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Mechanical Performance of Pyrolysis Biochar-Enhanced Sustainable Concrete

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Abstract

The mechanical properties were investigated of high-strength concrete with a water-to-binder (w/b) ratio of 0.5, utilizing a superplasticizer to control workability. Biochar from sugarcane bagasse (BCS) was used as a partial cement replacement at levels of 1%, 3%, 5%, or 7% by weight. The biochar was produced using the pyrolysis process, involving thermal decomposition of biomass under limited oxygen conditions. Testing was conducted on 100 × 200 mm cylindrical specimens and 100 × 100 × 350 mm beams. Based on the experimental results, the 1% BCS replacement was optimal for improving concrete strength. This improvement was attributed to the finely ground biochar particles (10–30 μm), having a size comparable to cement particles, thereby enhancing packing density. Furthermore, the porous structure of the biochar facilitated internal curing by retaining water and gradually releasing it to promote long-term hydration. The fresh concrete slump was regulated according to ASTM C143, and mechanical properties (compressive strength, splitting tensile strength, and flexural strength) were evaluated. After 28 days of water curing, specimens with the 1% BCS had increased compressive, tensile, and flexural strengths by 7.45%, 5.85%, and 2.5%, respectively. However, when the BCS replacement exceeded 1%, the porosity and void content within the concrete matrix increased. Excessive biochar led to particle clumping and poor dispersion, resulting in large air pockets and interconnected gaps around biochar clusters. These voids acted as weak points that hindered load transfer and served as sites for crack initiation, causing a continuous decline in mechanical performance. This study established a sustainable pathway for the valorization of sugarcane bagasse into an engineered supplementary cementitious material, demonstrating dual benefits in carbon sequestration and mechanical performance optimization for sustainable high-strength concrete.

Keywords: biochar, cement, pyrolysis, water curing, sustainable concrete, mechanical properties

1. Introduction

Currently, the cement industry is a primary contributor to global climate change, accounting for approximately 5% of global carbon dioxide (CO_2) emissions that are mainly due to the calcination process of limestone and the intensive use of fossil fuels during production [1–7]. To mitigate these environmental impacts, contemporary research has focused on reducing the clinker factor by incorporating waste materials as supplementary cementitious materials (SCMs) such as fly ash, silica fume, and biochar. These materials not only enhance the compressive strength of concrete but also reduce the demand for Portland cement, for example [8], a study investigated the utilization of olive waste ash (OWA) as a constituent to develop high-strength geopolymer concrete and found that OWA significantly enhanced the compressive strength of the geopolymer concrete while increasing its microstructural density. At a curing age of 28 days, replacing fly ash at a 20% ratio resulted in an 8.9% increase in compressive strength, whereas replacing ground granulated blast furnace slag at a 30% ratio yielded the peak strength enhancement of 20%. Furthermore, a combined replacement of both precursors at a 30% ratio led to a 17.8% increase in compressive strength. thereby lowering production burdens and atmospheric carbon emissions. Biochar, a carbon-rich material produced through pyrolysis, has gained considerable attention not only for its ability to improve mechanical strength but also for its potential in active carbon sequestration. Recent advancements in 2024 emphasized that the performance of biochar-cement composites depended heavily on innovative designs of particle size distribution, which could substantially refine the matrix microstructure [9,10]. Typical feedstocks for biochar production are readily available sources of biomass with a high carbon content such as agricultural and horticultural residues. For example, the effects of rice straw biochar on high-strength concrete have been studied using stress-strain diagrams and the elastic modulus [11]. Additionally, coconut shells have been trialed as a replacement for natural gravel to determine the optimum substitution ratio [12]. Furthermore, past study [13]. evaluated peanut shell ash (PSA) and sunflower shell ash (SSA) as cement replacements (up to 40%) in sustainable high-strength concrete. The findings indicated that 30% SSA or 10% PSA offered acceptable compressive strengths (57–66 MPa), which, while lower than for silica fume, substantially reduced environmental impacts.

Sugarcane Bagasse (SB), a byproduct of the sugar industry left after juice extraction, is a major agricultural waste. Although some sugar mills utilize wet bagasse as boiler fuel, currently, much of it is stockpiled or incinerated, creating highly flammable biomass that poses fire hazards to industrial sites and surrounding areas [14,15]. Therefore, sustainable management of sugarcane bagasse is crucial. Enhancing concrete performance with biochar represents an effort to reduce carbon emissions from cement production, sequester atmospheric carbon, and increase compressive strength. Notably, the published research has not extensively explored sugarcane bagasse biochar (BCS) in high-strength concrete. Utilizing BCS as an SCM (as binder replacement) constitutes a novel innovation, distinguishing it from past studies that primarily used biochar as an aggregate replacement.

