Next Materials 9 (2025) 100959

Contents lists available at ScienceDirect

Next Materials

journal homepage: www.sciencedirect.com/journal/next-materials

Research article

Bamboo biochar and carbonation enhanced the compressive and flexural strength of cement mortar

Siew Choo Chin [a,b,*], Pravina K. Gunasekaran [a], Jialing Che [c], N. Anand [d], Jolius Gimbun [b,e]

[a] Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Gambang 26300, Malaysia
[b] Centre for Research in Advanced Fluid and Processes (Fluid Centre), Universiti Malaysia Pahang Al-Sultan Abdullah, Gambang 26300, Malaysia
[c] School of Civil Engineering and Hydraulic Engineering, Ningxia University, Yinchuan 750021, China
[d] Department of Civil Engineering, Karunya University, Karunya Nagar, Coimbatore 641114, India
[e] Department of Biotechnology, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu 602105, India

ARTICLE INFO

Keywords:
Bamboo
Biochar
Filler
Carbonation
CO_2 sequestration
Cement mortar
Sustainable materials

ABSTRACT

The construction industry faces growing pressure to adopt sustainable materials that enhance both structural performance and environmental benefits. This study investigates the potential of bamboo biochar as a sustainable filler to strengthen cement mortar while contributing to CO_2 sequestration. The primary objective is to evaluate the effects of bamboo biochar addition, alongside carbonation treatment, on the mechanical properties of cement mortar. The surface morphology of the biochar was characterized using scanning electron microscopy, while mortar mixes with varying water-to-cement (w/c) ratios (0.45–0.55) and biochar dosages (2 %–8 %) were prepared. Flowability, compressive, and flexural strength tests were conducted on samples cured for 7–56 days, with a control mix for comparison. Results revealed that a 6 % biochar addition with a w/c ratio of 0.45 yielded optimal performance, achieving compressive and flexural strengths of 46.98 MPa and 9.60 MPa, respectively. Carbonation further enhanced these strengths by up to 24 % and 9 %, while biochar incorporation increased CO_2 sequestration by 53 % compared to the control. These findings demonstrate that bamboo biochar not only improves mechanical strength through mechanisms such as internal curing, filler effect, nucleation, and improved interfacial bonding but also contributes to carbon capture. This dual benefit underscores its significance as a promising material for sustainable and resilient construction practices.

1. Introduction

Inert or low-reactivity waste biochar additions have drawn particular attention in response to the growing need for alternative additives [1]. Mineral powders like fly ash and blast-furnace slag are often used as fillers in cementitious materials to alter the material's rheology, enhance its physical characteristics, or lower production costs [2]. However, the restricted supply of fly ash and blast-furnace slag by the year 2050 will account for less than 20 % of the world's cement needs [3]. It is anticipated that by 2050, the total yearly consumption of cement will have increased to 4.68 Gt from 4.13 Gt in 2016 [4]. As the demand for cement increases, the conventional carbon dioxide (CO_2) emission reduction measures used by the cement sector will not be adequate to guarantee the requisite mitigation. Thus, professionals in the cement industry have concluded that using environmentally hazardous carbon capture and storage (CCS) is an inevitable solution [5]. Biochar has been discovered to possess a porous structure, a large specific surface area, and a strong attraction for nonpolar molecules, rendering it a novel CO_2 adsorbent [6–8]. Biochar produced thorough biomass pyrolysis at anaerobic conditions or under low oxygen presence [9]. Because of its characteristics and effectiveness in storing carbon dioxide, biochar is now considered a potential material for use in the building sector [10]. Researchers have been exploring alternative filler materials with a smaller carbon footprint and eco-friendliness over the past few years [11]. Significant interest focuses especially on the application of biochar as a filler in cementitious materials to improve the material's durability and strength [2].

The composition of biochar, the size of the particles, and the water-to-cement ratio, is known to affect the material strength [12]. Rodier et al. [13] found that addition of 2 % sugarcane biochar as filler somewhat reduced the mortar strength. The author further explained that after curing, the mortar's high-water content increases porosity. Given

* Corresponding author at: Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Gambang 26300, Malaysia.
E-mail address: scchin@umpsa.edu.my (S.C. Chin).

https://doi.org/10.1016/j.nxmate.2025.100959
Received 31 March 2025; Received in revised form 7 July 2025; Accepted 15 July 2025
Available online 22 July 2025
2949-8228/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

the inverse relationship between porosity and mechanical characteristics, the high porosity cementitious material has poor results. However, several authors with various types of biochar reported an increment in mortar's mechanical properties at certain biochar addition (Table 1). For instance, the research on wood sawdust [2,14–16] showed an enhancement in mechanical properties with an addition of 0.5–2 %. Gupta and Kua [2] studied the effect of particle size when biochar used as fillers reported an improvement in compressive and flexural strength using 1–2 % of ground biochar. According to Danish et al. [11], owing to the greater capacity to absorb water, the propensity to lower the water-to-cement (w/c) ratio, and compaction impact, micro-sized biochar particles are better than nano-sized ones. Furthermore, Dixit et al. [17] who studied different particle sizes of biochar concluded that the greatest effect was shown with fine biochar at 5 % addition. This may be due to the inhibition of macropores formation by the fine biochar resulting in a hardened mortar with greater compaction and improvement in the efficiency for stress transfer under load [15]. Apart from sawdust biochar, there are also other biochars like coffee powder [14], bamboo [18], and rice husk [19], which are reported as having an increase in mechanical strength when applied at the optimum dosage. It has to be noted that the amount of biochar addition that correspond to increase in mortar strength differs according to the type feedstock and the conditions of processing to produce the biochar [14]. Most of the researchers had stated to have an optimal dosage of $<$ 5 % biochar addition yielded a better mechanical property, but addition of $>$ 5 % biochar filler is seldom reported to increase the compressive and flexural strength of cement. For example, a study on corn stover biochar reported an optimum of 6 % dosage due to the particle size [20]. Praneeth et al. [20], explained that the particle size has a stronger strengthening effect than pozzolanic action which can function as a self-curing agent and nucleation site for C-S-H gels. Biochar's filler impact is observed to be able to outweigh its pozzolanic effect [21].

The water-to-cement ratios may affect the strength of cement mortar. Cement mortar's workability can be improved by increasing the amount of water addition with increasing amount of biochar use [22]. The capacity of the added biochar to absorb water helps to maintain higher levels of free water in the mortar's porous structure, which explicates the lessening in flowability [12]. Choi et al. [23] showed that flowability reduces as the percentage of biochar added to cement mortar increases. This is due to presence of carbon in the biochar which has a porous microstructure and ability to hold water. Cuthbertson et al. [22] suggested increasing the w/c ratio from 0.4 to 0.48 for 1.5 g of biochar added to 10 g of cement. However, Maljaee et al. [12] on the other hand stated that irrespective of the water-to-cement ratio, biochar addition as a filler in cement mortar has been linked to more pronounced effects on the mortar's early strength. In conclusion, more investigation is needed attributing to the w/c ratio and mechanical properties by altering various parameters like type of feedstocks, size of pores, etc. [11].

The carbonation of concrete is beneficial as it functions as a form of carbon sequestration. Additionally, concrete carbonation may enhance its strength [24]. Carbon dioxide can diffuse into the porous structure of concrete, where it reacts with calcium hydroxide from cement hydration to form calcium carbonate [25]. The formation of calcium carbonate enhances concrete strength and hardness. Furthermore, carbonation improves the durability of concrete by reducing porosity, making it more resistant to freeze-thaw cycles and cracks [26].

Table 1
Different percentages of biochar used as filler.

Type of biochar	Percentage (%)	Ref
Mixed wood sawdust	0.25,0.50,1,2	[2]
Sugarcane bagasse	2	[13]
Coffee powder and hazelnut shells	0.5,0.8,1	[14]
Mixed wood sawdust	1,2,5,8	[15]
Mixed wood sawdust	2	[16]
Rice husk	10,20,30,40. (+ cenosphere)	[19]
Woodchips	0.8,1,1.5,2,2.5	[27]
Softwood	0.8,1	[28]

Carbon-rich bamboo biochar may enhance concrete carbonation, leading to increased carbon dioxide uptake and improved concrete strength. This effect is realized through increased CO_2 absorption capacity, faster carbonation kinetics, and improved microstructure and durability. Biochar possesses high porosity and surface area, providing more sites for CO_2 adsorption. The presence of micropores in biochar allows it to store and retain CO_2 more effectively, facilitating more efficient CO_2 diffusion into concrete [29]. These characteristics of biochar may accelerate the carbonation process. However, excessive biochar addition (>10 %) may reduce concrete strength due to its water absorption properties. In contrast, a small amount of biochar (<5 %) can aid in enhancing concrete carbonation.

