse aggregates

Coarse aggregates in the form of crushed stones having nominal maximum size of 9.5 mm and minimum size of 5 mm were used. The aggregates used were washed, cleaned and dried from the local market.

Water

All concrete specimens were prepared and cured using potable tap water that was free of organic matter, dissolved salts and other impurities. The water/cement ratio was kept constant at 0.7 during the study.

Source and nature of BBQ coal biochar

In the present study, BBQ (barbecue) coal biochar was used, BBQ is a type of biochar that is produced through controlled carbonization (slow pyrolysis) of hardwood biomass in an environment with limited oxygen. In analogy with slow pyrolysis, BBQ coal is created at high temperatures (400–700°C) either by traditional coal kiln or by industrial reports. The material produced is porous and rich in carbon and is very similar to the biochar specifically prepared for use, making it a nearly ideal and economically viable alternative to laboratory-made biochar.

The BBQ coal was bought by a local commercial supplier Tandojam, Sindh. The use of BBQ coal as biochar removes the need for dedicated pyrolysis plant, lowers the production expenses and the practical and scalable application of biochar in construction material at field level. This is in line with the overall goal of promoting low-cost, environmentally friendly and sustainable construction methods.

Preparation of BBQ biochar for concrete use

Once the BBQ coal was purchased it was initially inspected and sorted by eye to ensure all of the coal was carbonized and there were no other wood components, ash or foreign material. The sorted coal was then oven dried at 80°C for 16-20 hours to allow for the removal of any water from the coal that may have remained and for all subsequent measurements to be made on a dry weight basis.

The BBQ coal was ground after drying and the final particle size distribution was fine and homogeneous using a mortar and pestle. The ground biochar was then screened through an 850 µm (No. 20 ASTM) sieve to achieve uniform particle size and uniform dispersion within the cement matrix during concrete mixing. The rest of the biochar was put in airtight containers to avoid reabsorption of water before application.

Testing of BBQ biochar

The following physicochemical properties were measured before the BBQ biochar was added to the concrete mixes:

Ash content

Measured using loss-on-ignition (LOI) method. Oven dried biochar was burnt at 750°C for 6 hours in a muffle furnace in air. The mass of the residue was measured as ash.

$$\text{Ash (\%)} = \frac{W_1 - W_2}{W_1} \times 100$$

Where:

W_1 = Weight before ignition (g)

W_2 = Weight after ignition

Organic matter

Determined as the difference between 100 and ash content (%).

Carbon content

Estimated as the organic matter content divided by the Van Bemmelen factor (1.77) as put forward by Sohi et al. (2009). This gave a rough estimate of total organic carbon (TOC).

pH

Measured from a 1:5 (Biochar: Distilled water) suspension, shaken for 1 hour and then measured using a calibrated pH meter.

Experimental design

The experiment was conducted using a Completely Randomized Design (CRD) with five treatments and three replications per treatment. The treatments included various percentages of BBQ coal biochar substituting for cement by weight as shown in Table 1. The study has been using the concrete mix ratio of 1:2:4 (cement: fine aggregate: coarse aggregate).

Table 1 Composition ratio (1:2:4) of various biochar incorporated concrete under different treatment levels

S. No.	Treatment	BBQ Biochar(g)	Cement(g)	Fine Aggregate(g)	Coarse Aggregate(g)
1	BCC-0	0	300	600	1200
2	BCC-5	15	285	600	1200
3	BCC-10	30	270	600	1200
4	BCC-15	45	255	600	1200
5	BCC-20	60	240	600	1200

The control treatment (BCC-0) had no biochar added, whereas BCC-5, BCC-10, BCC-15 and BCC-20 had 5%, 10%, 15% and 20% of the cement replaced by BBQ biochar respectively. The results were statistically reliable due to the number of replications made 3 times.

Preparation of biochar incorporated concrete

The biochar incorporated concrete were prepared by manual mixing based on the quantities of the constituents given in Table 1, as per the composition ratios. First, all dry ingredients (cement, fine aggregate, coarse aggregate and BBQ biochar) were accurately weighed on a digital balance and thoroughly mixed in a clean tray for about three minutes until a uniform mixture was achieved. Then water was slowly added in while mixing until it became a homogenous concrete mix. The water-cement ratio (w/c) was kept constant at 0.7 for all the treatments.

The prepared concrete mix was poured into steel moulds with dimensions 10 cm × 10 cm × 10 cm (cube moulds) and 10 cm × 10 cm × 50 cm (wood moulds for beam) in three layers. A tamping rod was used to compact each layer to remove the air voids and to ensure a uniform compaction. A trowel was used to level and smooth the surface of the blocks.

The moulds were allowed to set at ambient temperature for 24 hours after casting. Demoulding the concrete blocks, these are then placed in clean water for curing periods of 7 days and 28 days. For one test, each treatment combination was formulated in triplicate (n=3) resulting in 15 blocks per each curing period.