Therefore, the purpose of the current study was to address the issue of excessive agricultural industry waste by converting sugarcane bagasse into biochar and investigating its effects on the physical and mechanical properties of high-strength concrete, including compressive strength, splitting tensile strength, and flexural strength. In addition, this research included microstructural and chemical composition analyses. The specific objectives were: 1) to investigate the morphology of biochar using scanning electron microscopy (SEM); and 2) to evaluate the compressive, splitting tensile, and flexural strengths of the concrete to identify the optimum replacement level for improving the mechanical properties of high-strength concrete.

2. Materials and methods

2.1 Materials

Ordinary Portland cement (OPC-GU) has a specific gravity of 3.15 and is used for general concrete works and structural concrete applications according to the standards of ASTM C150 [16]. The coarse aggregate used in the current study was chipped stone that had been washed to remove impurities and sediment. The maximum size of coarse aggregate was 9.5 mm. The chipped stone was chosen for this research to give a target compressive strength of 40 MPa. The use of chipped stone in the mixing of concrete helps to reduce voids and gaps within the concrete, thereby providing uniformity and enhancing the overall strength of the concrete matrix. The fine aggregate used were river sand in a saturated surface dry condition. The Type F superplasticizer admixture was characterized as mostly sodium lignosulfonate and naphthalene sulfonate, according to the ASTM C494-92 [17]

2.2 Biochar preparation and processing

The biochar was prepared using waste sugarcane from the sugar industry in Nakhon Sawan Province, Thailand. The sugarcane bagasse was cleaned and then sun-dried or oven-dried at a low temperature (about 100 °C) to remove the moisture until completely dry, which reduced the moisture level to less than 10%. Next, the bagasse was pyrolyzed, initially at 200–300 °C for 1–2 hours to remove the remaining moisture and volatile compounds and ensure the stability of the material. Subsequently, the temperature was gradually increased at a heating rate of 10 °C/min, with the bagasse being further pyrolyzed for 2–4 hours in a horizontal kiln produced by local villagers. During the pyrolysis process, the kiln was closed hermetically to ensure oxygen-limited conditions that minimized any oxidative reactions and the carbon was fully carbonized. Upon completion, the reactor was allowed to cool slowly for at least 24 hours to avoid thermal shock and structural damage to the resulting biochar. After cooling, the biochar was pulverized into particles (size 10–30 μm), with the size designed to match the size of cement particles. For comparison, ordinary Portland cement (OPC) normally has a wide particle size distribution in the range of 1–100 μm, with a median particle size (d50) of 10–20 μm [18]. This particle size comparability was critical since it promoted homogenous dispersion (uniformity), reduced segregation, and enabled the biochar to act as an effective micro-filler. Research has supported utilizing biochar with an engineered particle size distribution (such as d50 in the range 15–25 μm) which is close to the value of cement, in order to increase the packing density of the matrix and promote a higher degree of hydration, thus increasing the compressive strength [19], as shown in Figure 1.

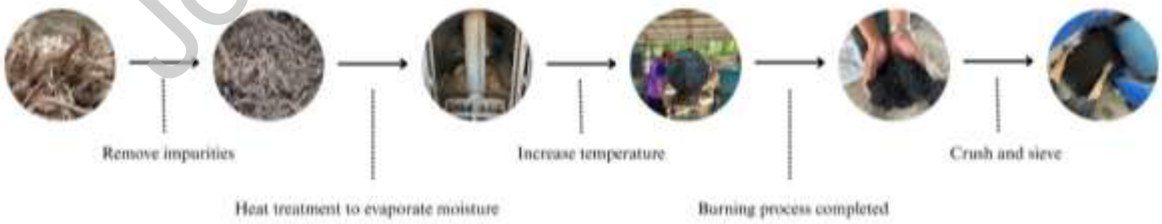

Figure 1: Production process of biochar from sugarcane bagasse

2.2 Test methods

Concrete mixtures were proportioned according to ACI 211 [20] to evaluate the impact of biochar sugarcane bagasse (BCS) on high-strength concrete. The mix design utilized a fixed water-to-cement ratio of 0.5, with cement replaced by BCS at levels of 0% (control), 1%, 3%, 5%, or 7% by weight, as detailed in Table 1. Fresh concrete workability was assessed based on the slump test in accordance with ASTM C143, maintained within a target range of 160 ± 25 mm [21].

For specimen preparation, two types of molds were used: cylindrical molds (100 mm diameter × 200 mm height) and beam molds (100 × 100 × 350 mm). Casting and demolding occurred after 24 hours, after which all specimens underwent continuous water curing at ambient temperature until the designated testing ages of 7, 14, and 28 days.

The mechanical properties and physical characteristics were evaluated according to international standards: compressive strength (ASTM C39) [22]; splitting tensile strength (ASTM C496) [23]; and flexural strength (ASTM C78) [24]. Additionally, the hardened density and microstructure were analyzed in accordance with ASTM C642 [25] and scanning electron microscopy (SEM) analysis, respectively. A comprehensive summary of the testing program, including specimen types and curing durations, is provided in Table 2.

