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Curing Effect on the Strength of Cement Mortar with Bamboo Biochar

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ABSTRACT

During the ongoing crisis, there is a growing apprehension regarding the escalating quantity of agricultural waste. As a result, it becomes imperative to explore alternative approaches for utilizing this surplus agricultural waste. Bamboo biochar is generated through the pyrolysis process, which involves subjecting it to high temperatures in an environment with limited oxygen. A recent study proposes the utilization of agricultural byproducts such as bamboo biochar as a partial substitute for cement in mortar. This research experiment involved incorporating varying percentages of bamboo biochar as a partial replacement for cement to assess the strength of cement mortar under different curing methods (water, air, and heat). The production of cement emits significant amounts of greenhouse gases, contributing to global environmental impact. The cement industry is recognized as the primary contributor to greenhouse gas emissions, accounting for approximately 6% of global warming. This study employs bamboo biochar as a partial replacement for cement in mortar to reduce cement usage in the construction industry. The study aims to determine the optimal water/cement ratio (0.40, 0.45, and 0.50) for enhanced flowability in mortar mixtures with a cement:sand ratio of 1:2.25. Additionally, it seeks to identify the optimal percentage of bamboo biochar in cement mortar to achieve optimal performance and determine the most effective curing method for cement mortar. The samples were subjected to curing for durations of 3 days, 7 days, and 28 days. Based on the obtained results, the optimal percentage for compressive strength was determined to be 2%, while for flexural strength, it was 0.5%. The water immersion curing method proved to be the most effective approach for curing mortar when partially replacing cement with bamboo biochar.

Keywords: *Bamboo, Biochar, Cement, Optimum percentage, Compressive strength, Flexural strength*

1. INTRODUCTION

The prosperity of a nation and the well-being of its people depend significantly on the construction sector. It plays a vital role in economic growth and has a direct impact on the quality of life [1]. To minimize the negative effects on the environment and human welfare, it is imperative to adopt sustainable practices within the construction industry. Moreover, the construction sector serves as a cornerstone for economic development, influencing the engagement of other sectors within the economy [2]. Nevertheless, there are concerns about the potential environmental and societal consequences of the construction industry due to the projected surge in demand for cement and concrete in the upcoming years [3].

The production of Portland cement, a fundamental ingredient in concrete, emits harmful gases and particles that contribute to the issue of global warming. It is estimated that for every ton of Portland cement produced, an equivalent amount of one ton of CO_2 is generated [4]. To address these challenges, there is a growing exploration of alternative approaches and materials such as mortar. Mortar, consisting of a premixed combination of cement, sand, and additives, is considered a potential solution [5].

The construction industry is actively pursuing the development of eco-friendly concrete mix designs to address the environmental pollution associated with cement production. Simultaneously, it aims to maintain durability and resolve issues related to concrete and mortar [4]. One widely adopted alternative approach involves incorporating additional cementitious materials such as fly ash, silica fume, rice husk ash, sugarcane bagasse ash, and powdered granulated blast furnace slag as substitutes for Ordinary Portland Cement in concrete [6]. These alternative materials hold significant promise in mitigating the environmental impact of cement production and promoting sustainable practices within the construction sector.

In the pursuit of reducing carbon emissions and fostering environmentally friendly practices, Liu et al. [7] explore the utilization of bamboo biochar as a partial replacement for cement [7]. Biochar production from agricultural residues presents an encouraging solution for managing large volumes of waste and mitigating greenhouse gas emissions from open-field burning. Bamboo biochar, with its high organic carbon content and resistance to degradation, is investigated in this study. The researchers conducted experiments using cement mortar samples with varying proportions of bamboo biochar, subjected them to different curing conditions, and evaluated durability by measuring parameters such as compressive strength, water absorption, chloride ion penetration, and carbonation depth [8].

Curing significantly influences the strength development of both alkali-activated slag fly ash blended concrete and cement mortar. It facilitates the proper hydration of cementitious materials in both cases, forming robust and durable bonds. Insufficient or inadequate curing can lead to reduced strength and compromised durability in both materials. Therefore, ensuring appropriate curing practices is crucial to achieving optimal strength and durability in cement mortar [9].

