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Review Article

Biochar as a Sustainable Cement Replacement for Enhancing Concrete Composite Properties: A Review

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Abstract

Concrete, a highly adaptable and extensively utilized material, encounters difficulties stemming from the environmental repercussions of cement manufacturing and the exhaustion of natural resources such as river sand and gravel. These concerns have stimulated investigation into sustainable alternatives like biochar, a carbon-dense substance generated by the thermochemical conversion of biomass. Biochar's distinctive characteristics, such as elevated surface area, porosity, and cation exchange capacity, render it a viable supplemental cementitious material (SCM). This study evaluates the impact of biochar inclusion on concrete's mechanical characteristics, concentrating on compressive, tensile, and flexural strengths. Research indicates that biochar enhances early-age compressive strength, with findings documenting an increase of up to 40% at a 2% replacement rate. Nonetheless, elevated doses (>5%) diminish strength owing to heightened porosity and water requirements. Flexural strength exhibited considerable enhancements, especially with presoaked biochar and certain feedstocks, but tensile strength advantages were noted at less replacement levels (e.g., 5%). The results underscore biochar's potential as a supplementary cementitious material for sustainable concrete, including enhancements in early-age strength and environmental advantages such as carbon sequestration. Future research should concentrate on improving biochar dose and assessing long-term performance to improve its applicability in extensive building uses.

Keywords: Biochar-concrete, SCMs, Compressive Strength, Sustainable Materials, Carbon Sequestration.

Introduction

Due to its unique benefits over other building materials, concrete is a highly sought-after building material worldwide [1]. It is notable for being easily accessible, reasonably priced, and extremely strong [2]. The great demand for concrete is draining premium river sand and gravel, which raises questions over resource availability. Though local resources are better, allocation is sometimes unfair. The growing demand aggravates concrete industry difficulties as the usage of river sand and gravel is still very essential [3]. Besides, Cement output has increased significantly due to the rise of the construction industry, with an annual production reaching 10 billion tons [2, 4]. The detrimental environmental implications of cement manufacture have been brought to light in recent studies. These effects include ecological damage from the extraction of raw materials as well as the release of greenhouse gases and particle pollutants throughout the manufacturing process. These environmental effects have been made worse by the growing demand for concrete [1]. In order to create more affordable and environmentally friendly construction methods, researchers have looked into mixing cement with substitute materials such as fly ash, recycled aggregate, rice husk ash, and biochar made from different biomass sources [1,5-7].

Produced by thermochemically converting biomass, animal dung, municipal trash, and other organic materials in an oxygen-limited environment, biochar is a carbon-rich, sustainable material [8]. Researchers are interested in it because of its unique properties, which include stability, a high surface area, porosity, functional groups, and cation exchange capacity. As a result, it can be used in a variety of ways. Biochar is prized for its easy and quick preparation, cost-effectiveness, reusability, and environmental friendliness [9]. It has proven useful in a number of industries, including anaerobic digestion [10], wastewater treatment [11], chemical recovery [12], agriculture [13], and carbon sequestration [14]. Biochar has been shown in recent research to have the potential as an additional cementitious material (SCM) in the construction of sustainable concrete [7,15- 17]

The incorporation of biochar into construction materials has been the subject of several publications [18-22], with an emphasis on the material's mechanical qualities, including workability, hydration kinetics, and durability. In this paper the mechanical strength properties are reviewed altogether from the result of previous studies to get a better idea on the usage of biochar as a supplemental cementitious material.

Effect on Mechanical Strength

Effect on compressive strength

The effects of biochar on the mechanical characteristics of mortar were examined by Choi et al [23]. The switchgrass and hardwood biochar used in the authors' mortar was used to replace 5–20% of the cement by weight. According to the study, after 28 days, adding 5% more biochar to the cement increased its compressive strength by about 10% (Fig. 1).

It was observed that the water requirement of the reference mortar was smaller than that of the mortar with the added biochar due to the fact that biochar possessed a high water retention capacity that further contributed to its internal curing during its setting phase. Similarly, a study reported by Gupta et al. [24] showed that even the addition of only 2% mixed wood biochar to the cement mass enhanced the strength of concrete samples by 40% after 7 days. More importantly, Gupta et al. [25] determined that the replacement of cement mass with 0.5%, 1%, and 2% mixed wood sawdust-based biochar pyrolyzed at