Table1. Mix proportions of concrete

Concrete	**BCS**	**W/B**	**Cement**	**Water**	**SSD aggregates**		**BCS**	**SP^a**
					Coarse	**Fine**		
	(%)	W/(C+BCS)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)
BCS0	0	0.5	395.00	197.5	1075	715	0	3.950
BCS1	1	0.5	391.05	197.5	1075	715	3.95	6.257
BCS3	3	0.5	383.15	197.5	1075	715	11.85	6.130
BCS5	5	0.5	375.25	197.5	1075	715	19.75	6.000
BCS7	7	0.5	367.35	197.5	1075	715	27.65	5.878

BCS = Biochar from sugarcane, SSD = Saturated surface dry, SP^a; Superplasticizer, W/B = Water-to-binder ratio

Table2. Characteristics of samples used in property evaluation

Property tested	**Testing method**	**Sample type**		**Number of Samples**	**Curing (days)**		
		Cylinder (100 × 200 mm)	**Beam** (100 × 100 × 350 mm)		**7**	**14**	**28**
Slump test	ASTM C143	-	-	3			
Density test	ASTM C642	✓	-	3		✓	✓
Compressive test	ASTM C39	✓	-	3	✓	✓	✓
Splitting tensile	ASTM C496	✓	-	3	✓	✓	✓

test							
Flexural tensile test	ASTM C78	-	✓	3	✓	✓	✓
SEM	ASTM C642	✓	-	3			✓

SEM = scanning electron microscopy

3. Results and discussion

3.1 Hardened state properties

3.1.1 Compressive strength development

Based on the results of the compressive strength tests, the replacement of cement with biochar production at 1% produced the highest compressive strength, which was attributed to the optimum dispersion of biochar particles. Furthermore, because of the highly porous nature of the biochar it had good water holding capacity (internal curing). As the concrete hardened, the stored water was released slowly [26], allowing for hydration of the cement to continue. In addition, [27] the pozzolanic property of sugarcane bagasse biochar enabled it to react with the calcium hydroxide ($Ca(OH)_2$) generated during cement hydration, forming additional C-S-H gel and making the concrete matrix more dense and therefore having a higher compressive strength. When cured for 7, 14 and 28 days, the compressive strength increased by 8.21, 5.63 and 7.45%, respectively (Fig. 2). These results were consistent with other findings [28], which suggested that low replacement levels of biochar (1–3%) optimized compressive strength (increasing it by up to 22%), primarily through the internal curing effect. In contrast, the performance of BCS in the current study differed considerably from other studies, where biochar was used to replace coarse aggregates, such as coconut shells, which typically result in an immediate reduction in strength even at the lowest replacement levels due to the inherent weakness of the larger coconut shell biochar particles. The current study demonstrated that utilizing BCS as an SCM provided superior mechanical benefits compared to aggregate replacement; its fine particle size and micro-filler effect promoted a more refined microstructure and improved interfacial bonding, whereas coarse biochar aggregates introduce structural weak points from the onset Furthermore, the inclusion of error bars representing the standard deviation (SD) in the analysis corroborated the statistical significance of this strength enhancement. For example, at 28 days of curing, the compressive strength of the 1% biochar mixture (39.85 ± 0.41 MPa) had a narrow margin of error and a distinct, non-overlapping SD range compared to the control group (37.09 ± 0.63 MPa). This minimal experimental variance and clear separation of error bars confirmed that the 7.45% increase was a definitive and reliable outcome of the biochar's micro-filling and internal curing mechanisms, rather than random testing variability. The current results were consistent with another study [29] that presented the experimental results from the use of rice straw biochar to improve the strength properties of cement, where there was a significant enhancement in the strength of the test blocks, especially at 1% replacement, yielding an average increase in strength of 51%. Other studies have investigated the use of coarse aggregate replacement in cement, producing results different from the current study. For example, [30] reported that the compressive strength of the concrete decreased with an increase in the replacement level of coarse aggregate with coconut shell. Specifically, 5% replacement produced an 8.30% reduction in the compressive strength. In [31], compressive strength testing was conducted on mortar composed of partial substitution with peanut shell biochar. Based on those results, the compressive strength of the 3% peanut shell biochar replacement was 12% less than with 1% replacement. The lower compressive strength at the 3% replacement level could be attributed to the increased porosity of the mortar resulting from the higher biochar contents which may have impaired the full development of strength, notwithstanding the benefits that could have arisen from enhanced cement hydration. In this regard, the optimum replacement level of 1% for BCS in the current study was notably lower than that of other agricultural residues, such as sunflower shell ash (30%) or sugarcane bagasse ash (10–30%), reported in recent studies [12, 13]. This difference was driven primarily by the chemical composition; while biomass ashes are characterized by a high reactive silica content (exceeding 50–80%), which facilitates extensive pozzolanic reactions at higher dosages, BCS functions predominantly as a micro-filler and internal curing agent. At replacement levels above 1%, the high carbon content and the tendency of lightweight biochar particles to agglomerate led to the formation of macro-voids, as confirmed by the SEM analysis, which limits its effective replacement dosage compared to mineral-rich ashes.