The objective of the research is to experimentally investigate the impact of curing conditions and the percentage of bamboo biochar as a partial substitute for Ordinary Portland Cement on mortar strength. The study examines compressive and flexural strength performance in bamboo biochar mortar under various curing conditions, including immersion, open ambient, and heat curing.

2. METHODOLOGY

2.1. Bamboo Biochar Preparation

The bamboo used in this study was obtained from Tadom Hill Resort, situated in Banting, Selangor. To produce biochar, the bamboo was subjected to pyrolysis in a retort under limited oxygen conditions for 4 to 6 hours at temperatures reaching 600 °C. Then, the biochar was shredded into smaller pieces and processed further using the Los Angeles Abrasion Machine for grinding. To achieve a specific particle size, the biochar underwent sieving through a 45 μm sieve plate.

2.2. Cement and Sand

Ordinary Portland Cement was utilized to make the mortar's cement. In the manufacturing of this sort of cement, the Malaysian Standard MS 522: Part 2: 2007, ASTM C109 [10], for Portland cement, was followed. The used were locally available river sand with a mesh size of 2.36 mm.

2.3. Detail Specimen

In this study, a mortar was prepared by mixing it in a mortar mixer for 1 minute. The mixture consisted of a water-to-cement ratio of 0.45, was chosen to achieve a percentage of flowability between 60% and 80%, which is better than ratios of 0.4 and 0.5 according to ASTM C1437 [11]. The cement-to-sand ratio of 1:2.25 was used to ensure the maximum compressive strength of the mortar mix. To cast the mortar samples for the compressive strength test, a cube-shaped mould measuring 50 mm x 50 mm x 50 mm was used. For the flexural strength test, a prism-shaped mould measuring 40 mm x 40 mm x 160 mm was used. Three curing methods were employed: water curing, air curing, and heat curing. For heat curing, the samples were placed in an oven at a temperature of 60 °C for 6 hours. The number of cubes required for the compressive strength test at different percentages of bamboo biochar replacement, at 3, 7, and 28 days, as listed in Table 1.

2.3. Experiment Method

2.3.1. Flowability test

As aforementioned using ASTM C1437, the flowability of the cement mortar was assessed using a flow table. The flow table was first cleaned to ensure no debris or dust was found, then a mortar cone was formed by pouring the fresh cement paste layer by layer into the mould. It was tamped 25 times with a tamper, by pouring a mortar cone onto a flat surface and measuring the spread diameter, which provided insights into the workability and consistency of the mortar. It was poured layer by layer and tamped to ensure uniform filling of the cement paste into the mould.

Table 1 Total specimens and mix design of mortar used for 3, 7, and 28 days of curing for various percentages.

Curing Method	Mixes of Biochar (%)	Cubes	Prism	Cement (g)	Biochar (g)	Sand (g)	w/c (g)
Water Curing Method	Control Sample	9	9	3372	0	5391	1524
	1	9	9	3338.28	33.72	5391	1524
	2	9	9	3304.56	67.44	5391	1524
	3	9	9	3270.84	101.16	5391	1524
Air Curing Method	Control Sample	9	9	3372	0	5391	1524
	1	9	9	3338.28	33.72	5391	1524
	2	9	9	3304.56	67.44	5391	1524
	3	9	9	3270.84	101.16	5391	1524
Heat Curing Method	Control Sample	9	9	3372	0	5391	1524
	1	9	9	3338.28	33.72	5391	1524
	2	9	9	3304.56	67.44	5391	1524
	3	9	9	3270.84	101.16	5391	1524

Upon filling the mould, the top of the mould was cut off evenly and the mould was removed carefully after 1 min. The table was finally dropped 25 times immediately after the removal and measurement was taken.