Testing of biochar incorporated concrete

Water absorption

Water absorption is the percentage gain in mass of a dry material after a specified period of time in water. It is a measure of the porosity and durability of the concrete. The concrete blocks were oven-dried at 105°C for 24 hours after curing to get the dry weight (W_d). After the dried blocks were submerged in water for 24 hours and the saturated surface-dry (SSD) weight (W_w) was recorded. The water absorption was calculated according to IS: 3495 (Parts 1-4, 1992) as follows:

$$WA (\%) = \frac{W_w - W_d}{W_d} \times 100$$

Where:

WA = Water absorption (%)

W_w = Weight of Saturated surface-dry block (g)

W_d = Weight of oven-dry block (g)

Bulk density

Bulk density is the mass of dry material per unit volume, including all the internal pore space. Bulk density of concrete blocks was determined by dividing the oven-dry mass of each specimen with the geometrically measured volume of the specimen. The dimensions of 10 cm × 10 cm × 10 cm sized cubic blocks were measured using vernier calliper and volume of the blocks were computed. Bulk density was calculated by the following formula.

$$\text{Bulk density } \left(\frac{\text{g}}{\text{cm}^3}\right) = \frac{M}{V}$$

Where:

M = Oven-dry mass of the block (g)

V = Volume of the block (cm³)

Compressive strength

The compressive strength of a material is the resistance that it offers to failure when it is subjected to axial compression. It is the most important mechanical characteristic of concrete. The concrete blocks were taken out from the curing tank after the respective curing period (7 and 28 days) and surface dried and tested for compressive strength on Compressive Testing Machine (CTM) as per IS: 516-1959 (Method of test for compressive strength of concrete). A constant loading rate was used to apply the load to the opposite faces of the cube. The highest load at failure was noted and compressive strength was worked out as follows:

$$\sigma = \frac{M_f}{A_p}$$

Where:

σ = Compressive Strength (N/mm²)

M_f = Maximum applied load at failure (N)

A_p = Plane (cross-sectional) area of the cube (mm²)

Flexural strength

The notched beam specimens were tested in three-point bending to evaluate flexural strength. The beam specimens were cast in the 10 cm × 10 cm × 50 cm dimensions and cured with the cube specimens. Notched beams were tested under Crack Mouth Opening Displacement (CMOD) control in a servo-electric Universal Testing Machine (INSTRON 8862) over a net beam span of 400 mm with a clip on displacement gauge fixed at the notch.

The applied load was measured continuously using a load cell. Peak load was noted and used to calculate nominal flexural strength by using the following formula. The tests were carried out according to the recommendation (1985) of RILEM TC-50 FMC. To get representative values, at least three beam specimens were tested per treatment.

$$f_b = \frac{P \times L}{b \times d^2}$$

Where:

f_b = Flexural Strength (N/mm²)

P = Maximum applied load at failure (N)

L = Span length of beam (mm)

b = Width of beam (mm)

d = Depth of beam (mm)

Thermal damage resistance (elevated temperature)

The concrete samples for each treatment were exposed to high temperature to evaluate the thermal stability and fire resistance of the biochar-incorporated concrete. All test specimens were oven-dried at 105°C for 24 hours before the determination of the moisture and before reaching a constant dry mass to remove free moisture from each specimen.

An electric pyrolysis reactor, with a capacity of 2-3 blocks per batch was used. The temperature increased until it reached the desired temperature of 500°C. The specimens were stored at this temperature for 1 hour. After the heating cycle, the reactor was switched off, and specimens were left to cool inside the reactor to prevent thermal shock to the specimens. The cooled specimens were then moist cured for 7 days prior to testing compressive strength after post heating, where moist curing after thermal damage results in degradation of the cementitious matrix than air cooling (Arioz, 2007) giving a conservative measure of residual strength. The following parameters were recorded before and after the thermal exposure:

Mass loss

The mass loss analysis was made by determining the weight of the specimen before and after heat treatment.

$$\text{Mass Loss (\%)} = \frac{W_1 - W_2}{W_1} \times 100$$

Where:

W_1 = Mass before heat (g)

W_2 = Mass after heat (g)

Residual compressive strength

Residual compressive strength is the remaining compressive strength of concrete specimens which have been exposed to high temperature or any deterioration process. It is used to assess how much of a load bearing capacity is lost due to thermal damage. The residual compressive strength can be determined as the ratio of post heating compressive strength to the pre heating compressive strength by the following formula:

$$\text{Residual Strength(\%)} = \frac{\sigma_a}{\sigma_b} \times 100$$

Where:

σ_a = compressive strength after exposure (N/mm²)

σ_b = original compressive strength before exposure (N/mm²)

Calculation of carbon sequestration

The highly stable aromatic carbon structure contained in BBQ coal biochar allows to sequester carbon for several hundred to thousands of years within the concrete matrix making it a long-term carbon sink (Lehmann et al., 2006). The following parameters were used to estimate the amount of carbon sequestered per kg of biochar added to each of the concrete treatments.

Carbon content of BBQ biochar

The carbon content of BBQ coal biochar was determined, following the Loss-on-Ignition (LOI) method. The carbon content of biochar is expected to be in the range of 30–90% depending on the type of feedstock and the pyrolysis conditions (Sohi et al., 2009). All the calculations of carbon sequestration were based on the carbon content derived from the LOI.