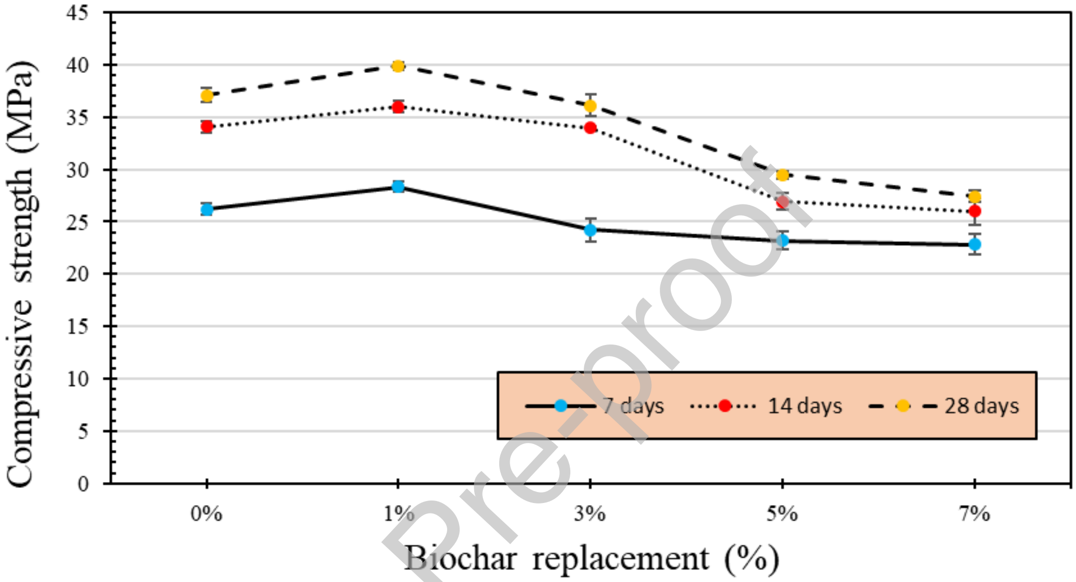

Figure 2: Comparison of compressive strength of sugarcane bagasse (BCS) in concrete

3.1.2 Splitting tensile strength

For this test, at a curing age of 7 days, the splitting tensile strength of the concrete rose by 14.96% and 5.11% with cement replaced with biochar at 1% and 3%, respectively. At curing ages of 14 and 28 days, the splitting tensile strength of the concrete increased by 9.82% and 5.85%, respectively, for 1% biochar replacement. Based on these results, biochar influenced this property similarly to its effect on compressive strength and may have contributed to the improvement in strength in the latter stages of curing [31], as shown in Fig. 3. Furthermore, the reliability of these improvements was substantiated by the evaluation of the SD error bars. Notably, at 7 day of curing, where the most significant percentage increase was observed, the optimal 1% biochar replacement (32.15 ± 1.24 MPa) exhibited a clearly separated SD range from the control mixture (27.97 ± 1.90 MPa) with completely non-overlapping error margins. While the SD ranges slightly converged at 28 day of curing (42.44 ± 1.63 MPa for the 1% replacement versus 40.05 ± 1.08 MPa for the control), the consistently low variance across the testing periods validated the statistical significance of the strength gain. This consistency confirmed that the enhancement in tensile strength was a reliable outcome of biochar inclusion, not an artifact of random testing fluctuations. [32] stated that under moist curing conditions, mortar with pre-soaked biochar had tensile strength values comparable to those of the plain mortar and mortar with dry biochar. This implied that pre-soaked biochar did not contribute additional benefits in improving the tensile strength when there was sufficient available external moisture. [33] presented analytical results showing that the relationships between the tensile strength (s), Young's modulus and fracture energy in terms of the porosity (P) generally followed similar trends as those reported in the existing literature. Furthermore, that study showed that the influence of P and grain size (G) on s are usually separable, although the size of the cracks formed around pores was related to G. The interfacial transition zone) between the cement matrix and biochar particles was denser and smoother than the one between the sand particles and the cement matrix. This improved bonding interface contributed to the improvement in the splitting tensile strength of the concrete [13,15,34].