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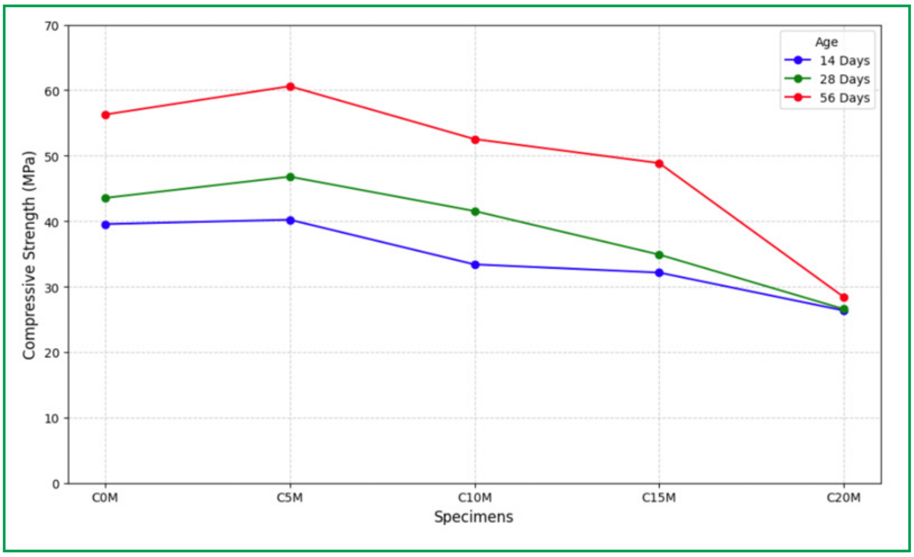

Figure 1. Compressive strength [23].

500°C resulted in improvements in 7-day compressive strength of 18%, 13%, and 10%, respectively. These strength gains for the same replacement levels were 16%, 10%, and 9%, respectively, at 28 days. The percentage difference in the increase in strength between 7-day and 28-day gains was 11.11%, 23.08%, and 10.00% for 0.5%, 1%, and 2% replacement levels, respectively. It is, however, mentioned that gains in strength beyond 28 days were lower than the 7-day gains. Application of biochar seems to offer early-age benefits to strength improvement, whereas it eventually tapers off at later ages. Biochar application can thus be considered as one of the promising additives for the improvement of short-term concrete properties. Its long-term effects are yet to be researched upon, and optimum usage has to be determined.

In their investigation of the effects of biochar produced from wood waste on composites under both dry and wet curing conditions, Sirico et al. [26] found that adding 5% biochar to the composites increased their compressive strength for all curing times (Fig. 2).

By adjusting the mixing ratio between 2 and 8 weight percent of binder, Park et al. [27] examined the impact of oilseed rape biochar and mixed softwood biochar on the compressive strength of mortar. They found that irrespective of the kind of biochar, 4 weight percent of binder produced the highest strength. Kim et al.'s findings [28] for biochars derived from rice husks, spruce trees, and Miscanthus straw incorporating n-octadecane revealed comparable outcomes: specimen strengths rose with 4% biochar addition, but specimen strengths decreased with 6% biochar addition. Thus, the authors came to the conclusion that adding biochar to cement in place of 4% of its mass could improve both strength and thermal conductivity [28].

Samples containing artificial stone (AS), lightweight artificial stone (LAS), and PCM artificial stone (PAS) specimens are compared with samples containing biochar made from spruce tree (ST), rice husk (RH), and Miscanthus straw