2.3.2. Physiochemical and mechanical properties

A Hitachi TM3030 scanning electron microscope with energy dispersive X-ray spectroscopy (SEM-EDX) was used to determine the surface morphology and elemental composition of the biochar. After reaching the prior curing days the samples were taken for mechanical property tests. The compressive strength and flexural strength tests were done according to ASTM C109 [10] and ASTM C348 [12], respectively. The compressive strength and flexural strength test machines were cleaned first to avoid debris and dust content. The respective samples were placed onto the machine plate. The result was taken as the machine generation. The strength of the mortar was determined by subjecting the cured specimens to standardized loads, measuring the maximum load they could bear. This testing method helped evaluate the structural integrity and resistance of the mortar to applied forces.

3. RESULTS AND DISCUSSION

3.1. Physiochemical Properties

The SEM analysis of the bamboo biochar in Fig. 1 shows there is a formation of honey-comb-like structures and pores. This structure formation is found to be similar in not just bamboo biochar [7], [13] but also other types of biochar like rice husk, food, and wood waste biochar [14], [15]. It has been reported that this formation occurs due to the pyrolysis process which releases organics and volatiles matter. Moreover, this had also been detected to allow a self-curing effect for cementitious material by absorbing water.

Table 2 shows the elemental composition of biochar. It can be seen that the biochar consists of a high carbon content. Biochar is known to have a carbon-rich material and it does have high attention due to its high carbon content and stable structure [16]. Moreover, according to Gupta et al. [17] biochar with this unique characteristic can act as a carbon sequestration material. After the carbon, the oxygen (O_2) content is noted to be quite higher than other elements more oxygenated functional groups, such as hydroxyl, carboxylate, and carbonyl, may be present in biochar with a higher C/O ratio. This could account for biochar's high cation exchange capacity (CEC) values, which show that the surface of the material is more negatively charged [18].

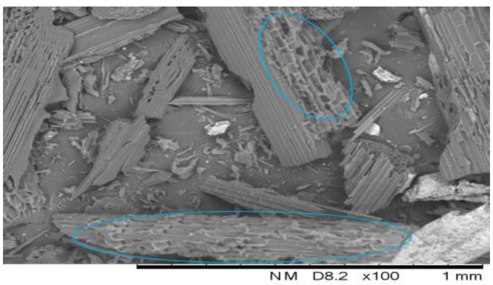

Fig. 1 Surface morphology of bamboo biochar

Table 2 Elemental composition of bamboo biochar.

Element	Weight (%)
Ca	75.608
O_2	16.868
Si	3.939
K	3.062
Fe	0.127
Al	0.114

3.2. Compressive Strength

Fig. 2 shows the compressive strength results of various cement mortars namely, control containing 0% bamboo biochar and those with bamboo biochar ranging from 1-3% under water curing for 3, 7, and 28 days. An early strength increase was observed in 3 days of water curing of mortar containing 1% bamboo biochar with 35.16 MPa and eventually showed a decreasing trend at 2% and 3%. This may be possibly due to the usage of excessive amounts of bamboo biochar will reduce the C-S-H formation of cement hydration, which will negatively impact mechanical performance [7]. Even though the compressive strength drops in 2% and 3% addition with 24.48 MPa and 24.44 MPa, respectively, it is still higher than the control sample (23.66 MPa). This shows that overall, the early strength of bamboo biochar containing mortar is higher compared to the control sample.

At 7 days of water curing, the compressive strength continues to increase compared to the 3-days of curing. Cement mortar with a 3% addition of bamboo biochar gives the highest compressive strength at 42.28 MPa. This improvement can be attributed to the pozzolanic reaction, which leads to the development of more hydrated products and denser microstructures, resulting in increased compressive strength [19]. Meanwhile, there is a slight reduction in 1% bamboo biochar mortar with 33.87 MPa compared to 3 days of curing (35.16 MPa). However, the difference is not significantly different ($P > 0.05$), therefore the compressive strength is essentially similar or even higher depending on the standard deviation of the data.