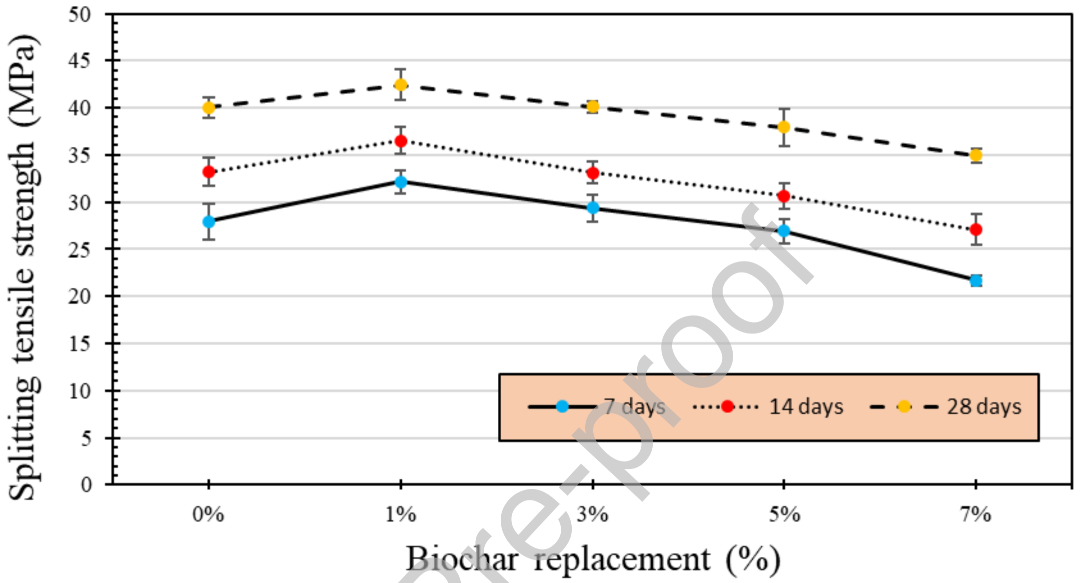

Figure 3. Splitting tensile strength of sugarcane bagasse (BCS) in concrete

3.1.3 Flexural tensile strength

The results of this test were consistent with the results obtained from the two previous experiments. Specifically, concrete with 1% BCS had improved flexural strength by 1.81%, 14.14% and 2.5% at 7-, 14- and 28-days curing age, respectively. This was due to the appropriate replacement level of biochar particles being distributed in the pore spaces of the concrete itself, where they acted as a bridge between the particles of biochar and the hydrated cement, enhancing flexibility and preventing premature failure, as mentioned in [35] and shown in Fig. 4. Examining the data dispersion based on the SD error bars further confirmed the robustness of this test. Notably, at 14 days of curing—where the peak flexural strength improvement of 14.14% occurred—the error margin of the optimal 1% biochar mixture (46.11 ± 1.76 MPa) was separated completely from that of the control group (40.32 ± 1.38 MPa) with no overlap. This distinct gap serves as strong empirical evidence, proving that the enhanced flexural performance was a genuine consequence of the biochar's internal curing and particle bridging mechanisms, rather than a mere experimental fluctuation. In [36], experiments were performed using carbon nano/microparticles obtained from controlled pyrolysis of peanut shells (PS) and hazelnut shells (HS). These materials increased the flexural strength of the cement composites by a maximum value of 5.4 MPa at replacement levels in the range 0.2–0.5 wt%. These results were consistent with [37], where pyrolyzed hazelnut shells were used and were reported to improve the performance of cement composites in terms of compressive strength, peak load under flexure, fracture energy, and durability. The presence of the sugarcane biochar helped to change the crack propagation pattern and prevented straight-line cracks, thus requiring more energy for the material to fail [38]. Additionally, because of its extremely porous structure, biochar has the ability to soak up water inside the concrete and slowly release it over time. This slow release of water continues the hydration of cement over a longer period, leading to more complete hydration and increased strength of the concrete.