Carbon sequestration calculation

The amount of carbon sequestered within each concrete block, which includes carbon sequestered by the biochar and carbon lost through cement production, was determined as follows:

$$\text{Carbon sequestered (g)} = \text{Mass of biochar (g)} \times \frac{\text{Carbon content (\%)}}{100}$$

To express the carbon sequestration in terms of CO₂ equivalent (CO₂-eq), the molecular weight ratio of CO₂ to C ($44/12 \approx 3.67$) was applied:

$$CO_2 - eq \text{ sequestered (g)} = \text{Carbon sequestered (g)} \times 3.67$$

All the biochar treatments (BCC-5, BCC-10, BCC-15 and BCC-20) were used in these calculations to quantify and compare the carbon sequestration potential as biochar substitution rates increased. The results were reported per block.

Statistical analysis

The data obtained from all the experiments were analyzed statistically by Analysis of Variance (ANOVA) under Completely Randomized Design (CRD). The Least Significant Difference (LSD) test at 5% level of significance ($p \leq 0.05$) was used to compare mean values of all measured parameters. The statistical analysis was done using the program STATISTIX 8.1.

Results

Characterization of BBQ Biochar

The proximate analysis of BBQ biochar showed 43% ash content, 57% organic matter, 32.20% carbon content and a pH of 9.1 (Table 2). The ratio of carbon to CO₂ equivalent for the calculations was 3.67.

Table 2 Proximate characterization of BBQ biochar used in this study

Parameter	Value
Ash Content (%)	43
Organic Matter (%)	57
Carbon Content (%)	32.2
pH	9.1
Carbon-to-CO ₂ Equivalent Ratio (CO ₂ /C)	3.67

Physical Properties

The experimental treatments showed highly significant difference for bulk density at 7 and 28 days as determined by ANOVA ($p < 0.05$). The bulk density of the biochar blends showed a consistent decrease with increasing biochar content. At 28 days, it ranged from 2.232 g/cm³ in BCC-0 to 2.080 g/cm³ in BCC-20 (Figure 1). The LSD_{0.05} value (0.0335 g/cm³) showed that there was no significant difference between BCC-0 and BCC-5 (Table 3).

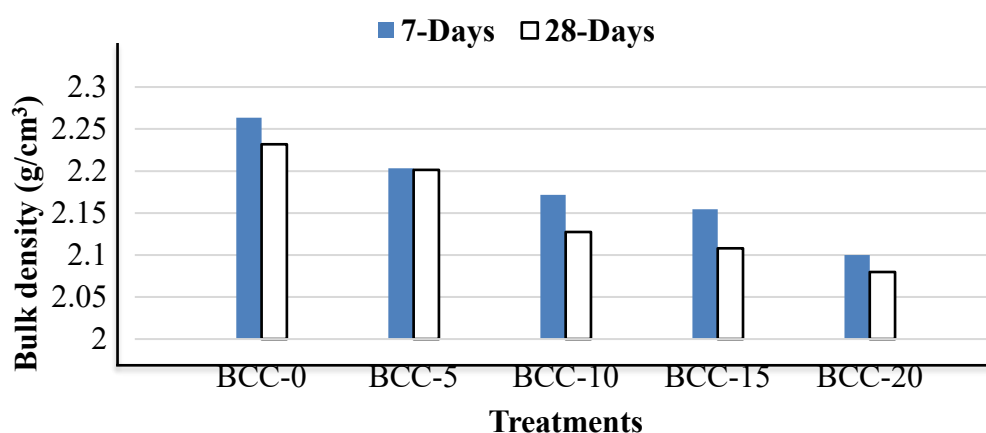


Figure 1: Bulk density of biochar incorporated concrete

Table 3 ANOVA summary and mean bulk density (g/cm^3) of biochar incorporated concrete

Treatment	Biochar (%)	7-days Density	28-days Density	% Change (28-days)	LSD Groups
BCC-0	0	2.264	2.232	—	A
BCC-5	5	2.203	2.201	-1.39%	A
BCC-10	10	2.172	2.127	-4.70%	B
BCC-15	15	2.154	2.108	-5.56%	B
BCC-20	20	2.100	2.080	-6.81%	C

Note. $LSD_{0.05} = 0.0335 \text{ g}/\text{cm}^3$. Means sharing the same letter are not significantly different.

There was a correlation between biochar replacement and water absorption. At 28 days, it ranged from 4.82% (BCC-0) to 8.27% (BCC-20), representing a 71.58% increase (Figure 2). Remarkably, all the treatment mixes other than BCC-20 were within the prescribed limit of 8% provided by IS: 3495 for concrete block application (Table 4).