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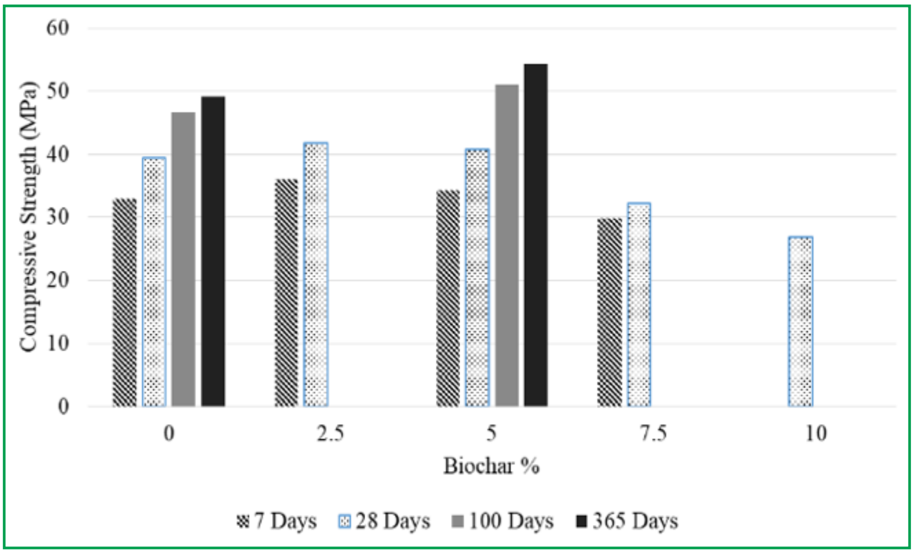
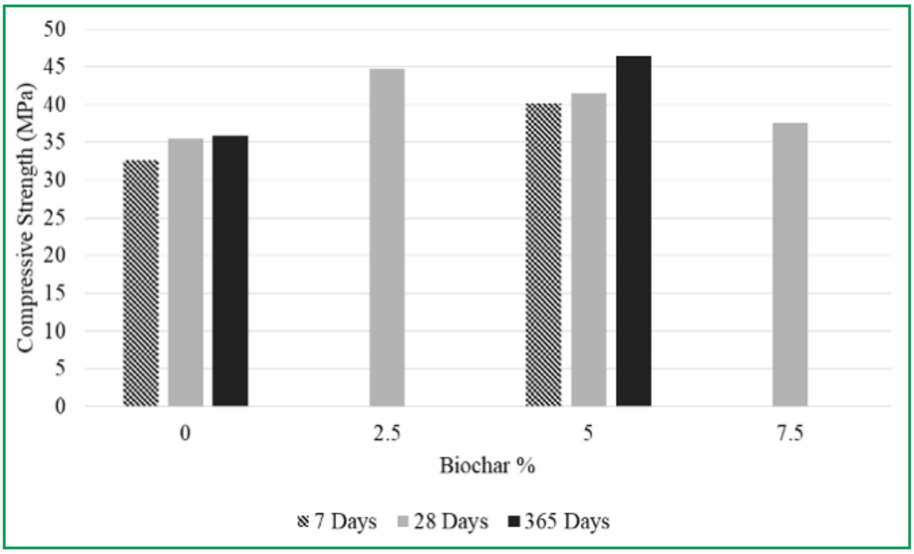


(a) Water curing



(b) Dry curing

Figure 2. Average compressive strength for different curing times and conditions with increasing biochar (wood waste) additions [26]

(MS). A representative carbon material called xGnP is used to compare samples containing biochar with biochar. In comparison, RHB replacements of 0, 2, and 5% of the cement mass resulted in increases in compressive strength of 31.7%, 40.3%, and 40.5% from 7 to 28 days, according to a study by Yang and Wang [29]. But in every instance, there was no increase in compressive strength when compared to the control specimen.

In a study, Chindaprasirt and Rukzon [30] found that adding rice husk ash (RHA) to cement (10–20% of the mass) increased the cement's compressive strengths by 2-3% after 7 and 120 days. When the mass replacement was increased to 40%, they also observed a 20% decrease in strength. Another study using RHB by Zeidabadi et al. [17] found that replacing 5% of the cement with RHB increased the compressive strength by around 12% when compared to the

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control, which was explained by the biochar particles' early age filler action. Nevertheless, the aforementioned research showed that raising the pace at which biochar is replaced raises the concrete's carbon percentage, which raises the need for water and lowers compressive strength.

Effect on flexural Strength

While increasing the dosage of biochar, Gupta and Kua [31], found that increasing the dosage rate of biochar did not increase the flexural strength significantly. This constitutes a slight gain in strength which may be attributed to air voids that form in the tensile plane due to the very small size and porous nature of the biochar particles. The maximum flexural strength obtained for mortar is that containing presoaked and dried biochar (Fig. 3). Akhtar and Sarmah [32] also showcased the improvement in flexural strength by up to 20%, with an additive of 0.1% biochar from chicken litter, rice husk, and paper mill waste. Similarly, Maljaee et al., [33] also reported a similar trend but emphasized that the higher porosity at 4% forest wood biochar triggered more fractures when under tensile stress.

Suarez-Riera et al. [34] studied utilizing biochar as both a filler in concrete and a cement alternative. They observed that replacing cement with biochar marginally lowered flexural strength by 2%, while employing biochar as a filler premixed with 2.3% of water-superplasticizer boosted it by nearly 15%. The study also demonstrated that biochar as a filler enhanced fracture energy more than as a cement replacement, indicating higher ductility. Additionally, the influence on flexural strength varies depending on the biochar's feedstock, agreeing with Khushnood et al. [35], who showed that peanut shell biochar, due to its lower density, gave superior mechanical strength than hazelnut shell biochar.