Although various studies have investigated the incorporation of biochar in cementitious materials, research specifically focused on bamboo biochar remains limited. Notably, Ahmad et al. [18] and Liu et al. [30] examined the potential of bamboo biochar to enhance the mechanical performance of cement-based materials, reporting improvements in flexural and compressive strength, respectively. However, neither study addressed the carbon dioxide sequestration potential of cement mortar containing bamboo biochar. Furthermore, essential properties such as density and water absorption of bamboo biochar-modified mortar have yet to be reported. These parameters are critical for determining concrete classification and understanding the influence of biochar on cement hydration and strength development. In this study, waste bamboo biochar derived from bamboo charcoal production is utilized as a filler in cement mortar. Bamboo is a fast-growing, renewable resource with mechanical properties comparable to conventional structural materials [31]. The aim is to enhance the mechanical properties of mortar while contributing to carbon capture, supporting the United Nations Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action) and SDG 11 (Sustainable Cities and Communities). Given the limited application of bamboo biochar as a filler in cement mortar, this research further investigates its use, focusing on optimizing mix design through varying biochar dosages and water-to-cement (w/c) ratios. Additionally, carbonation studies are conducted to assess the CO_2 sequestration potential of bamboo biochar in cement mortar.

2. Materials and method

2.1. Biochar preparation

Bamboo, a by-product of building material from Tadom Hill Resort in Banting, Selangor, was used to produce biochar through a pyrolysis process, as illustrated in Fig. 1. The bamboo was subjected to pyrolysis for five hours at a temperature of up to 600 °C in a retort under restricted oxygen conditions. Subsequently, the resulting bamboo biochar was shredded using a shredding machine. The shredded biochar was then ground at 1500 rpm in a rotary ball mill containing 27 agate balls. To achieve a finer particle size, the biochar was sieved using a $<$ 37 μm mesh sieve following the grinding process. The acid or alkaline nature of the bamboo biochar was analysed using a Hammett indicator.

2.2. Cement and sand

All mortar mixes in this study were prepared using Ordinary Portland Cement (OPC) Type I, in accordance with ASTM C150. The particle size of OPC typically ranges from 1 to 50 μm μm [31]. Locally available natural river sand was used as the fine aggregate, with a sand-to-cement ratio of 2.75:1 [7]. The sand was oven-dried at 110 °C for 24 h prior to casting to eliminate moisture and ensure accurate determination of the sand-to-cement ratio. The fine aggregate used consisted of natural river sand with a particle size distribution compliant with ASTM C33. The

Fig. 1. Bamboo biochar process flow using pyrolysis method.

sand particles were smaller than 2.36 mm, with a fineness modulus of 2.54 and a specific gravity of 2.65.

2.3. *Water-to-cement cement ratio*

The water-to-cement (w/c) ratios selected for this study were 0.45, 0.50, and 0.55. These ratios were determined based on the results of a flowability test conducted in accordance with ASTM C1437. Trial mixes with w/c ratios of 0.35 and 0.40 exhibited flow percentages of 75 % and 80 %, respectively. However, these mixes were found to be very stiff and difficult to cast. Therefore, the w/c ratio range was set between 0.45 and 0.55 to ensure adequate workability.

2.4. *Mix design*

The specimens for the compressive strength test were prepared using cube-shaped moulds with dimensions of 50 mm × 50 mm × 50 mm, in accordance with ASTM C109. Similarly, specimens for the flexural strength test were prepared using prism-shaped moulds (40 mm × 40 mm × 160 mm) following ASTM C348. Table 2 presents the mortar mix designs incorporating bamboo biochar as a filler, with biochar contents ranging from 0 % to 8 % and water-to-cement (w/c) ratios of 0.45, 0.50, and 0.55, respectively.

The mortar samples were mixed using a Hobart mixer. The dry materials—cement, biochar, and sand—were mixed for approximately one minute before water was added. Mixing continued for an additional two minutes. The fresh mortar was then poured into the moulds placed on a vibrating table. Vibration continued for approximately one minute, or until surface bubbling diminished. The specimens were demoulded after 24 h and subsequently water-cured for 7, 14, 28, and 56 days prior to mechanical testing. A total of 216 cubes and 216 prisms were cast to ensure triplicate specimens for each mix design.

Table 2
Mix design of bamboo biochar as filler in mortar.

Percentages (%)	Cement (g)	Sand (g)	Water/cement 0.45, 0.50, 0.55	Biochar (g)
0	2970	8200	1340, 1485, 1635	-
2	2970	8200	1340, 1485, 1635	59.4
4	2970	8200	1340, 1485, 1635	118.8
6	2970	8200	1340, 1485, 1635	178.2
8	2970	8200	1340, 1485, 1635	237.6

An initial screening was conducted to evaluate the influence of water-to-cement (w/c) ratio and biochar content on the compressive and flexural strength of the mortar. The results indicated that a w/c ratio of 0.45 combined with 2 % biochar yielded the highest compressive and flexural strength. However, mortar samples incorporating 1–3 % biochar also demonstrated promising mechanical performance. Consequently, these compositions, along with a control mix without biochar, were selected for further evaluation under accelerated carbonation conditions.

2.5. *Flowability test*

The water-to-cement ratio was evaluated using a flow table test in accordance with ASTM C1437. A mould with a thickness of 25 mm was placed at the center of the flow table, which had been cleaned and dried beforehand. The mortar was filled into the mould in three layers, with each layer tamped 25 times using a tamping rod, applying sufficient pressure to ensure uniform compaction. Excess mortar was then removed using a straight edge, leaving the surface flush with the top of the mould. The mould was carefully removed, and the tabletop was raised and dropped 25 times within 15 s from a height of 12.5 mm. The resulting spread diameter of the mortar was measured using a measuring tape.

2.6. *Measurement of density and water absorption*

The density and water absorption of the cement mortar was measured according to ASTM C642. Initially, the cement mortar was dried at 110 °C to remove moisture content then weighed with analytical balance for its dry weight. The specimen is then immersed in water container that can measure changes in volume accurately up to ±0.1 mL. The container is subjected to sonication to remove trapped bubble. The changes in the water volume are recorded for density calculation. For the case of water absorption, the sample is immersed in water until saturated for 48 h before weighed again. The weight of the dry and saturated sample was compared to determine the water absorption.

2.7. Surface morphology, composition and mechanical test

The surface morphology of bamboo biochar was examined using a scanning electron microscope (SEM) (JSM-IT200, Jeol). Imaging was conducted at an accelerating voltage of 10 kV, with magnifications of 100×, 500×, and 1000×. Elemental analysis of the bamboo biochar was carried out using X-ray fluorescence spectroscopy (XRF) (ZSX Primus II, Rigaku). The compressive strength test was conducted using a compression testing machine (CTM) in accordance with ASTM C109, while the flexural strength was measured following ASTM C348 using a manual flexural testing machine. Prior to mechanical testing, dust and debris were removed from the machine's base plate. All tests were performed in triplicate, with the average values reported and the standard deviations presented as error bars.

2.8. Sample carbonation and analysis

The carbonation of the specimens was carried out in a hermetically sealed Perspex box, similar to the setup described by Gupta et al. [7]. The samples were exposed to carbon dioxide in the carbonation chamber for 28 and 56 days. Fig. 2 illustrates the configuration of the carbonation chamber. The samples were placed inside the chamber, which was hermetically sealed after the introduction of pure CO_2. The pressure within the chamber was maintained at 15 kPa, monitored using a pressure gauge connected to both the CO_2 tank and the chamber, in accordance with ASTM C1910. Following carbonation, the samples were subjected to phenolphthalein testing and thermogravimetric analysis (TGA).

The phenolphthalein indicator was used to assess the carbonation depth in accordance with ASTM D1093. Upon completion of the designated curing periods, the mortar cubes carbonated for 28 and 56 days were removed from the chamber. The cubes were then split in half, and phenolphthalein solution was sprayed onto the freshly exposed cross-sectional surfaces. A measuring tape was used to determine the carbonation depth. This method evaluates the extent of carbonation, defined as the reaction of CO_2 with calcium hydroxide ($Ca(OH)_2$) in the cement matrix to form calcium carbonate ($CaCO_3$). Understanding carbonation depth is essential for evaluating the durability and CO_2 sequestration potential of cementitious materials such as concrete and mortar. In addition, mortar samples before and after carbonation were subjected to thermogravimetric analysis (TGA) using a Hitachi STA7000 series instrument. The prepared samples were placed in a crucible and heated from 20 °C to 1000 °C at a constant heating rate of 10 °C/min under a nitrogen gas atmosphere. Carbonated samples were also tested for compressive strength.