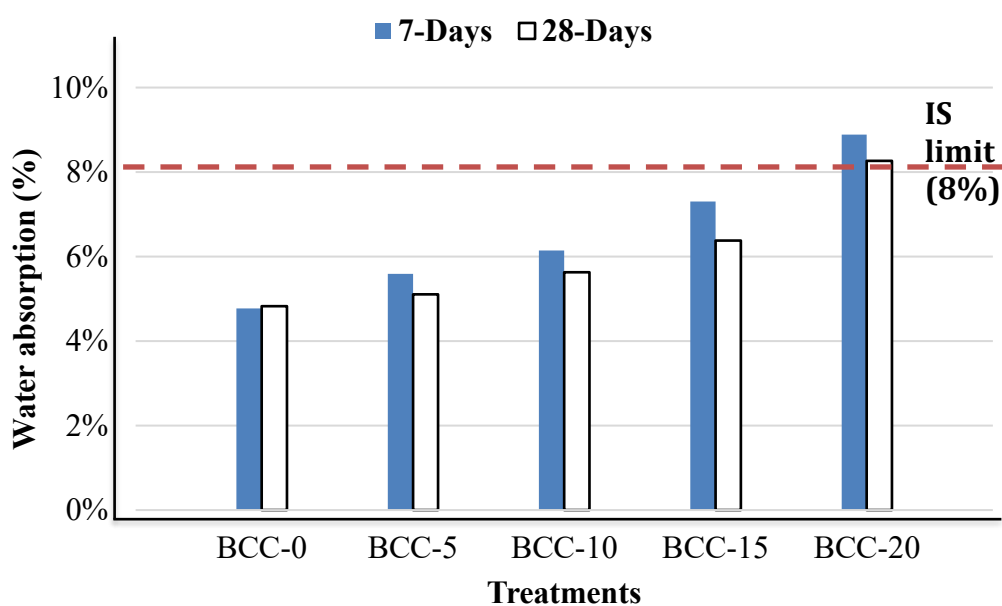


Figure 2: Water absorption (%) of biochar incorporated concrete

Table 4 ANOVA summary and mean water absorption (%) of biochar incorporated concrete

Treatment	Biochar (%)	7-days Absorption	28-days Absorption	% Change (28-days)	LSD Groups
BCC-0	0	4.77	4.82	—	C
BCC-5	5	5.59	5.11	+6.02%	BC
BCC-10	10	6.14	5.63	+16.81%	BC
BCC-15	15	7.30	6.38	+32.37%	B
BCC-20	20	8.88	8.27	+71.58%	A

Note. $LSD_{0.05} = 1.3208\%$. Means sharing the same letter are not significantly different.

Mechanical Properties

The compressive strength of the biochar mixes was found to decrease with the addition of increasing amounts of biochar. The control mix (BCC-0) had the maximum strength of 22.01 N/mm² after 28 days (Figure 3). The statistically marginal drop of only 4.45% in BCC-5 at 21.03 N/mm² was quite comparable. The minimum required M20 grade is 20N/mm² and BCC-5 was found to be higher. But BCC-20 had the minimum strength of 12.16 N/mm² which is 44.75% less than the control (Table 5).

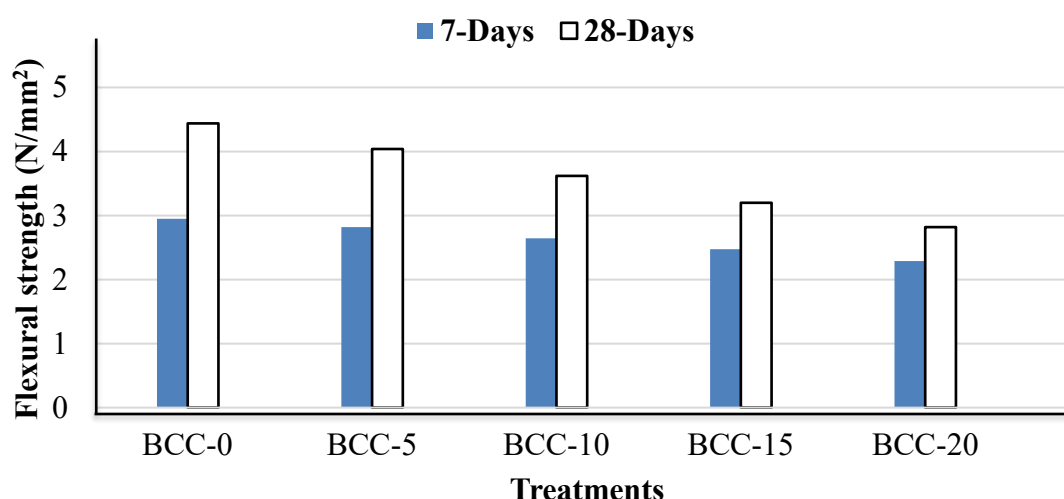


Figure 3: Compressive strength of biochar incorporated concrete

Table 5 ANOVA summary and mean compressive strength (N/mm²) of biochar incorporated concrete

Treatment	Biochar (%)	7-days Strength	28-days Strength	% Change (28-days)	LSD Groups
BCC-0	0	16.35	22.01	—	A
BCC-5	5	15.86	21.03	-4.45%	A
BCC-10	10	13.90	19.39	-11.90%	B
BCC-15	15	12.26	16.22	-26.31%	C
BCC-20	20	10.30	12.16	-44.75%	D

Note. $LSD_{0.05} = 1.4363 \text{ N/mm}^2$. Means sharing the same letter are not significantly different.