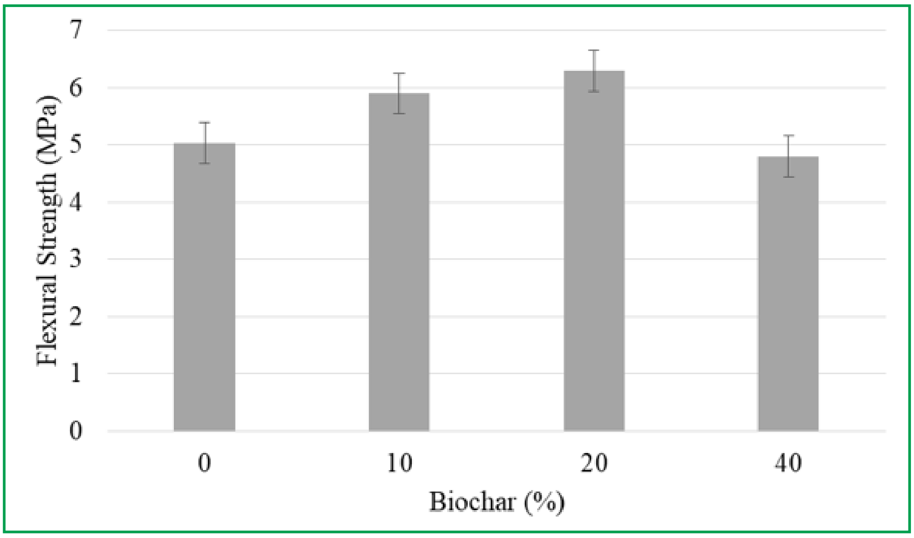

Figure 3. Flexural Strength using Biochar. [37]

Ahmad et al. [36] discovered that adding 0.08 wt% bamboo-derived biochar to cement increased the toughness and flexural strength of cement composites. Similarly, Praneeth et al. [37] observed a 26% improvement in flexural strength when 20% poultry litter-based biochar was used to replace 10-40% of sand in mortar compared to the control.

However, Gupta et al. [38] showed that biochar typically did not significantly alter flexural and splitting tensile strength, save for a modest improvement with 1% wood waste biochar. Overall, studies suggest that increasing biochar concentration in concrete eventually affects flexural strength, with outcomes depending largely on the feedstock utilized [33, 35, 38].

Effect on tensile strength

Asadi Zeidabadi et al. [39] found that adding 5% treated bagasse biochar to concrete increased tensile strength by 78%, while treated rice husk ash reduced it due to its porous microaggregate structure weakening the concrete matrix. Akhtar and Sarmah [32] identified 0.1 wt% rice husk content as optimal for enhancing split tensile strength but noted a negative impact on compressive strength due to irregular pore structure. Conversely, Gupta et al. [38] observed no significant improvement in split tensile strength with food or rice waste biochar, except for a sample with 1% wood waste biochar, likely due to its self-curing properties. Biochar can slightly increase concrete's flexural strength at lower levels (1-3 wt%), but higher levels (5 wt% and above) lead to a significant reduction. This decrease is due to biochar's high porosity, low hardness, and larger fineness, which create voids and reduce the concrete's effective bearing capacity [40].

Conclusions

This study aims to examine the influence of biochar as a supplemental cementitious material (SCM) on the mechanical characteristics of concrete, with an emphasis on compressive, tensile, and flexural strengths. The data show that biochar can boost early-age compressive strength, with best gains found at lower replacement amounts (e.g., 2-5%). Additionally, flexural and tensile strengths revealed moderate increases depending on the biochar dose, feedstock type, and pre-treatment procedures. However, larger replacement levels led to strength decreases because to increased porosity and water consumption.

These results accord with the study's aims by proving biochar's potential to improve short-term mechanical characteristics while contributing to sustainability through reduced cement usage and carbon sequestration. While biochar shows potential as an SCM, additional study is needed to identify the long-term impacts of biochar on concrete performance, optimize its replacement ratios, and evaluate its economic feasibility for large-scale building applications.

This research highlights the need of using sustainable materials like biochar in the construction sector to solve environmental concerns and lower the ecological impact of cement manufacturing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Md. Saniul Haque Mahi: conceptualization, supervision. **Md. Abdul Mun-Im-Dinar:** methodology, writing- original draft preparation, resources. **Tanjun Ashravi Ridoy:** visualization.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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