At 28 days of water curing, an increasing trend in compressive strength was observed in control mortar, and mortar containing 1% to 2% bamboo biochar with the highest value of 47.49 MPa. A slight reduction in strength in 3% addition with 45.05 MPa (5%). It was found that up to 41% increment in the compressive strength for 2% bamboo biochar addition compared to the control mortar. It was observed that a 2 - 3% biochar addition yielded the highest strength. The increment of the strength can be explained by the ability of the biochar to absorb and retain water is linked to the strength increase that resulted from its addition. Dry biochar particles absorbed some of the water used to mix the concrete, lowering the free water-to-cement ratio in the concrete matrix. A high capillary water content causes a high capillary porosity in the cementitious matrix, which is bad for the development of strength [20].

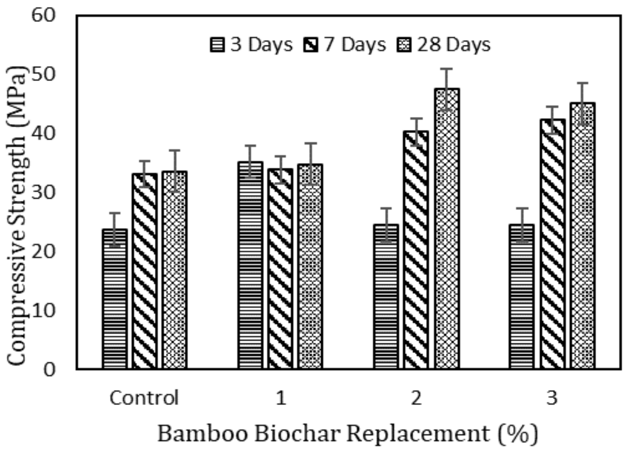

Fig. 2 Compressive strength of biochar mortar under water curing

Fig. 3 shows the compressive strength results of various cement mortars (i.e., control, 1%, 2%, 3% addition of bamboo biochar) under air curing for 3, 7, and 28 days. The early strength on 3rd day of curing shows that the control sample has the highest strength compared to the other percentages with 31.31 MPa. Compressive strength at 3 days can sometimes appear higher than at 7 and 28 days due to various factors, including early hydration. During the initial stages of concrete curing, there is a rapid formation of hydration products, leading to an increase in strength. The early hydration process typically peaks within the first few days, contributing to higher compressive strength values at 3 days [21], [22]. Meanwhile, mortar samples containing 1 - 3% addition of bamboo biochar show an increasing trend in compressive strength. The addition of 3% bamboo biochar exhibits the highest results at 7 and 28 days, 33.10 MPa and 33.75 MPa, respectively. The mortar containing 2% biochar addition increases the compressive strength by 55.1% and 12.6% for 7 and 28 days of curing, respectively. Overall, the compressive strength observed in air curing is lower than that of water curing. This shows that the curing methods have an influence on the strength [20]. This is ascribed to the mortar matrix's decreased porosity, which is due to the absorption of some water of the biochar particles' during mixing. As a result, even in the absence of an external water source, the biochar particles can function as an internal moisture reservoir to maintain hydration. By preventing free water from evaporating and promoting hydration through internal curing, the particles of biochar densify and reinforce the mortar in two ways [20]. In this curing method, the compressive strength results for curing ages of 7 and 28 days outperform the control sample. The results are lower compared to water curing samples. Several studies reported the same result with lower strength for air curing when compared with water-cured samples [23], [24]. According to Agostini et al. [24] the internal curing of water curing is more noticeable due to the water present in the material which provides stiffness and lowers the interfacial transition zone microcracking between the material and cement paste. However, a study by Gupta et al. [25] reported high improvement in terms of strength for air-cured samples. The author stated that it could be due to the pre-soaked biochar which contributes to a smaller amount of free water in the mixes.