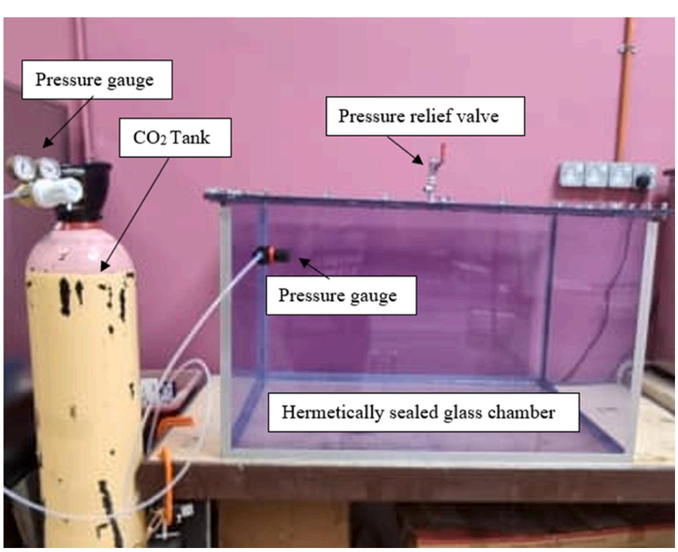

Fig. 2. The carbonation chamber.

3. Results and discussion

3.1. Surface morphology and mineral compositions

The morphology and pore structure of biochar was analysed using SEM before and after size reduction (Fig. 3). Initially the most of the biochar particles has a size below 100 µm, however upon grinding and sieving most of the particles are below 3 µm. This shows that the biochar typically has a low particle size range after pyrolysis. However, there a few particles found to have more than 100 µm, which had been reduced through the grinding and sieving process. A similar result on bamboo biochar particles has also been reported by several other authors [30,32, 33]. The irregular structure and rather smooth surface of the particles are reminiscent of other forms of biochar that are stated to function well as an interlocking agent in cement composites [34–36]. Additionally, the particles have visible honeycomb-like features and a porous microstructure in the arrow shown in Fig. 3a. When organics and volatiles are produced during the pyrolysis process, pores and honeycomb-like structures are formed. These structures can absorb water and provide mortar and concrete a self-curing effect [30,36]. Besides that, the material's textural and porous nature is said to be favourable for the capture of CO_2 [37,38].

Table 3 shows the elemental composition of bamboo biochar obtained from XRF analysis. The results showed the composition of the bamboo biochar is largely carbon (60.2 %), with oxygen accounting for the second-highest percentage (32.8 %), indicating a very stable biochar. According to ASTM C618, a material must have at least 70 % silicon dioxide (SiO_2), aluminium dioxide (Al_2O_3) and iron dioxide (Fe_2O_3) overall to be designated as class N pozzolan. Bamboo biochar is suitable to be used as filler in cementitious material owing to its lower content of oxides, according to Gunasekaran and Chin [39]. Several other authors who studied plant-based biochar also concluded that biochar is more suitable to be used as filler [40–42]. However, there are also some authors have said that plant-based biochar poses some pozzolanic activity [30,43]. It has to be noted that not all plant is rich in siliceous content, but there is exception for instance for the like of rice husk and bamboo leaves. High silica content in cementitious materials is generally associated with increased compressive strength of cement mortar [44,45]. The mineral composition of the plant material used for biochar production influences its behavior as either an inert filler or a reactive pozzolan. For bamboo biochar, the presence of SiO_2 and Fe_2O_3 indicates potential pozzolanic activity, suggesting it acts as a partially reactive filler within the cement matrix.

A pH measurement of the biochar using a Hammett indicator revealed an alkaline nature, with pH values ranging from 8.2 to 10. Although accurately determining the pH of solid samples is challenging, the Hammett indicator provides a reliable qualitative assessment. The bamboo biochar was confirmed to be alkaline, which may promote cement hydration and, consequently, improve mortar strength. Cement hydration is the fundamental mechanism responsible for strength development in mortar, driven by the reaction of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) in the cement with water to produce calcium silicate hydrate (C-S-H) gel.

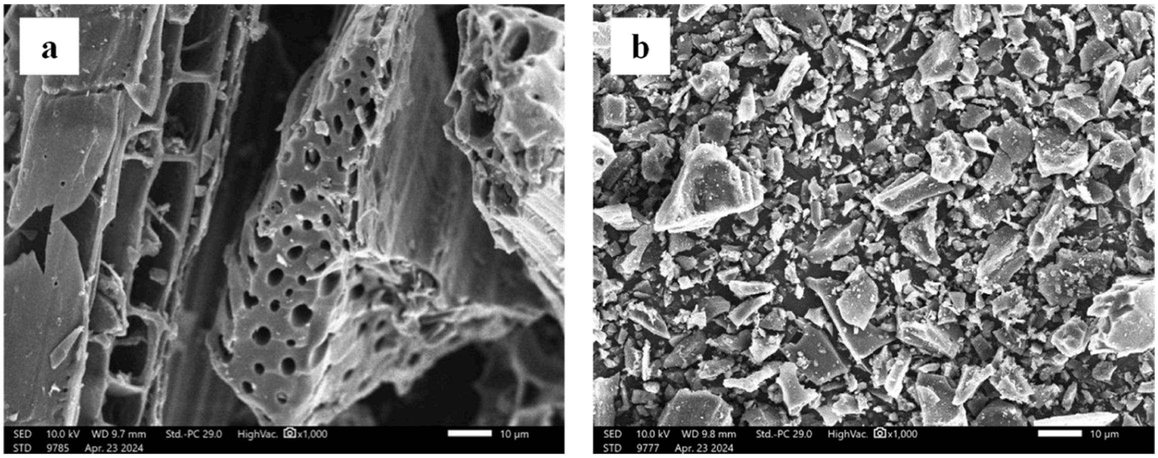

Fig. 3. Surface morphology of bamboo biochar after the pyrolysis process. a) Before grinding, b) After grinding and sieving.

Table 3
Elemental composition of bamboo biochar.

Element	Weight (%)
C	60.2
O	32.8
K	2.41
Si	0.99
Fe	1.66

Table 4
Flowability of different w/c ratios of fresh cement paste.

Biochar content (%)	Flowability (%)		
	0.45 w/c	0.50 w/c	0.55 w/c
0	125	128	130
2	124	127	129
4	117	120	125
6	113	116	121
8	105	114	117

3.2. *Flowability test*

Fig. 4 shows the flowability test graph of different w/c ratios (0.45, 0.50, 0.55) for various percentages of biochar dosage in mortar. The overall result shows that the flowability of the fresh cement paste decreases as the dosage increases. This is because the carbon in the biochar has a water-retention capability and a porous microstructure [23]. The flow trend is also noted to increase for each percentage as the w/c ratio increases. As shown in Table 4, the highest flow for 0.55 w/c ratio of 0 % and 2 % is 130 % and 129 % respectively. This comparison shows that there are very minimal differences between the control sample and the 2 % dosage compared to the other dosages of biochar. As the w/c ratio decreases with the increased dosage percentages, the flow decreases. However, the overall flow is also observed to be within the standard range of 110 ± 5 % [46] from 2 % up to 8 %. Thus, a given dosage of biochar with an adequate w/c ratio did not affect the fluidity of the mixture.

3.3. *Compressive strength*

The results of the compressive strength tests for various percentages with 0.45 w/c ratio are presented in Fig. 5. The early strength of all percentages is slightly lower than the control sample (29.36 MPa). The highest early strength was contributed by 2 % (26.23 MPa) and 8 % (25.96 MPa). A similar result was denoted by Praneeth et al. [20] which also had the highest increment on early strength with 2 and 8 % corn stover biochar substitution. This indicates there is a slight improvement of early strength upon the addition of biochar. The biochar's small particle size and water retention ability, which can have a filler effect and reduce the local water-cement ratio near biochar particles, respectively, are responsible for this increase in early strength. As for the

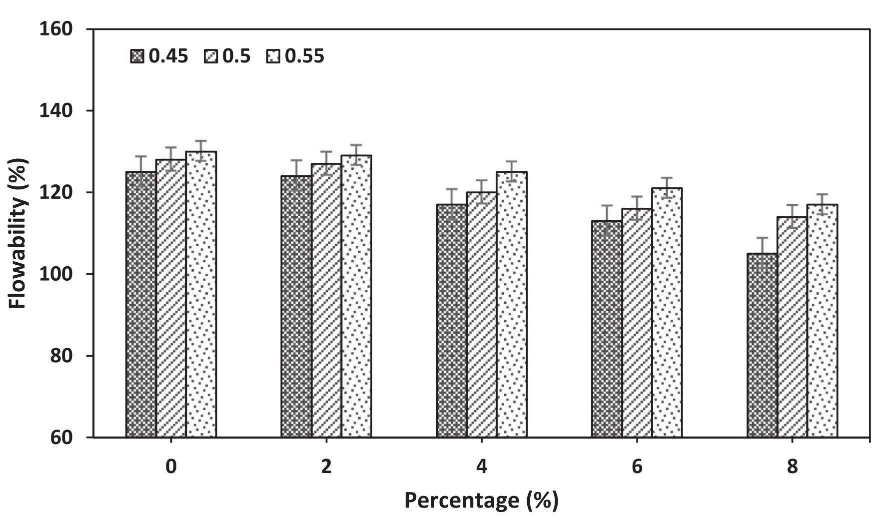

Fig. 4. Effect of biochar content on cement paste flowability.