The same was observed for flexural strength. The control (BCC-0) had 4.44 N/mm² after 28 days and BCC-5 had 4.04 N/mm² after 28 days (Figure 4). This was a mere 9.01 % reduction, indicating that biochar can easily be incorporated at the low level required. As replacement levels (BCC-10, BCC-15 and BCC-20) were increased, the reduction increased progressively as 18.47%, 27.93% and 36.49% respectively (Table 6).

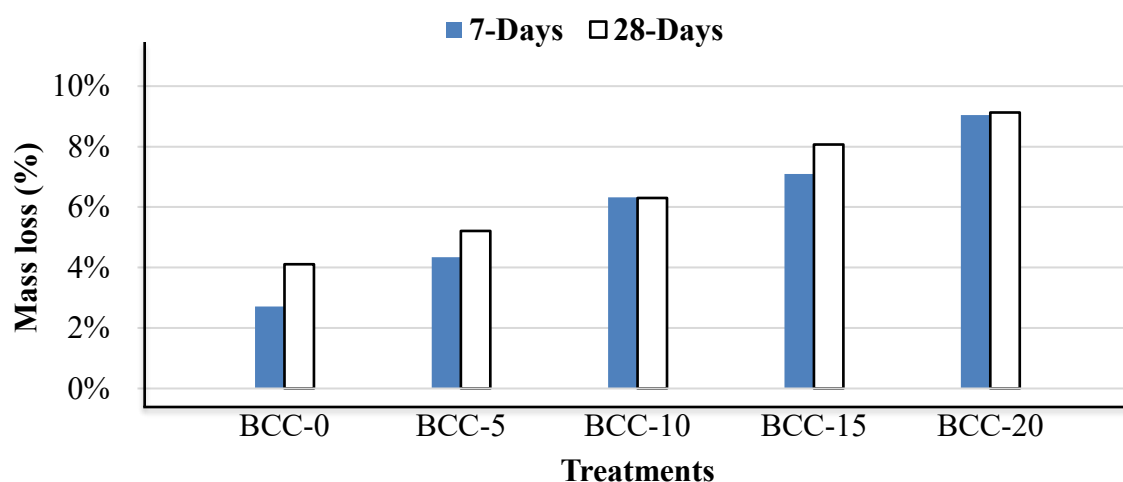


Figure 4: Flexural strength of biochar incorporated concrete

Table 6 ANOVA summary and mean flexural strength (N/mm²) of biochar incorporated concrete

Treatment	Biochar (%)	7-days Strength	28-days Strength	% Change (28-days)	LSD Groups
BCC-0	0	2.95	4.44	—	A
BCC-5	5	2.82	4.04	-9.01%	AB
BCC-10	10	2.64	3.62	-18.47%	BC
BCC-15	15	2.47	3.20	-27.93%	C
BCC-20	20	2.29	2.82	-36.49%	C

Note. $LSD_{0.05} = 0.8045 \text{ N/mm}^2$. Means sharing the same letter are not significantly different.

Thermal Damage Analysis

The weight loss after exposure to 500°C was more for higher biochar contents. At 28 days, mass loss was higher in BCC-20 than in BCC-0, at 9.12% and 4.11% respectively (Figure 5), and was believed to be due to the combustion and volatilization of BBQ charcoal residual organic carbon (Table 7).

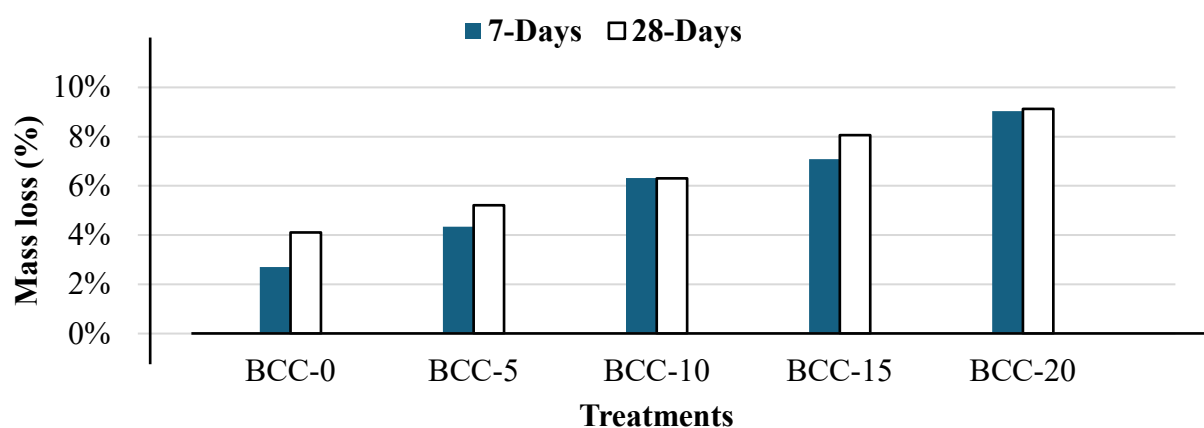


Figure 5: Mass loss of biochar incorporated concrete

Table 7 ANOVA summary and mean mass loss (%) of biochar incorporated concrete

Treatment	Biochar (%)	7-days Loss	28-days Loss	% Change (28-days)	LSD Groups
BCC-0	0	2.71	4.11	—	A
BCC-5	5	4.35	5.21	26.76%	A
BCC-10	10	6.32	6.30	53.29%	B
BCC-15	15	7.09	8.07	96.35%	B
BCC-20	20	9.04	9.12	121.90%	C

Note. $LSD_{0.05} = 1.6591\%$. Means sharing the same letter are not significantly different.