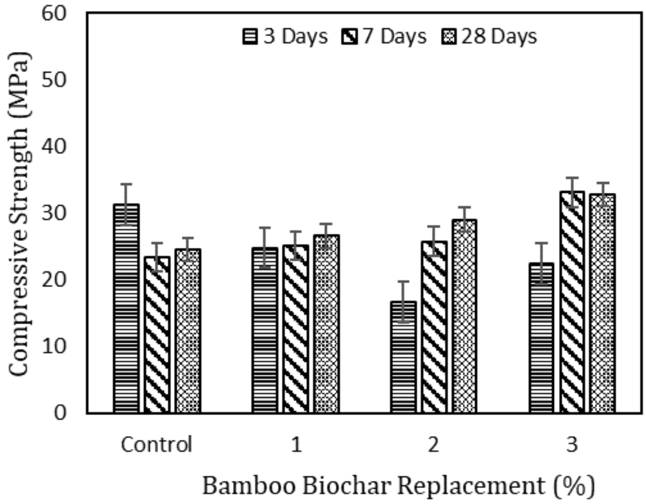

Fig. 3 Compressive strength of biochar mortar under air curing

Among the three curing methods, the heat curing method yields the lowest values of compressive strength as shown in Fig. 4. The highest compressive strength at 3 days of heat curing was recorded as 27.2 MPa with mortar containing 1% biochar followed by 2% biochar addition with 18.9 MPa. The mortar with 1% bamboo biochar shows a decreased trend from 3-28 days. In contrast, 2% and 3% addition show an increase in compressive strength, with 2% addition gives higher in compressive strength (24.64 MPa) compared to 3% addition (18.20 MPa). On the 28th day of curing, there is a 0.1% reduction for the mortar with 1% biochar and simultaneously there is a 9.6% improvement in the mortar with 2% biochar compared with the 7 days of curing. This can be due to the 2% biochar addition being the best addition of biochar upon reaching the 28th day of curing. One contributing factor to its superiority over other percentages is that heat curing accelerates the hydration process in cementitious materials. However, the presence of bamboo biochar particles can act as heat sinks, absorbing heat and reducing the available temperature for hydration. Consequently, this can lead to slower and incomplete hydration of the cementitious materials, resulting in reduced strength development and a decrease in compressive strength [24]. The strength was also higher than the control samples except for mortar with 3% biochar for all the curing days. This could be due to the high amount of biochar addition under this particular condition causing the cement matrix to be unable for the sufficient production of C-S-H gel causing it to have relatively low strength. Overall, the strength of the biochar had been observed to be relatively lower than the water and air curing methods. This can be attributed to the lower thermal conductivity of bamboo biochar compared to traditional cementitious materials [26]. The optimal heat-curing condition identified in the study was 60 °C for 6 hours. Even though the mortar with 1% biochar seems to be 1.3 MPa higher than the ones containing 2% biochar, but still the latter is chosen as optimum mix when compared to all the other curing methods.