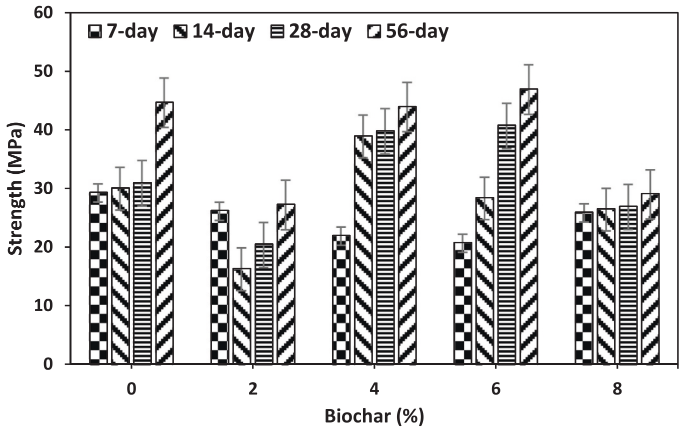

Fig. 5. Compressive strength for 0.45 w/c ratio.

28-day strength, 6 % shows the highest strength followed by 4 % with 40.79 MPa and 39.86 MPa respectively compared to the control sample (31 MPa). The strength seems to be reduced at 8 % which may be due to the diluting effect [47] as the addition of biochar increases. Liu et al. [30] stated that the addition of a high amount of biochar can lead to a significant decrease in hydration which causes it to lose strength. On 56 days after curing, the overall trend increases for all percentages. A similar trend was reported by Gupta and Kashani [40] when investigating the compressive strength up to 56 days. The 4 % show slightly lower strength with 43.99 MPa compared to the control sample (46.15 MPa). This can be because of the addition of a small amount of biochar which causes fewer amounts of C-S-H gel formation. The highest percentage is also for 6 % dosage with 46.98 MPa which shows a slight increase of 1.8 % compared to the control sample.

The compressive strength for a w/c ratio of 0.5 is shown in Fig. 6. This graph also shows an upward trend in the majority of the dosage. The early strength is the same as the 0.45 w/c ratio with 2 and 8 % showing the highest. However, the strength for all percentages is slightly lower than the control sample. For 28-day and 56-day the trend of strength is similar. A small reduction in 2 % addition can be seen before increasing back to 4 %. The improvement of strength at 4 % is because the packing (or filling effect) is improved at this percentage compared to the earlier and later content of biochar [48]. The strength then continues declining at 8 % addition. The highest strength is noted to be on 56 days of curing for 6 % dosage with an improvement of 11.78 % compared to the control sample. The overall strength of this mixes with 0.5 w/c result however is lesser than 0.45 w/c ratio mixes. This occurs because of the increase in the w/c ratio which causes the reduction in strength [49].

In Fig. 7, the compressive strength for 0.55 w/c ratio is depicted. The overall strength depicts the least values compared to 0.45 w/c and 0.50 w/c ratio. As aforementioned, this graph also shows a majority of upward strength. It can also be noted that the strength for all percentages increases from 7 days of curing up to 56 days of curing. Even though all values up to 56 days are in increasing trend the results produced are slightly lower than the control sample. Also noticed that the early strength of 2 % is higher and tends to drop on day 14 before increasing back again on the following days. According to a study on the impact of admixture on strength, adding more admixture content slows down the reaction, increases workability, and decreases compressive strength [50]. In conclusion, after comparing all the results for strength and w/c ratio, 6 % dosage with 0.45 w/c ratio is observed to be the best result even though the enhancement in terms of compressive strength is not significant.

3.4. Flexural strength

The flexural strength of 0.45 w/c is presented in Fig. 8. The figures show an upward trend in all curing days for all percentages of biochar. As for the early strength, all percentages were lower higher than the control sample except 4 % dosage with 7.77 MPa. However, as the curing days increase, the strength also seems to increase. At 28 days, the highest strength was depicted by 6 % with 9.32 MPa compared to the control sample with 8.46 MPa. The trend is also similar at 56 days of curing. The strength of 6 % depicts the highest strength with 9.60 MPa compared to the control sample with 9.17 MPa on 56 days. An increment of 2.3 % is observed. This shows that the biochar added has the filler effect which fills in the cement matrix for better packing upon adding up to 6 %. Gupta and Kua [19] also stated that biochar causes a micro-filler effect because of the smaller particle size inducing the micro-filler effect due to its fine particle size distribution. The strength starts reducing after adding 6 % which had been explained to be due to the formation of air voids and pores during the flexural test upon the addition of extra biochar which causes the tensile plane to open up and eventually reduces the energy required for crack propagation and the flexural load bearing capacity [50]. There is a slight drop in 4 % dosage before the strength gains back to 6 % dosage. This could be due to the effect of the type of biochar used in this study as the same slight reduction had been noticed in compressive strength as well. The reduction is observed to be not significant as it is in a very minimal

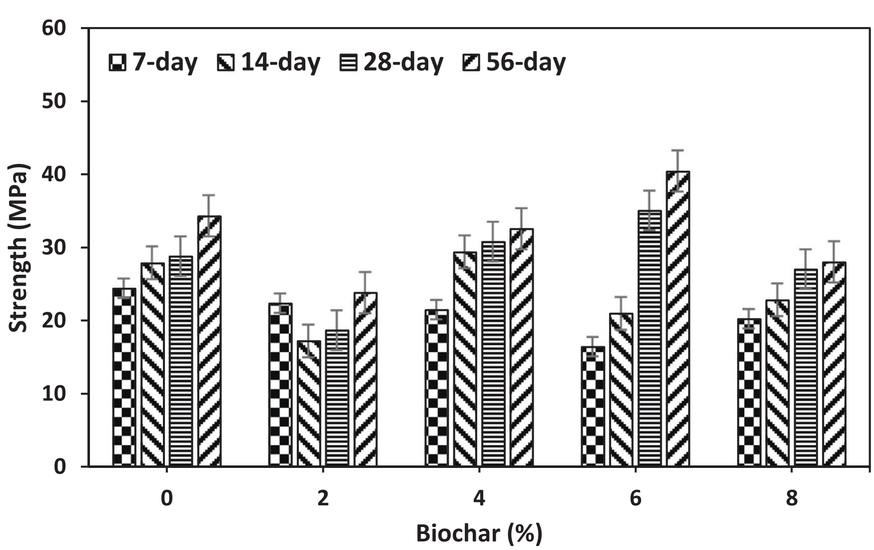

Fig. 6. Compressive strength for 0.50 w/c ratio.

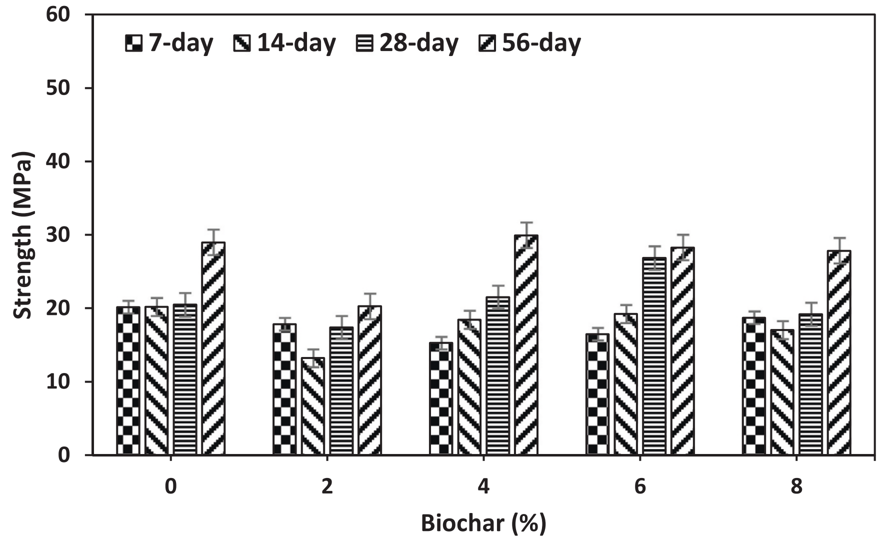

Fig. 7. Compressive strength for 0.55 w/c ratio.

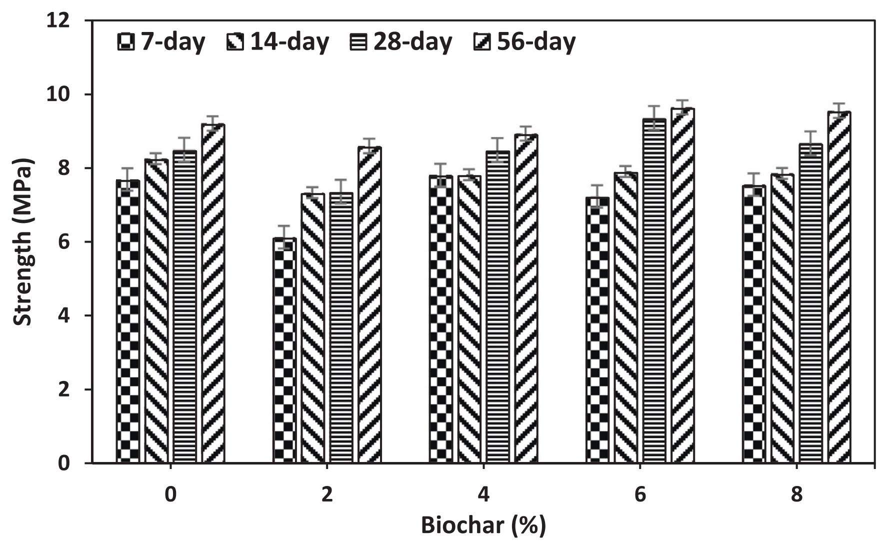

Fig. 8. Flexural strength for 0.45 w/c ratio.