Figure 6 shows that the control mix had a residual compressive strength after 28 days of 81.69% of the pre-heating strength, whereas BCC-5 had a residual compressive strength of 77.75% of the pre-heating strength after 28 days. Out of all the BCCs, BCC-20 showed the minimum residual strength of 60.20%. The LSD analysis showed that there was no significant difference (Table 8) between BCC-0 and BCC-5.

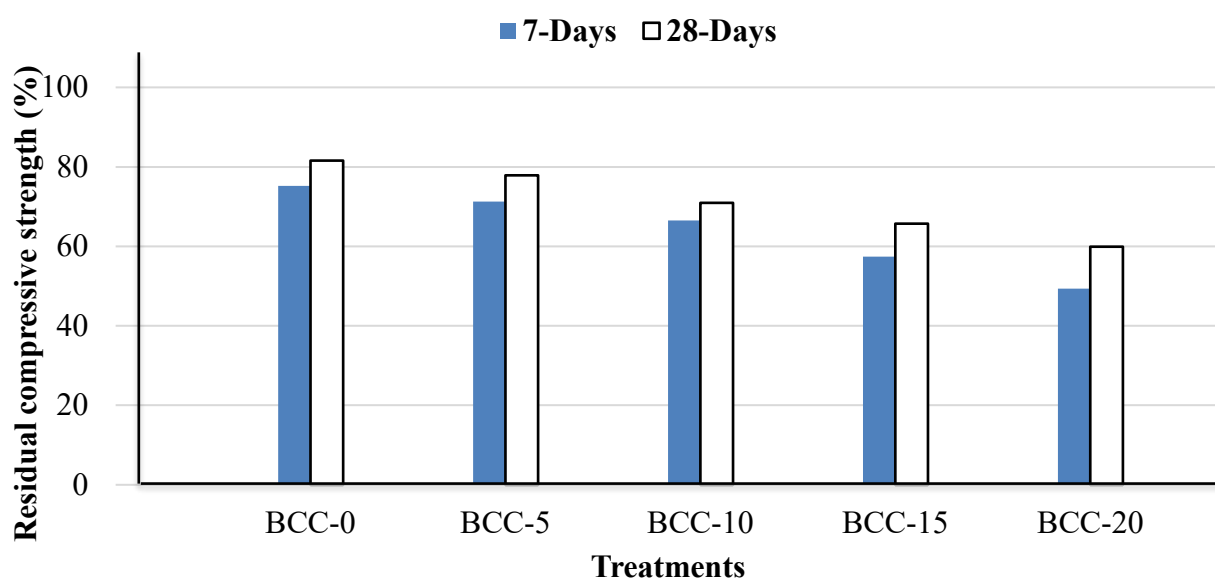


Figure 6: Residual compressive strength of biochar incorporated concrete

Table 8 ANOVA summary and mean residual compressive strength (%) of biochar incorporated concrete (28-Days)

Treatment	Pre-heating (N/mm ²)	Post-heating (N/mm ²)	Residual (%)	% Change	LSD Groups
BCC-0	22.01	17.98	81.69	—	A
BCC-5	21.03	16.35	77.75	-4.82%	A
BCC-10	19.39	13.73	70.81	-13.32%	A
BCC-15	16.22	10.63	65.54	-19.77%	B
BCC-20	12.16	7.32	60.20	-26.31%	B

Note. $LSD_{0.05} = 11.481\%$. Means sharing the same letter are not significantly different.

Carbon Sequestration Estimation

The CO₂ sequestration potential increased with biochar replacement rate as shown in figure 7, which was calculated by multiplying the biochar carbon content with the conversion factor. The CO₂ sequestration potential was seen to increase with increasing biochar replacement rate (figure 7) which was calculated with the conversion factor and the biochar carbon content. The sequestration of 17.73 g CO₂-eq per block for BCC-5 and up to 70.90 g CO₂-eq per block for BCC-20 (Table 9) shows that the BCCs performed better than the others did.