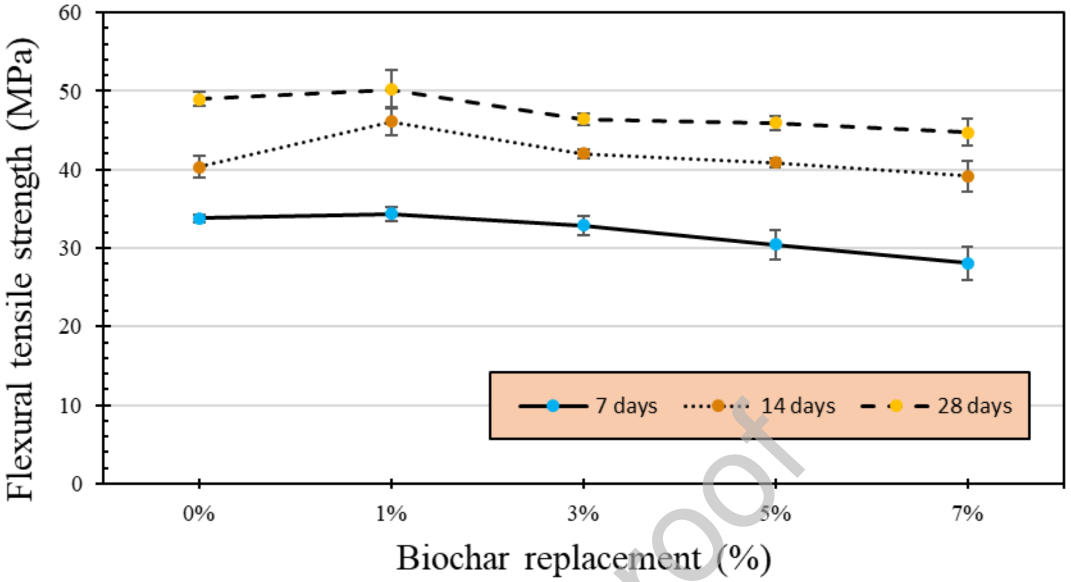

Figure 4: Flexural tensile strength of sugarcane bagasse (BCS) in concrete

3.2 Evaluation of the Microstructure and Chemical Composition

3.2.1 Scanning electron microscopy of biochar from sugarcane

Fig. 5 shows the microstructure of the concrete using SEM, after partial replacement of the cement with BCS, according to ASTM C642 [23]. With 1% biochar replacement (Fig. 1(a)), the concrete surface is relatively dense and the biochar particles are quite well distributed within the cement matrix. There is no distinct agglomeration, with only a few large voids present. Most of the porosity is made up of tiny pores, which could be due to the inherent structure of the biochar itself. In contrast, with 3% biochar (Fig. 3(b)), regions are evident where the biochar particles are closely clustered together forming small groups (micro-agglomeration) in some areas. Around these clusters there are medium-sized voids, due to the incomplete hydration of the cement at the edges of the particles resulting in the formation of interconnected gaps. A similar pattern is observed with 5% biochar (Fig. 3(c)), where the agglomeration of biochar particles is more pronounced (macro-agglomeration), forming large island-like clusters surrounded by macro-voids. These voids tend to interconnect forming weak zones in the concrete matrix which may severely hamper load transfer. With 7% biochar (Fig 3(d)), there are several large agglomeration zones. The voids surrounding these agglomerated clusters are larger in size and present an interconnected network, which could be an initiation site for cracks and possible paths for crack propagation that could seriously compromise the overall strength of the concrete [35].

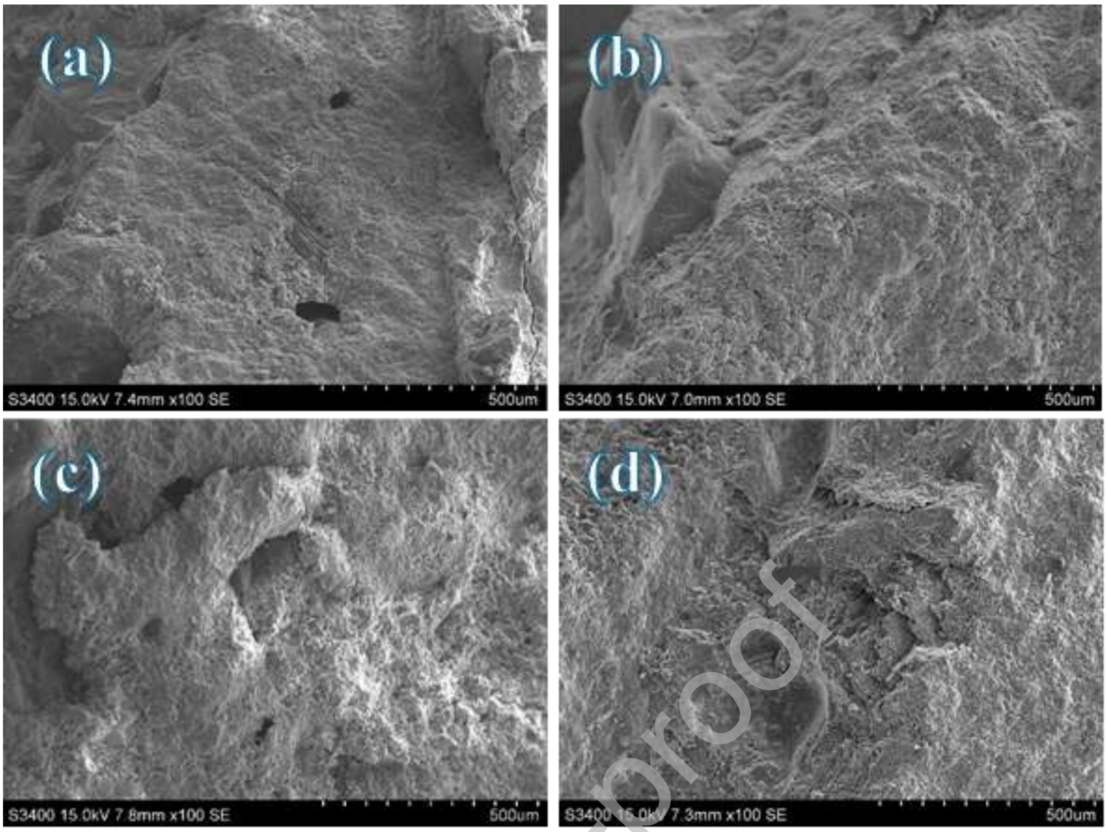

Figure 5. Microstructure photo of sugarcane biochar samples: (a) with biochar instead of 1% (b) with biochar instead of 3% (c) with biochar instead of 5% (d) with biochar instead of 7%