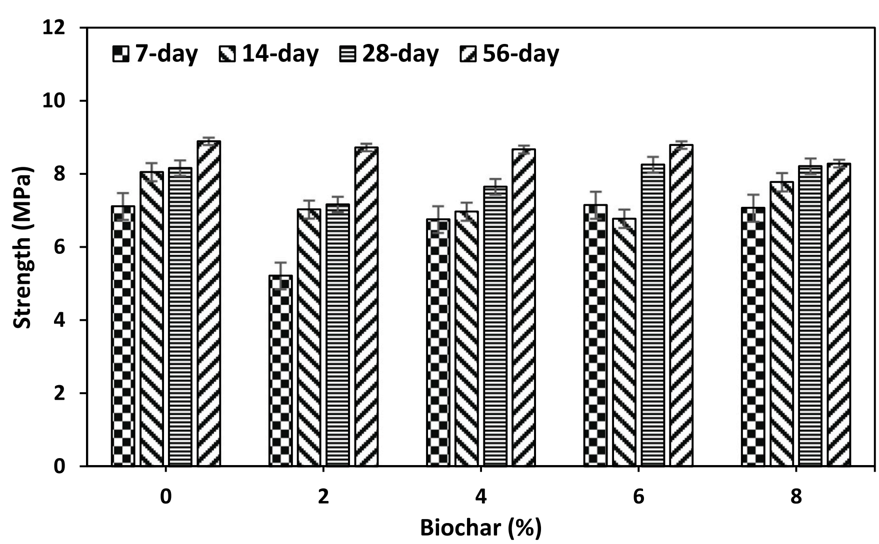

Fig. 9. Flexural strength for 0.50 w/c ratio.

percentage difference. The overall strength comparing all days, however, shows a reduction after 6 % dosage which shows that 6 % can be the optimum percentage of dosage to be added as filler.

The 0.5 w/c ratio for the flexural strength test is shown in Fig. 9. It can be seen that the overall early strength for all dosages is also slightly lower than the control sample. The strength shows an upward trend on 28 days of curing. The highest dosage was 6 % (8.25 MPa) followed by 8 % (8.21 MPa). There was a 0.5 % and 5.5 % increment respectively. On 56 days of curing, the highest strength dosage was 6 %. Even though 6 % tends to record a reduction when compared to the control sample it is not a significant decrease as it is only 0.57 %.

The graph of 0.55 w/c ratio for flexural strength is shown in Fig. 10. The trend is typically the same with 0.45 w/c and 0.5 w/c with an upward trend from 7 days of curing until 56 days of curing for all percentages. The highest percentage to be noted is 6 % with 8.74 MPa compared to the control sample with 7.51 MPa on 56 days. The strength was also noted to decrease after the addition of 6 % dosage which shows that the strength reduces upon the addition of biochar despite the w/c ratio used. The increase in strength for the 0.55w/c ratio is also not significant as it is slightly lower than the other w/c ratio. Overall, these w/c ratio shows a much lower strength compared to 0.45 and 0.50 w/c. This is due to the higher w/c ratio used which causes it to fall in the lower range [22]. To sum up, the strength is noted to decrease as the w/c ratio increases due to the increase in workability of the mortar which causes the reduction in strength. It is also not a significant increase in terms of flexural strength but still an optimal 6 % dosage of bamboo biochar with a 0.45w/c ratio can be used as filler in cement mortar. A higher strength of bamboo biochar is produced at a ratio of 0.45w/c, which ensures an efficient balance between cementitious materials and water content [51].

3.5. Mortar density and water absorption

The control cement mortar exhibited a density of 2416.5 kg/m^3, whereas the mortar containing 8 % bamboo biochar had a reduced density of 2206.9 kg/m^3 as shown in Fig. 11. A clear decreasing trend in mortar density was observed with increasing biochar content, attributed to the lower density of biochar compared to sand. Consequently, higher biochar content results in a lighter mortar; however, the mixes in this study do not meet the criteria for classification as lightweight concrete (< 1900 kg/m^3).

Water absorption in cement mortar incorporating bamboo biochar was higher than that of the control mix (6.76 %) as shown in Fig. 11. The highest water absorption was observed from the mortar containing 8 % biochar (10.21 %). This increase is primarily due to the porous structure of biochar, which introduces additional internal surface area and capillary pathways, promoting water retention and absorption. The enhanced water absorption may contribute to improved hydration processes, particularly the formation of calcium silicate hydrate (C-S-H)

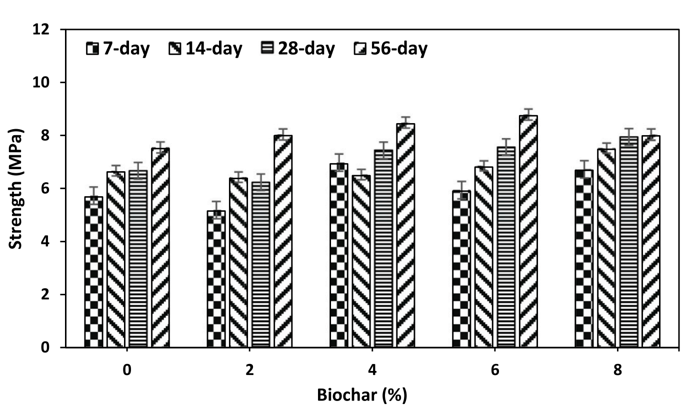

Fig. 10. Flexural strength for 0.55 w/c ratio.

gel, which likely explains the observed improvement in compressive strength in biochar-modified mortars. However, it should be noted that, at higher biochar content (>6 %) the mortar strength is negatively affected due to increase in porosity, reduction in matrix continuity and dilution effect.

3.6. Carbon sequestration and cement mortar strengthening

The carbonation depth can be easily assessed using the phenolphthalein test, which allows for a simple observation of the depth and rate of qualitative carbonation. The phenolphthalein solution indicates the degree of carbonation by turning the uncarbonated part of the mortar bright pink (pH > 12), the semi-carbonated part light pink, and the completely carbonated part colourless (pH < 9). The carbonation process lowers the pH of the cement mortar, creating a distinct colour gradient. As carbonation starts at the surface of the mortar specimens and gradually progresses toward the centre of the cubes, the outermost layer becomes colourless. As additional calcium carbonates form on the surface of the mortar, it becomes more difficult for CO_2 to penetrate deeper into the material [52,53]. The result in Fig. 12 shows that addition of bamboo biochar increased the carbonation depth by about 53 % from 21.1 % to 32.2 % for the sample without biochar and with 3 % biochar, respectively after 56 days. The carbonation depth is directly proportional to the CO_2 sequestration by the mortar sample. The result from this work implies that addition of 3 % bamboo biochar significantly increases the CO_2 sequestration potential of the cement mortar. The biochar addition was capped at 3 % for carbonation test, since the sample containing 3 % biochar become nearly colourless after 56 days, indicating that it has reached full carbonation.

The results of the carbonation depth calculations for 28 days and 56 days demonstrate a clear trend, whereby the carbonation depth increases over time for all samples. The greatest carbonation depth was achieved from the sample containing higher biochar addition. This is consistent with the natural progression of carbonation in cementitious materials, where CO_2 continues to penetrate deeper into the material as time passes, a well-documented phenomenon in cement-based materials [11]. The control sample without biochar addition had no measurable carbonation at 28 days, which is common for early carbonation stages, while the biochar samples started showing noticeable carbonation depths. The sample containing 3 % biochar showed the highest carbonation depth (12.47 mm) at 28 days, suggesting that a higher biochar content enhances the carbonation process due to its increased surface area and ability to absorb CO_2. Biochar has a porous structure that provides more surface area for CO_2 to interact with, which accelerates the carbonation process [7]. Bamboo biochar, in particular, can absorb CO_2, making it an effective material for carbon sequestration in construction [54]. This ability of biochar to absorb CO_2 contributes to the sustainability of cementitious materials by reducing their overall carbon footprint [55].

At 56 days, the carbonation depths increased significantly, as shown in Fig. 12. The carbonation depth continued to increase over time, with control sample (0 % biochar) showing a carbonation depth of 16.2 mm, reflecting the continued absorption of CO_2 into the material. This result shows that cement on its own contains ample porous structure that enable CO_2 adsorption to reach with calcium hydroxide to form calcium carbonate. However, presence of bamboo biochar enhanced the carbonation by having a greater CO_2 absorption capacity and faster carbonation kinetics. Biochar possesses high porosity and surface area, providing more sites for CO_2 adsorption. The presence of micropores in biochar allows it to store and retain CO_2 more effectively, facilitating more efficient CO_2 diffusion into concrete [29], resulting in a faster carbonation process. It can be observed from the carbonation depth, that the sample containing 3 % biochar exhibited the highest carbonation depth (32.2 mm) at 56 days. The sample containing 1 and 2.1 % of biochar showed higher carbonation depth compared to the control sample, but ultimately lower than the sample with 3 % biochar. This

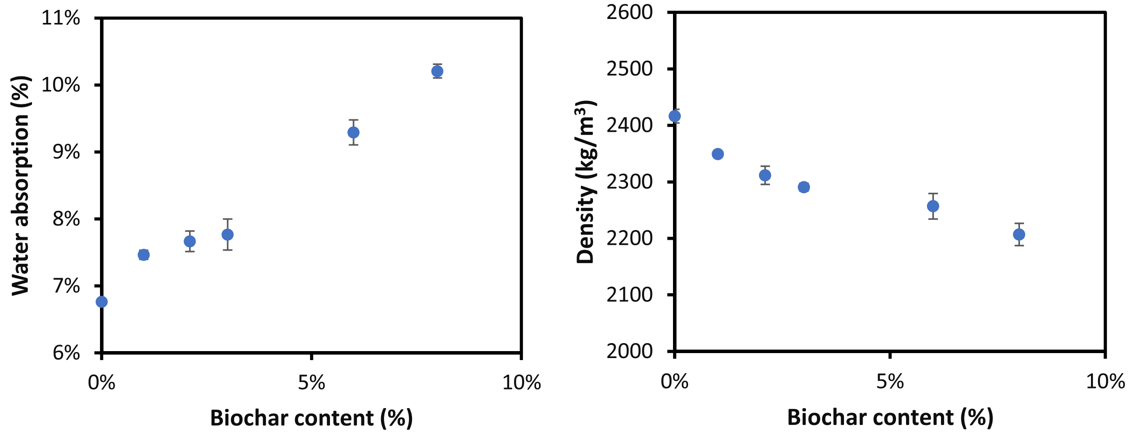

Fig. 11. Density and water absorption of cement mortar.

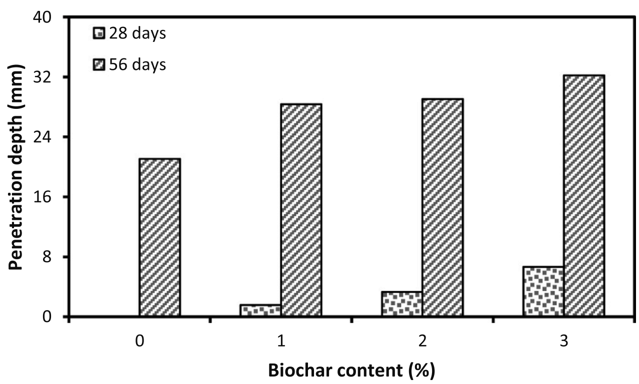

Fig. 12. Qualitative CO_2 sequestration from phenolphthalein test.

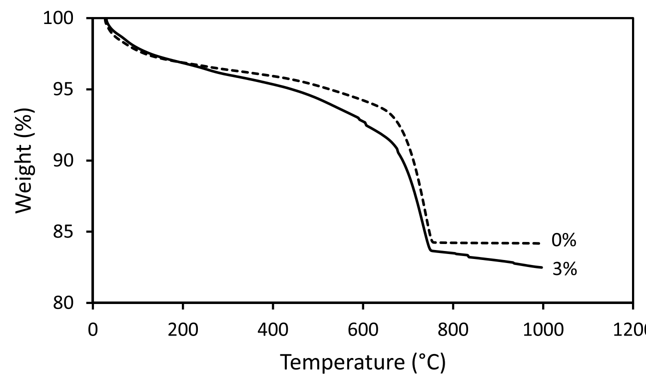

Fig. 13. Thermogravimetric analysis of sample containing 0 % biochar (control) and 3 % biochar after 56 days of carbonation.

suggests that 3 % biochar is the most effective in promoting carbonation over time, owing to its ability to provide more reactive sites for CO_2 absorption, which is similar to the trend observed in other studies involving biochar in concrete [20].

The 3 % biochar sample consistently showed the best results in both 28-day and 56-day carbonation depth measurements, demonstrating that higher biochar content enhances the carbonation process. Bamboo biochar, in particular, has the potential to absorb significant amounts of CO_2, contributing to the carbon sequestration potential of cementitious materials [54,56]. This finding is comparable to the work by Mishra et al. [29], which emphasized the role of biochar in accelerating carbonation and CO_2 sequestration in cement-based materials. Biochar not only improves the material's sustainability by enhancing its CO_2 absorption capacity but also contributes to long-term environmental benefits through carbon sequestration.

The thermogravimetric analysis can somehow reveal the level of carbonation in cement mortar as carbonates loss mass during heating, as the CO_2 is released. During heating calcium carbonates starts to decompose into calcium oxide and carbon dioxide at around 600 °C and the decomposition is complete at about 750 °C [57]. It can be observed from the TGA result in Fig. 13 that, the sample with 3 % biochar has a greater weight loss compared to the control sample. This indicates a significant formation of carbonate in the cement mortar with 3 % biochar. The result from the thermogravimetric analysis confirmed the finding from the phenolphthalein test, which shows a significantly higher level of carbonation for the mortar containing 3 % biochar.

In addition to CO_2 sequestration, carbonation enhances both the flexural and compressive strength of cement mortar. The strength improvement is primarily attributed to the formation of calcium carbonate ($CaCO_3$), which contributes to increased hardness and densification of the mortar matrix. During the hydration process, the high calcium content in cement leads to the generation of calcium hydroxide ($Ca(OH)_2$), which subsequently reacts with CO_2 to form calcium carbonate. Furthermore, the incorporation of bamboo biochar increases water absorption, as illustrated in Fig. 11, promoting additional cement hydration. The increased availability of hydration products, particularly $Ca(OH)_2$, facilitates greater carbonate formation during carbonation. This mechanism explains the higher strength gain observed in cement mortar containing bamboo biochar following carbonation. Comparison was made after 56 days of carbonation between the control sample and the sample containing 3 % biochar. In term of flexural strength, the sample containing 3 % bamboo biochar has a strength of 8.3 MPa, while the control sample (0 % biochar) has 7.6 MPa. This corresponds to about 9 % increase in flexural strength upon carbonation with presence of 3 % biochar. Meanwhile, for compressive strength, the sample containing 3 % biochar has a strength of 31.4 MPa, while the control sample has the strength of 25.4 MPa. The gain in compressive strength is quite remarkable at about 24 % after carbonation with presence of 3 % biochar. The findings suggest that bamboo biochar addition to cementitious materials may have a greater potential for CO_2 sequestration, while at the same time improving cement mortar strength, making it an ideal candidate for use in sustainable construction practices.

Fig. 14 showed the tested mortar sample for both the flexural and compressive strength. It was observed that the control sample without biochar is brighter in colour compared to the ones containing biochar. The crack pattern for the mortar containing biochar and control is not significantly different, although the former has a greater mechanical

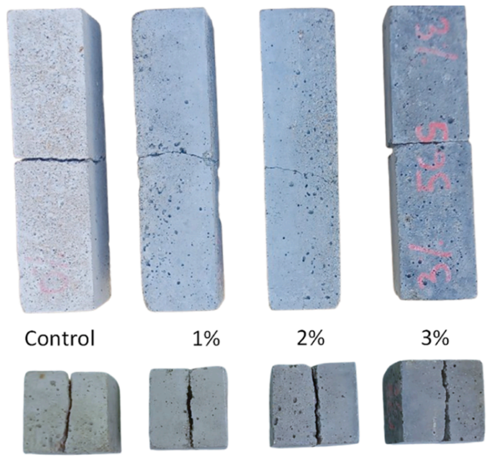

Fig. 14. Tested mortar specimen for compressive and flexural strength.

strength. The crack pattern may differ in other test such as those of strengthened concrete beam, but it was not in the scope of this work.

It is important to note that while the addition of bamboo biochar to the cement matrix enhances both mechanical strength and CO_2 sequestration capacity, incorporating more than 3 % bamboo biochar is not recommended. Exceeding this limit results in a significant reduction in the compressive and flexural strength of the cement mortar.

4. Conclusion

The bamboo biochar used in this study primarily consists of carbon, with minor amounts of iron, potassium, and silica, indicating its potential as a partially reactive filler. Mortar mixes with a water-to-cement (w/c) ratio below 0.45 were found to be too stiff for proper casting, while a w/c ratio of 0.55 improved flowability but reduced strength. The optimal mechanical performance was achieved at a 0.45 w/c ratio with 6 % biochar addition, yielding compressive and flexural strengths of 46.98 MPa and 9.60 MPa, respectively. Strength gains were most pronounced after 28 days of curing. The incorporation of bamboo biochar enhanced both compressive and flexural strength by approximately 5 % and contributed to CO_2 sequestration, as confirmed by phenolphthalein tests and thermogravimetric analysis. The highest carbonation level occurred with 3 % biochar addition, which further improved compressive and flexural strength by up to 24 % and 9 %, respectively. However, biochar contents exceeding 3 % negatively impacted mechanical performance. These findings highlight the potential of bamboo biochar to enhance strength and carbon capture in cementitious materials, supporting its use in sustainable construction. Future research should investigate the long-term durability and weathering performance of bamboo biochar-modified mortars.

Ethical approval

The authors of this work declare that they adhere to all applicable ethical guidelines and standards in the preparation and submission of this manuscript.

Funding

This research was supported by the Ministry of Higher Education Malaysia under grant number FRGS/1/2024/TK05/UMP/01/2 with UMPSA reference RDU240115. SCC and PKG are grateful to Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) for providing Postgraduate Research Grants Scheme (PGRS 2303215) and UMPSA Internal Grant RDU 223014.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The author would like to thank Dato' Lai Yeng Fock from Tadom Hill Resort for supplying bamboo biochar for this research.

References

[1] Y.C. Flores, G.C. Cordeiro, R.D. Toledo Filho, L.M. Tavares, Performance of Portland cement pastes containing nano-silica and different types of silica, Constr. Build. Mater. 146 (2017) 524–530, https://doi.org/10.1016/j.conbuildmat.2017.04.069.

[2] S. Gupta, H.W. Kua, Carbonaceous micro-filler for cement: Effect of particle size and dosage of biochar on fresh and hardened properties of cement mortar, Sci. Total Environ. 662 (2019) 952–962, https://doi.org/10.1016/j.scitotenv.2019.01.269.

[3] S.A. Miller, R.J. Myers, Environmental impacts of alternative cement binders, Environ. Sci. Technol. 54 (2019) 677–686, https://doi.org/10.1021/acs.est.9b05550.

[4] M. Schneider, The cement industry on the way to a low-carbon future, Cem. Concr. Res. 124 (2019) 105792, https://doi.org/10.1016/j.cemconres.2019.105792.

[5] V.M. John, B.L. Damineli, M. Quattrone, R.G. Pileggi, Fillers in cementitious materials—experience, recent advances and future potential, Cem. Concr. Res. 114 (2018) 65–78, https://doi.org/10.1016/j.cemconres.2017.09.013.

[6] K.G. Roberts, B.A. Gloy, S. Joseph, N.R. Scott, J. Lehmann, Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential, Environ. Sci. Technol. 44 (2010) 827–833, https://doi.org/10.1021/es902266r.

[7] S. Gupta, H.W. Kua, C.Y. Low, Use of biochar as carbon sequestering additive in cement mortar, Cem. Concr. Compos. 87 (2018) 110–129, https://doi.org/10.1016/j.cscm.2024.e03591.

[8] J. Liu, G. Liu, W. Zhang, Z. Li, F. Xing, L. Tang, Application potential analysis of biochar as a carbon capture material in cementitious composites: a review, Constr. Build. Mater. 350 (2022) 128715, https://doi.org/10.1016/j.conbuildmat.2022.128715.

[9] I. Baidoo, D.B. Sarpong, S. Bolwig, Biochar amended soils and crop productivity: a critical and meta-analysis of literature, Int. J. Dev. Sustain. 5 (2016) 414–432.

[10] A. Sirico, P. Bernardi, C. Sciancalepore, F. Vecchi, A. Malcevschi, B. Belletti, D. Milanese, Biochar from wood waste as additive for structural concrete, Constr. Build. Mater. 303 (2021) 124500, https://doi.org/10.1016/j.conbuildmat.2021.124500.

[11] A. Danish, M.A. Mosaberpanah, M.U. Salim, N. Ahmad, F. Ahmad, A. Ahmad, Reusing biochar as a filler or cement replacement material in cementitious composites: a review, Constr. Build. Mater. 300 (2021) 124295, https://doi.org/10.1016/j.conbuildmat.2021.124295.

[12] H. Maljaee, R. Madadi, H. Paiva, L. Tarelho, V.M. Ferreira, Incorporation of biochar in cementitious materials: a roadmap of biochar selection, Constr. Build. Mater. 283 (2021) 122757, https://doi.org/10.1016/j.conbuildmat.2021.122757.

[13] L. Rodier, K. Bilba, C. Onésippe, M.A. Arsène, Utilization of bio-chars from sugarcane bagasse pyrolysis in cement-based composites, Ind. Crops Prod. 141 (2019) 111731, https://doi.org/10.1016/j.indcrop.2019.111731.

[14] L. Restuccia, G.A. Ferro, Promising low cost carbon-based materials to improve strength and toughness in cement composites, Constr. Build. Mater. 126 (2016) 1034–1043, https://doi.org/10.1016/j.conbuildmat.2016.09.101.

[15] S. Gupta, H.W. Kua, S. Dai Pang, Biochar-mortar composite: manufacturing, evaluation of physical properties and economic viability, Constr. Build. Mater. 167 (2018) 874–889, https://doi.org/10.1016/j.conbuildmat.2018.02.104.

[16] S. Gupta, H.W. Kua, Effect of water entrainment by pre-soaked biochar particles on strength and permeability of cement mortar, Constr. Build. Mater. 159 (2018) 107–125, https://doi.org/10.1016/j.conbuildmat.2017.10.095.

[17] A. Dixit, S. Gupta, S. Dai Pang, H.W. Kua, Waste Valorisation using biochar for cement replacement and internal curing in ultra-high performance concrete, J. Clean. Prod. 238 (2019) 117876, https://doi.org/10.1016/j.jclepro.2019.117876.

[18] S. Ahmad, R.A. Khushnood, P. Jagdale, J.M. Tulliani, G.A. Ferro, High performance self-consolidating cementitious composites by using micro carbonized bamboo particles, Mater. Des. 76 (2015) 223–229, https://doi.org/10.1016/j.matdes.2015.03.048.

[19] S. Gupta, H.W. Kua, Application of rice husk biochar as filler in cenosphere modified mortar: preparation, characterization and performance under elevated temperature, Constr. Build. Mater. 253 (2020) 119083, https://doi.org/10.1016/j.conbuildmat.2020.119083.

[20] S. Praneeth, R. Guo, T. Wang, B.K. Dubey, A.K. Sarmah, Accelerated carbonation of biochar reinforced cement-fly ash composites: enhancing and sequestering CO2 in building materials, Constr. Build. Mater. 244 (2020) 118363, https://doi.org/10.1016/j.conbuildmat.2020.118363.

[21] C.E. Brewer, V.J. Chuang, C.A. Masiello, H. Gonnermann, X. Gao, B. Dugan, L. E. Driver, P. Panzacchi, K. Zygourakis, C.A. Davies, New approaches to measuring