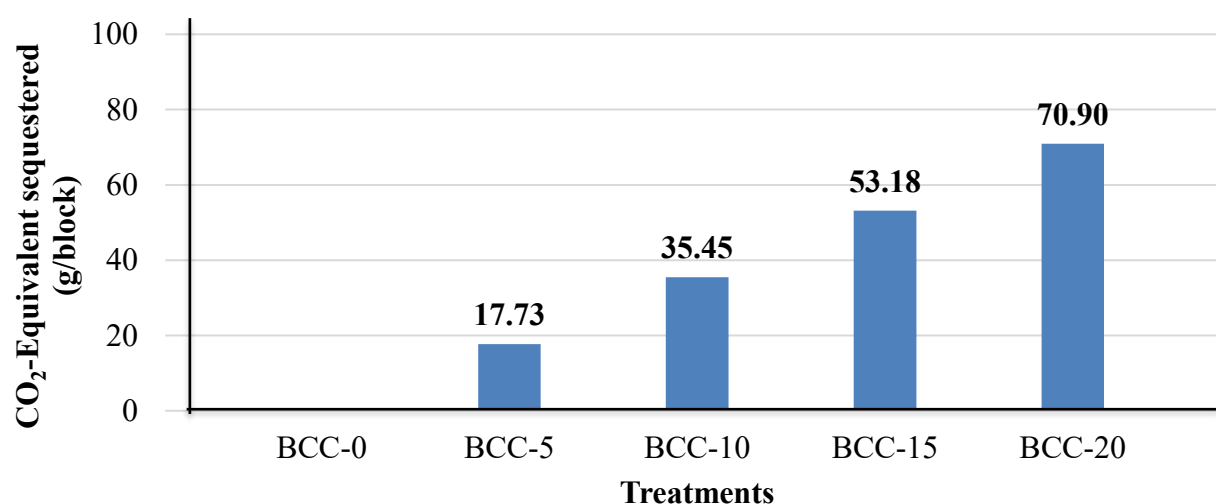


Figure 7: Carbon sequestration potential of biochar incorporated concrete

Table 9 Mean CO₂ equivalent sequestered (g/block) of biochar incorporated concrete

Treatment	Biochar Per Block (g)	Carbon in Biochar (g)	CO ₂ Equivalent Sequestered (g/block)
BCC-0	0	0	0
BCC-5	15	4.83	17.73
BCC-10	30	9.66	35.45
BCC-15	45	14.49	53.18
BCC-20	60	19.32	70.90

Note. Carbon content of biochar = 32.20%; CO₂ sequestered = Carbon (g) × 3.67 (CO₂/C molecular weight ratio).

Discussion

The BBQ biochar was characterized, with carbon content of 32.2%, ash content of 43% and pH of 9.1. The carbon content of BBQ charcoal is relatively low and this can be attributed to its variable production process with no controlled atmosphere conditions, as is typical for lab grade pyrolysis biochar (30–90%) (Sohi et al., 2010). This carbon content, however, falls within the range of carbon content known to be suitable for carbon sequestration applications in cementitious matrices (Akinyemi & Adesina, 2020). The alkaline pH values agree with Maljae et al. (2021) who have reported that pH values of biochars produced from lignocellulosic waste materials, when pyrolysed at temperatures higher than 400°C, can be of an alkaline nature, which can interact positively with the cement hydration environment.

The bulk density of the biochar incorporated concrete decreased from 2.232 g/cm³ (BCC-0) to 2.080 g/cm³ (BCC-20) at 28 days. This drop is mostly due to the fact that biochar has a lower density, but high porosity, which results in the displacement of high-density cement particles in the matrix. The findings here are consistent with Sirico et al. (2021) and Aman et al. (2022), which found that the wood-waste biochar caused noticeable reduction in the density of the concrete and biochar porosity was significant in reducing density, respectively. In areas such as Sindh (Singhal, 2023), the reduction in transportation expenses in non-load-bearing applications, such as partition walls and insulating blocks, due to the use of less cement in these structures is practically advantageous.

Water absorption increased from 4.82% in BCC-0 to 8.27% in BCC-20 at 28 days. The porous structure of biochar makes it to add more pores to the matrix of concrete, thus leading to this behavior. Most biochars have hydrophilic surface characteristics which promote moisture retention (Gupta et al., 2018). High water absorbing properties can make the concrete more susceptible to the effects of freeze-thaw and chemical attack, but it also provides an internal curing (Dixit et al., 2019). Likewise, it was found that wood waste sawdust increased the requirement of water, but the moisture released during the hydration process helped in internal curing as reported by Usman et al. (2018). Importantly, the water absorption of BCC-5 was 5.11% at 28 days which was still within permissible limit of 8 % as mentioned in IS 3495 of concrete block construction.

The compressive strength exhibited a steady and consistent decrease with the addition of biochar. The modified mix that produced the best performance was BCC-5 which had a compressive strength of 21.03 N/mm² at 28 days, which was a 4.45% decrease. This indicates that BBQ biochar has a low effect on the structural integrity when used at low replacement levels. As the biochar content increased, the strength also declined quickly until 20% biochar where it was reduced by 44.75%, from 24.02 N/mm² to 12.16 N/mm². The findings are similar to Legan et al. (2025) who reported on a negative impact of biochar on the compressive strength due to increased porosity in biochar and a reduction in the strength of the interfacial transition zone. Aman et al., (2022) reviewed the literature thoroughly and found that adding biochar between 0.08% and 5% is the best range to obtain higher compressive strength and higher addition reduces this strength. In addition, Maljae et al. (2021) reported that compressive strength of 28 days (CS₂₈) increased with 4% biochar replacement of cement, depending on the type of biochar and its dosage.

There are several reasons for the decrease in strength as the biochar content increases. Firstly, discontinuities created on BBQ charcoal, causing discontinuities in the cement paste matrix, and disrupting load transfer mechanisms. Secondly, the commercial BBQ charcoal may have residual volatile matter or a mixture of particle sizes which impact negatively on the hydration chemistry of cement (Akinyemi & Adesina, 2020). Third, due to the high water absorption capacity of biochar, it can impact the actual water/cement ratio, leading to a "wetter" initial mix and increased porosity after curing (Dixit et al., 2019). These limitations were not a problem as the BCC-5 mix achieved the minimum strength of 20 N/mm² required for the class M20 of concrete grade.