Based on the SEM observations in Fig. 3(b), 3(c), and 3(d), increasing the BCS content led to considerable agglomeration, resulting in the formation of macro-voids and interconnected gaps within the concrete matrix. These voids act as crack initiation sites, providing a clear explanation for the rapid decline in both the splitting tensile and flexural tensile strengths at the 5% and 7% BCS levels. Since tensile stress propagates most easily through these structural weak points, the overall mechanical integrity of the concrete is severely compromised. The microstructure of biochar may vary according to the biomass type. In [39], field emission scanning electron microscopy (FESEM) was carried out to analyze carbonized, micro-sized, coconut shell particles at different magnifications. Those FESEM observations showed that the micro-sized particles of coconut shell had smooth and glossy surfaces, with sharp, well-defined edges—a sign of their innate strength and toughness. Carbon dioxide sequestration by cement-based materials is a chemical process called carbonation in which carbon dioxide reacts with calcium hydroxide ($Ca(OH)_2$) and other elements contained in Portland cement. Biochar, with its highly porous structure and affinity for non-polar compounds, has a good CO_2 adsorption capacity. Furthermore, the addition of biochar to mortar has a substantial impact on the decrease in water permeability and sorptivity, which improves the mortar resistance to moisture penetration and long-term degradation [40,41].

Fig. 6 shows the physical nature and crystalline products resulting from the hydration process in the Portland cement. Figs. 6(a) and 6(b) show the porous structure of the biochar and hydration products, respectively. Due to biochar, which is a carbon-rich material, having a high capacity for water retention [8], it acts as an internal curing agent and thereby improves the efficiency of the cement hydration process. Furthermore, the porous structure of the biochar is responsible for greatly increasing the specific surface area available for the formation of hydration products, such as calcium silicate hydrate (C-S-H) and calcium hydroxide (CH), which are key products in the development of mechanical strength in concrete [27]. [42] found that the pyrolysis temperature had a substantial effect on the thermal and chemical characteristics of biochar samples. The biochars made at temperatures lower than 550°C had the capacity to adsorb about 5% water by weight, suggesting hydrophilic behavior. At this stage, the lignin in the biochar had not yet been converted into hydrophobic polycyclic aromatic hydrocarbons. In contrast, the biochars produced at temperatures above 650 °C became thermally stable and had hydrophobic characteristics as a result of the presence of aromatic compounds. Similarly [43], investigated mortar samples with a wide range of fineness values of inert mineral additives (180–2000 m^2/kg) and replacement values (up to 75%), showing that the degree of early hydration of mortar with non-reactive mineral fillers (such as quartz) was always higher than that of the reference mortar. These results confirmed that the hydration of the cement could be improved with the use of non-reactive mineral additives.

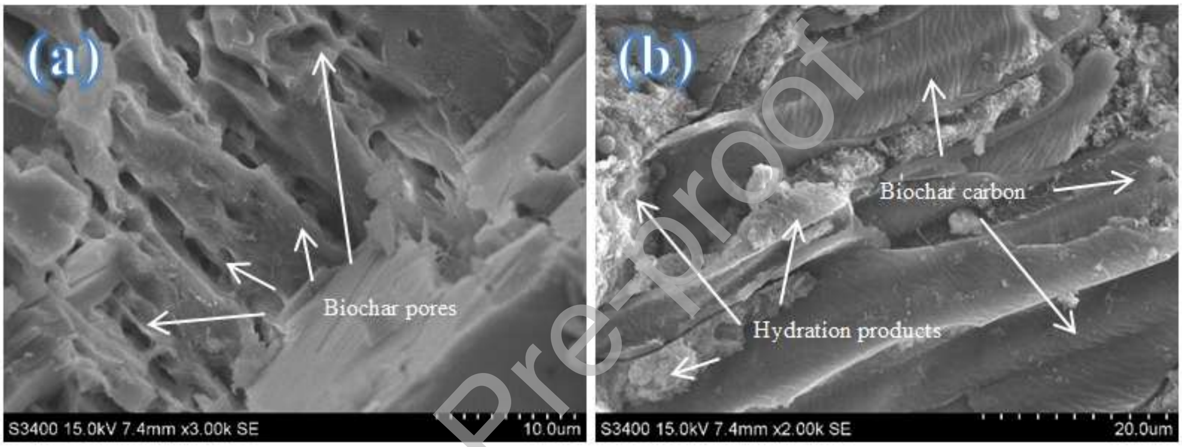

Figure 6. Microstructure images of sugarcane biochar samples: a) biochar pores and b) hydration products

4. Conclusions

This study assessed the effects of using sugarcane bagasse as biochar for the partial replacement in cement on the physical and mechanical properties of high-strength concrete. Four replacement levels were considered (1%, 3%, 5%, 7%) by weight of cement. The most important findings were:

1. The incorporation of 1% BCS was the optimum replacement level, yielding the highest mechanical performance with an increase in compressive, splitting tensile, and flexural strengths by 7.45%, 5.85%, and 2.5%, respectively, at 28 days of curing. The compressive strength of the 1% biochar mix was the strongest compared to the control mix with percentage increases of 8.21%, 5.63% and 7.45% at curing ages of 7, 14, and 28 days, respectively.