biochar density and porosity, Biomass Bioenergy 66 (2014) 176–185, https://doi.org/10.1016/j.biombioe.2014.03.059.
[22] D. Cuthbertson, U. Berardi, C. Briens, F. Berruti, Biochar from residual biomass as a concrete filler for improved thermal and acoustic properties, Biomass Bioenergy 120 (2019) 77–83, https://doi.org/10.1016/j.biombioe.2018.11.007.
[23] W.C. Choi, H.D. Yun, J.Y. Lee, Mechanical properties of mortar containing bio-char from pyrolysis, J. Korea Inst. Struct. Maint. Insp. 16 (2012) 67–74, https://doi.org/10.11112/jksmi.2012.16.3.067.
[24] L. Li, M. Wu, An overview of utilizing CO_2 for accelerated carbonation treatment in the concrete industry, J. CO2 Util. 60 (2022) 102000, https://doi.org/10.1016/j.jcou.2022.102000.
[25] Z. Zaker, A. Hosseini, S. Azizi, A.H. Korayem, An atomic approach to pore refinement in concrete: carbon dioxide to carbonate calcium, Cem. Concr. Res. 172 (2023) 107241, https://doi.org/10.1016/j.cemconres.2023.107241.
[26] F. Liu, Z. You, X. Yang, H. Wang, Macro-micro degradation process of fly ash concrete under alternation of freeze-thaw cycles subjected to sulfate and carbonation, Constr. Build. Mater. 181 (2018) 369–380, https://doi.org/10.1016/j.conbuildmat.2018.06.037.
[27] L. Restuccia, G.A. Ferro, D. Suarez-Riera, A. Sirico, P. Bernardi, B. Belletti, A. Malcevschi, Mechanical characterization of different biochar-based cement composites, Procedia Struct. Integr. 25 (2020) 226–233, https://doi.org/10.1016/j.prostr.2020.04.027.
[28] I. Cosentino, L. Restuccia, G.A. Ferro, J.M. Tulliani, Type of materials, pyrolysis conditions, carbon content and size dimensions: the parameters that influence the mechanical properties of biochar cement-based composites, Theor. Appl. Fract. Mech. 103 (2019) 102261, https://doi.org/10.1016/j.tafmec.2019.102261.
[29] G. Mishra, P.A. Danoglidis, S.P. Shah, M.S. Konsta-Gdoutos, Carbon capture and storage potential of biochar-enriched cementitious systems, Cem. Concr. Compos. 140 (2023) 105078, https://doi.org/10.1016/j.cemconcomp.2023.105078.
[30] W. Liu, K. Li, S. Xu, Utilizing bamboo biochar in cement mortar as a bio-modifier to improve the compressive strength and crack-resistance fracture ability, Constr. Build. Mater. 327 (2022) 126917, https://doi.org/10.1016/j.conbuildmat.2022.126917.
[31] G. Schumacher, L. Juniper, Coal utilisation in the cement and concrete industries. The coal handbook: towards cleaner production, Woodhead Publishing, 2013, pp. 387–426, https://doi.org/10.1533/9781782421177.3.387.
[32] L. Hernández-Mena, A. Pecora, A. Beraldo, Slow pyrolysis of bamboo biomass: analysis of biochar properties, Chem. Eng. Trans. 37 (2014) 115–120, https://doi.org/10.3303/CET1437020.
[33] Y. Wei, Y. Yan, Y. Zou, M. Shi, Q. Deng, N. Zhao, J. Wang, C. You, R. Yang, Y. Xu, Sulfonated polyaniline coated bamboo-derived biochar/sulfur cathode for Li-S batteries with excellent dual conductivity and polysulfides affinity, Electrochim. Acta 310 (2019) 45–57, https://doi.org/10.1016/j.electacta.2019.04.067.
[34] B.A. Akinyemi, A. Adesina, Recent advancements in the use of biochar for cementitious applications: a review, J. Build. Eng. 32 (2020) 101705, https://doi.org/10.1016/j.jobe.2020.101705.
[35] D. Suarez-Riera, L. Restuccia, G.A. Ferro, The use of Biochar to reduce the carbon footprint of cement-based materials, Procedia Struct. Integr. 26 (2020) 199–210, https://doi.org/10.1016/j.prostr.2020.06.023.
[36] S. Gupta, H.W. Kua, H.J. Koh, Application of biochar from food and wood waste as green admixture for cement mortar, Sci. Total Environ. 619 (2018) 419–435, https://doi.org/10.1016/j.scitotenv.2017.11.044.
[37] Y. Ji, C. Zhang, X.J. Zhang, P.F. Xie, C. Wu, L. Jiang, A high adsorption capacity bamboo biochar for CO2 capture for low temperature heat utilization, Sep. Purif. Technol. 293 (2022) 121131, https://doi.org/10.1016/j.seppur.2022.121131.
[38] Q. Li, T. Lu, L. Wang, R. Pang, J. Shao, L. Liu, X. Hu, Biomass based N-doped porous carbons as efficient CO2 adsorbents and high-performance supercapacitor electrodes, Sep. Purif. Technol. 275 (2021) 119204, https://doi.org/10.1016/j.seppur.2021.119204.
[39] P.K. Gunasekaran, S.C. Chin, Performance of bamboo biochar as partial cement replacement in mortar, Mater. Today. Proc. 109 (2024) 53–61, https://doi.org/10.1016/j.matpr.2023.06.322.
[40] S. Gupta, A. Kashani, Utilization of biochar from unwashed peanut shell in cementitious building materials–effect on early age properties and environmental benefits, Fuel Process. Technol. 218 (2021) 106841, https://doi.org/10.1016/j.fuproc.2021.106841.
[41] H. Maljaee, H. Paiva, R. Madadi, L.A. Tarelho, M. Morais, V.M. Ferreira, Effect of cement partial substitution by waste-based biochar in mortars properties, Constr. Build. Mater. 301 (2021) 124074, https://doi.org/10.1016/j.conbuildmat.2021.124074.
[42] Y. Zhang, Z. Ma, Q. Zhang, J. Wang, Q. Ma, Y. Yang, X. Luo, W. Zhang, Comparison of the physicochemical characteristics of bio-char pyrolyzed from moso bamboo and rice husk with different pyrolysis temperatures, BioResources 12 (2017) 4652–4669, https://doi.org/10.15376/biores.12.3.4652-4669.
[43] N. Claoston, A.W. Samsuri, M.H. Ahmad Husni, M.S. Mohd Amran, Effects of pyrolysis temperature on the physicochemical properties of empty fruit bunch and rice husk biochars, Waste Manag. Res. 32 (2014) 331–339, https://doi.org/10.1177/0734242X1452582.
[44] A.A. Abdalla, A. Salih Mohammed, Theoretical models to evaluate the effect of SiO2 and CaO contents on the long-term compressive strength of cement mortar modified with cement kiln dust (CKD), Arch. Civ. Mech. Eng. 22 (2022) 105, https://doi.org/10.1007/s43452-022-00418-4.
[45] A.A. Abdalla, A.S. Mohammed, S. Rafiq, R. Noaman, W.S. Qadir, K. Ghafor, H. AL-Darkazali, R. Fairs, Microstructure, chemical compositions, and soft computing models to evaluate the influence of silicon dioxide and calcium oxide on the compressive strength of cement mortar modified with cement kiln dust, Constr. Build. Mater. 341 (2022) 127668, https://doi.org/10.1016/j.conbuildmat.2022.127668.
[46] Standard Test Method for Flow of Hydraulic Cement Mortar (2020) ASTM C1437.
[47] K.Y. Foong, U.J. Alengaram, M.Z. Jumaat, K.H. Mo, Enhancement of the mechanical properties of lightweight oil palm shell concrete using rice husk ash and manufactured sand, J. Zhejiang Univ. Sci. A 16 (2015) 59–69, https://doi.org/10.1631/jzus.A1400175.
[48] M. Bediako, J.T. Kevern, Effects of chemical admixture on flow and strength properties of calcined clay used as a supplementary cementitious material, Br. J. Appl. Sci. Technol. 13 (2016) 1–6, https://doi.org/10.9734/BJAST/2016/22905.
[49] M.J. de Hita, M. Criado, Influence of admixtures on the workability and strength of sodium carbonate-activated slag/fly ash cement, Mater. Lett. 312 (2022) 131695, https://doi.org/10.1016/j.matlet.2022.131695.
[50] M.G. Beltrán, A. Barbudo, F. Agrela, J.R. Jiménez, J. de Brito, Mechanical performance of bedding mortars made with olive biomass bottom ash, Constr. Build. Mater. 112 (2016) 699–707, https://doi.org/10.1016/j.conbuildmat.2016.02.065.
[51] P. Selvanathan, P.K. Gunasekaran, Y.F. Lai, N. Anand, S.C. Chin, Curing effect on the strength of cement mortar with bamboo biochar, Int. J. Nanoelectron. Mater. (IJNeaM) 17 (2024) 465–471, https://doi.org/10.58915/ijneam.v17i3.1170.
[52] M.A. Glinicki, D. Jóźwiak-Niedźwiedzka, K. Gibas, M. Dąbrowski, Influence of blended cements with calcareous fly ash on chloride ion migration and carbonation resistance of concrete for durable structures, Materials 9 (2016) 18, https://doi.org/10.3390/ma9010018.
[53] P.F.E. Gunn, C.C. Onn, K.H. Mo, H.V. Lee, Enhancing carbon sequestration in cement mortar using high volume local rice husk biochar coupled with carbonation curing, Case Stud. Constr. Mater. 21 (2024) e03591, https://doi.org/10.1016/j.cscm.2024.e03591.
[54] W. Liu, Carbon sequestration in bamboo biochar mortar. Carbon Dioxide Sequestration in Cementitious Construction Materials, Woodhead Publishing, 2024, pp. 319–344.
[55] H.W. Kua, S.M.H. Tan, Novel typology of accelerated carbonation curing: using dry and pre-soaked biochar to tune carbon capture and mechanical properties of cementitious mortar, Biochar 5 (2023) 36, https://doi.org/10.1007/s42773-023-00234-w.
[56] J.L.D. Sacdalan, C.A.D. Bartolo, C.A.D. Bautista, G.G. Cruz, J.C. Muñoz, Bamboo-derived biochar as partial cement replacement in concrete for carbon dioxide capturing and sequestration, Chem. Eng. Trans. 106 (2023) 409–414, https://doi.org/10.3303/CET23106069.
[57] J. Gimbun, M.A.M. Ali, C.K. Cheng, S.Z. Abidin, M. Mel, S.C. Chin, Elucidating the clinker-based catalyst deactivation for biodiesel production in a continuous microwave-assisted reactor, J. Environ. Chem. Eng. 13 (2025) 115186, https://doi.org/10.1016/j.jece.2024.115186.