The same trend was observed for flexural strength which dropped from 4.44 N/mm² (BCC-0) to 2.82 N/mm² (BCC-20) at 28 days. The BCC-5 mix had a decrease of just 9.01%. This case is similar to the formation of weak interfacial zones between biochar particles and the cement paste, which decreases flexural strength with increasing biochar content. Gupta and Kua (2020) reported a strength gain of 20% with the incorporation of up to 10% biochar as a 10% replacement of cement, which may also explain why the mix of biochar alone did not yield sufficient strength in the present study as no supplementary cementitious materials (SCMs) such as silica fume or fly ash were used. In future studies synergistic improvement could be achieved if biochar is used in conjunction with SCMs.

Thermal damage tests at 500°C showed that all samples had a significant decrease in compressive strength. The control mix (BCC-0) still maintained 81.69% of compressive strength before heating and BCC-5 maintained 77.75% at 28 days. The retention of BCC-20 was the lowest (60.20%). This result shows that the thermal resistance of concrete is not significantly affected by the addition of biochar to the concrete and may slightly increase at 5% replacement. The improved thermal performance of BCC-5 may be attributed to its porous structure that facilitates thermal stresses to be released by the reduction of pressure during heating, thus reducing the pressure-induced explosive spalling and microcracking (Gupta & Kua, 2020).

Moreover, Sirico et al. (2021) found that the use of biochar in structural concrete also improved the internal curing and long-term durability without compromising the mechanical properties of the concrete. More reduction in mass loss after thermal exposure was found to be related to the higher biochar content in the charcoal due to the combustion of remaining volatile carbon during the high-temperature exposure.

The potential for carbon sequestration of biochar modified concrete was calculated as 17.73 g to 70.90 g CO₂-eq per block (BCC-5 to BCC-20). These are low estimates on the block level but it does have significance for building construction. Lehmann et al. (2006) demonstrated that biochar is a very stable carbon sequestration, with carbon stored for hundreds to thousands of years. A life cycle assessment (LCA) carried out by Campos et al. (2020) confirmed that the adoption of biochar in concrete always reduced environmental and health impacts when compared to traditional cement. They also observed that local BBQ charcoal also generates lower associated transportation volumes, which is a major drawback in this study because BBQ charcoal was purchased from local market in Sindh. The application of biochar in concrete blocks confers two climate change mitigation benefits; it replaces Portland cement, which is a high CO₂-consuming material, and, it permanently sequesters biogenic carbon (Akinyemi & Adesina, 2020). The Environmental issues are more relevant in the context of a rapidly growing construction industry in Pakistan.

Lastly, biochar @ 5% replacement was the most balanced and feasible treatment. The compressive strength and flexural strength were decreased by 4.45% and 9.01% respectively when compared with the control. The bulk density was decreased by 1.39%, water absorption was within the acceptable limits and was the meaningful carbon sequestered equivalent of 17.73 g CO₂ / block obtained. The findings align with the study by Singhal (2023) who concluded that using between 1–3% biochar is generally the optimum range, and with study by Legan et al. (2025) which reported that 5% biochar would give the best mechanical and environmental performance in mortar applications. Higher replacement levels (BCC-15 and BCC-20) offer greater carbon sequestration, but are not strong enough in compression and flexure to be structurally used. Such mixes may be used in non-structural, insulating or decorative concrete components where mechanical requirement is not as high as in structural concrete components, and environmental performance is also an important consideration.

Conclusion

This study evaluated the effects of partially replacing cement with commercially available BBQ coal biochar in concrete for carbon sequestration. The carbon content of biochar was found to be 32.20%, ash content 43% and alkaline pH 9.1, indicating its suitability for carbon sequestration and low cost in Pakistan. The results showed that the bulk density gradually decreased from 2.232 g/cm³ (control) to 2.080 g/cm³ at 20% replacement and was a desirable property for non-load bearing applications. With the addition of biochar, water absorption also increased but the biochar at 5% replacement mix (BCC-5) was still within the permissible limits of 8% as mentioned in IS: 3495. It was observed that compressive strength decreased with an increase in replacement level, with BCC-5 having a compressive strength of 21.03 N/mm² at the 28 day, which is above the M20 grade requirement of 20 N/mm², with a 4.45% decrease from the control. Similarly, the flexural strength reduced from 4.44 N/mm² to 2.82 N/mm² at 20% replacement, but BCC-5 has remained at 4.04 N/mm². Thermal testing at 500°C showed that BCC-5 had a residual compressive strength of 77.75% which was very close to the control's residual compressive strength of 81.69%. The carbon sequestration potential varied from 17.73 g CO₂-equivalent block for BCC-5 to 70.90 g block for BCC-20. Finally, it was decided that the 5% BBQ biochar replacement ratio is the optimal treatment, where a good structural performance, material economy and environmental benefit are achieved.

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