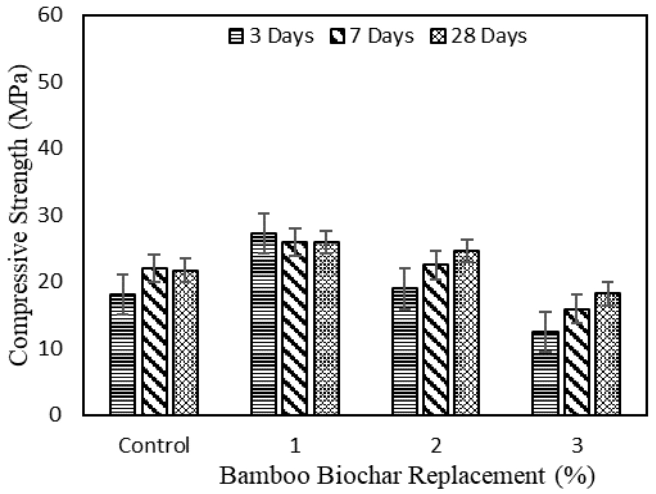

Fig. 4 Compressive strength of biochar mortar under heat curing

3.3. Flexural Strength

Fig. 5 shows that the flexural strength of all samples demonstrated a consistent upward trend as the curing period increased, indicating a progressive enhancement in their structural integrity and load-bearing capacity over time. All the samples showed a higher strength compared to control sample. Among all these samples, the 1% biochar replacement exhibited the highest flexural strength, reaching values of 10 MPa, 11.54 MPa, 11.71 MPa after 3, 7 and 28 days, respectively. An increment of 15.4% and 1.47% was observed for 7- and 28-days curing, respectively. There is a slight reduction in mortar with 2% biochar with an increment of 14% and 15.13% for 7- and 28-days, respectively. Addition of 3% biochar cause a notable reduction in flexural strength with only 10.07 MPa and 10.86 MPa for 7- and 28-days, respectively. Across all the obtained results, a notable improvement in the flexural strength was observed for the mortar containing bamboo biochar in comparison to the control sample. The data consistently demonstrated that the addition of bamboo biochar led to an enhancement in flexural strength, highlighting the positive impact of this modification on the structural properties of the samples. The observed enhancement in flexural strength can be attributed to the rapid consumption of bamboo biochar during the early stages of cement hydration under water curing conditions because the presence of bamboo biochar affects the hydration process by acting as a nucleation site and contributing to the formation of additional hydration products [27]. The utilization of bamboo biochar in the mortars demonstrates a positive influence on their mechanical properties, as evidenced by the observed improvements.

Fig. 6 presents the flexural strength of various samples at 3, 7, and 28 days of air curing. The overall graph depicts an upward trend. The early strength at 3 days of curing shows that the addition of 1% biochar is more prominent than other percentages. This trend continues up to the 7th day curing with the 1% biochar being the highest strength (8.98 MPa). Upon reaching the 28th day of curing, this result however differs as the 2% and 3% biochar depicts a higher strength with 11.03 MPa and 11.42 MPa, respectively. The 2% biochar was observed as the best mix for 28 days of curing. Nevertheless, the flexural strength of the bamboo biochar samples exhibited an increase compared to the control sample. This suggests that, in the case of air curing, the influence of the pozzolanic reaction induced by bamboo biochar on the development of flexural strength is more pronounced compared to the hydration reaction in plain mortar. The result was also similar for Muthukrishnan et al. [28]. The overall strength is noted to be lower than water curing method. This decline can be attributed to the weaker bonding between the bamboo biochar particles and the cementitious matrix, which is not as strong as the bonding provided by traditional cementitious materials. The presence of biochar particles in the mortar mixture can disrupt the interfacial bonding between the cementitious matrix and the aggregates, resulting in a reduction in flexural strength. Consequently, this weaker bond diminishes the resistance against bending forces and leads to an overall decrease in flexural performance. A similar result was obtained by Nasiru et al. [29]. Benammar et al. [30] also stated that air curing can negatively affect the mechanical properties of cementitious material because of the inadequate water content available for hydration process to take place.

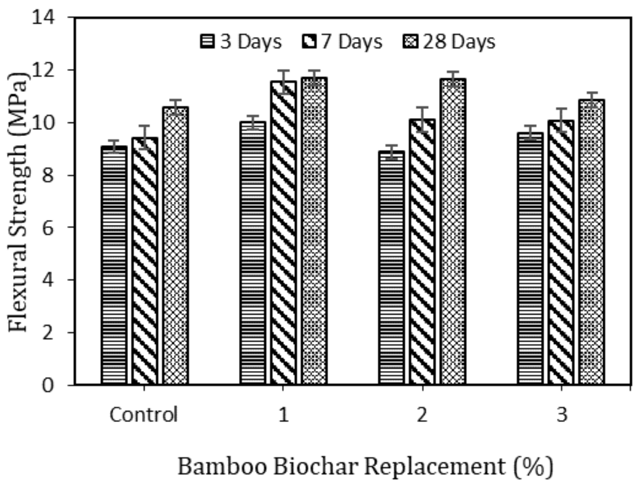

Fig. 5 Flexural strength of biochar mortar under water curing

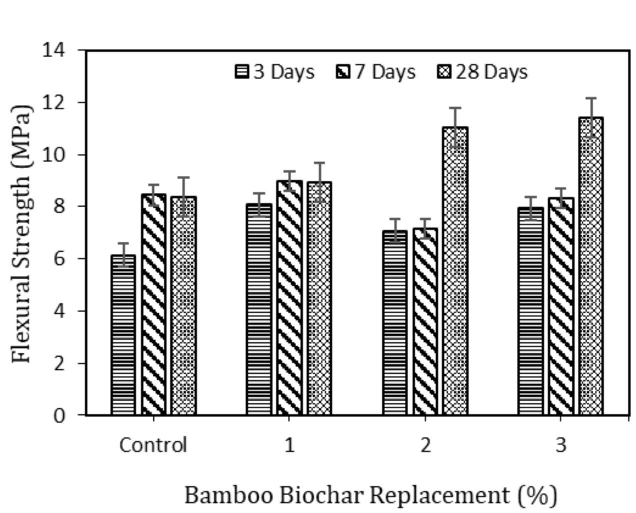

Fig. 6 Flexural strength of biochar mortar under air curing

Fig. 7 presents the results of flexural strength for bamboo biochar mortar with varying weight percentages of cement replacement at different durations of heat curing. The overall strength was observed to be the lowest compared to water and air curing. The low strength can be due to increased pores due to heat curing which cause the reduction in the matrix-dominated mechanical properties [31]. The highest strength (9.38 MPa) on 28-days of curing was achieved for 2% biochar. One contributing factor to its increment over other percentages is that heat curing accelerates the hydration process in cementitious materials. However, the presence of bamboo biochar particles can act as heat sinks, absorbing heat and reducing the available temperature for hydration. Consequently, this can lead to slower and incomplete hydration of the cementitious materials, resulting in reduced strength development. The flexural strength characteristics exhibit a comparable trend to the compressive strength when bamboo biochar is used as a partial replacement for cement. Both the flexural and compressive strength measurements demonstrate nearly similar patterns and trends, indicating a consistent relationship between the two strength parameters. The introduction of bamboo biochar as a cement replacement component affects both flexural and compressive strength comparably.

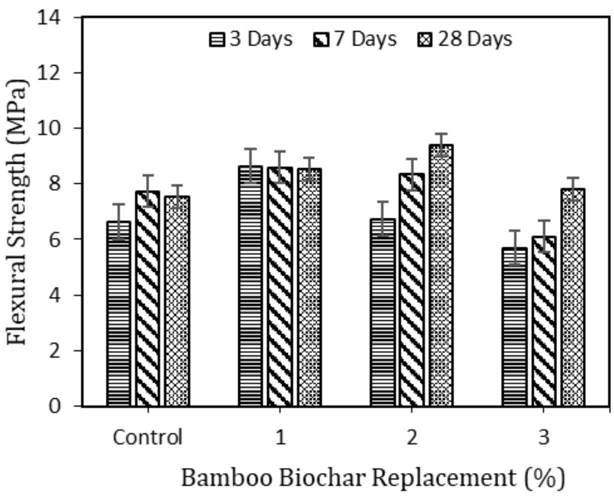

Fig. 7 Flexural strength of biochar mortar under heat curing

4. CONCLUSIONS

Among the various water/cement ratios considered for mortar mix, it was determined that a water/cement ratio of 0.45 exhibits the most favorable results when bamboo biochar is introduced as a partial replacement for cement. This water/cement ratio demonstrates optimal performance in terms of incorporating bamboo biochar into the mortar mixture, ensuring an effective balance between water content and cementitious materials. It was found that the most appropriate and optimum percentage for incorporating bamboo biochar into the mortar is 2% replacement (water > air >heat) in terms of compressive strength at 28 days. Additionally, for flexural strength, the optimal percentage of bamboo biochar replacement is 2% (water > air > heat). This percentage demonstrates the highest flexural strength results, suggesting that it is the most suitable proportion for improving the mortar's resistance to bending forces. Therefore, based on the findings, it is recommended to utilize a 2% replacement for compressive strength and a 2% replacement for flexural strength under water curing when incorporating bamboo biochar into the mortar mixture.

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