2. The strength enhancement at 1% BCS was attributed to the synergistic effect of the micro-filler action [44,14], which refined the matrix density, and the internal curing mechanism, where the porous biochar released moisture to promote continuous cement hydration In addition, an improvement in flexural strength was observed in the 1% biochar mix, especially at 14 days of curing (14.14% increase compared to the control).

3. Mechanical performance significantly declined at replacement levels beyond 1%. The SEM analysis confirmed that higher concentrations led to particle agglomeration and the formation

of macro-voids, which acted as crack initiation sites and compromised material integrity According to the data obtained from mechanical testing and microstructural analysis, 1% by weight of sugarcane bagasse biochar was the optimal amount to improve the strength, microstructure, and material integrity.

4. The study demonstrated that utilizing BCS contributed to a circular economy by converting agricultural waste into a high-value supplementary cementitious material that effectively sequesters biogenic carbon within the durable concrete matrix

In summary, the optimum incorporation of sugarcane bagasse biochar (BCS) at the 1% replacement level not only significantly improved the mechanical properties and refined the microstructure of the high strength concrete but also provided a tangible pathway for the sustainable valorization of agricultural waste. This approach uses a problematic and high-volume byproduct from the sugar industry and converts it into a high-value supplementary cementitious material. The implications for environmental and economic assessment are profound. The use of BCS, a known carbon negative material, promotes active carbon sequestration by sequestering biogenic carbon (fixed during the sugarcane's growth cycle) in the durable concrete matrix for long-term storage. This sequestration mechanism, combined with the reduction of the clinker factor, achieved by the direct replacement of cement, results in a dual mechanism to greatly reduce the embodied CO2 footprint of the concrete. Therefore, this research provides a strong case for the use of BCS as a green construction material, and successfully bridges the gap between material performance optimization and immediate global goals for decarbonization and the shift to a circular economy.

Limitations and future work

While the 1% replacement level produced promising results for sustainable construction, several limitations must be addressed for widespread implementation. First, the inherent variability of biochar quality, which depends on feedstock characteristics and specific pyrolysis conditions, presents a challenge for quality control and standardization. Second, the high porosity of biochar greatly increases water absorption, requiring precise optimization of the water-to-binder ratio and chemical admixtures to mitigate water demand without compromising workability.

Future research should prioritize a comprehensive life cycle assessment to quantify the net carbon reduction and a cost-benefit analysis to ensure economic feasibility at an industrial scale. Furthermore, investigating the "Industrial Symbiosis" model—linking sugar mills directly to the cement industry—is recommended to streamline the supply chain, reduce transportation costs, and establish a robust circular economy for BCS-enhanced concrete

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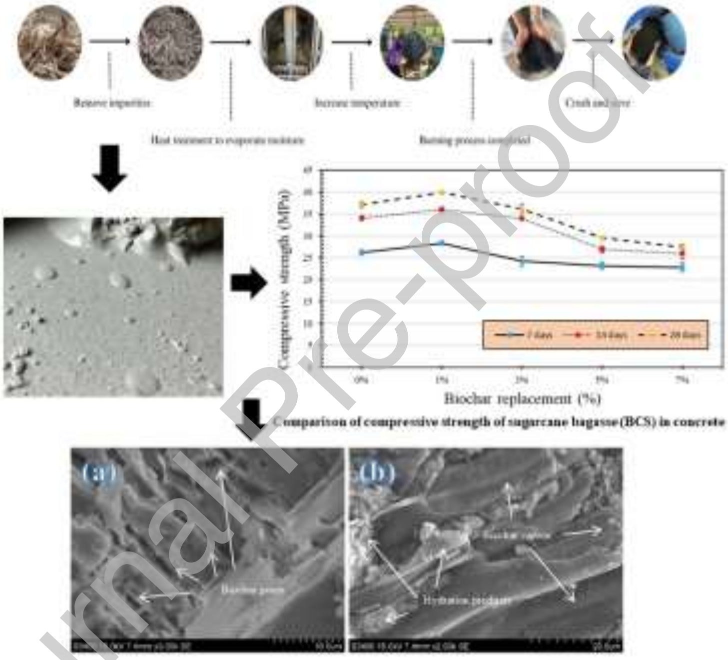
GRAPHICAL ABSTRACT



Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: