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Research Article

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Abstract

Valorizing agricultural residues in cementitious materials can reduce Portland cement demand while creating a productive pathway for biomass waste. This study evaluated coconut shell char (CSC), produced by pyrolysis at 750 °C for 2 h, as a partial cement-replacement constituent in mortar. CSC had a specific gravity of 2.20, a median particle size (D50) of 18.4 µm, and a carbon content of 88.0 wt.%. Mortars containing 5–30 vol.% CSC of the combined cement–CSC solids were assessed for fresh unit weight, flowability, setting time, and 28-day compressive and flexural strength. Increasing CSC decreased fresh unit weight from 2282.8 to 2177.3 kg/m³ and flow from 114.0% to 84.0%, while initial/final setting times increased from 185/228 to 270/339 min. The 5% mixture achieved the highest compressive and flexural strengths, 38.1 and 3.5 MPa, respectively, compared with 31.6 and 3.2 MPa for the control. Higher dosages caused progressive strength loss. Overall, 5–10% CSC provided the best balance between cement displacement, fresh-state performance, and mechanical response, supporting coconut-shell waste valorization in sustainable mortar.

Keywords: coconut shell char; biomass waste valorization; biochar; cement replacement; sustainable mortar; mechanical performance; resource efficiency

1. Introduction

Portland-cement production is associated with substantial greenhouse-gas emissions and intensive consumption of mineral resources, creating strong interest in lower-impact binder systems and circular use of waste-derived materials (Lin et al. 2023; Liu et al. 2022; Senadheera et al. 2023). Biomass residues can be thermochemically converted into carbon-rich char and incorporated into cement-based materials, providing a potential route to combine waste valorization with partial displacement of conventional constituents (Lin et al. 2023; Liu et al. 2022; Maljaee et al. 2021b; Murali and Wong 2024; Senadheera et al. 2023). However, the environmental relevance of such substitution depends on achieving acceptable engineering performance at realistic dosages rather than assuming that the presence of biochar alone guarantees a lower-impact material.

The fresh-state response of biochar-containing cementitious materials is governed largely by particle morphology and water interaction. Rough surfaces, irregular geometry, internal porosity, and high specific surface area can increase water demand and interparticle friction, thereby reducing flowability (Gupta and Kua 2018; Salem and Fen-Chong 2025). Porous char can also retain part of the mixing water and modify early hydration conditions, which may alter setting behavior (Li et al. 2025; Salem and Fen-Chong 2025). These effects are particularly important when biochar is used as a cement-replacement constituent because excessive water demand can offset practical benefits.

Mechanical performance is typically dosage dependent. At low contents, fine biochar particles may contribute through micro-filling, local packing improvement, nucleation-related effects, or enhanced particle-matrix interaction; at higher contents, cement dilution, porosity, and weaker matrix continuity can dominate (Chen et al. 2022; Chen et al. 2023; Gupta and Kua 2018; Hylton et al. 2024; Maljaee et al. 2021b; Murali and Wong 2024; Salem and Fen-Chong 2025; Tan et al. 2020; Zaid et al. 2024; Zhao et al. 2024). Consequently, identifying a practical dosage window is central to evaluating whether a waste-derived char can provide both material efficiency and acceptable structural performance.

Coconut shell is a relevant biomass feedstock in tropical regions because it is abundant, lignocellulosic, and capable of producing carbon-rich char after pyrolysis (Sarkar and Wang 2020). Previous studies have examined coconut- and wood-waste biochar in mortar (Gupta et al. 2020), coconut-shell-biochar-based biocomposites (Anoop and Palanisamy 2025), and coconut shell biochar in recycled aggregate concrete (Arandara et al. 2024). Recent work on biochar-modified cementitious systems also confirms that pyrolysis conditions, particle size, moisture state, and dosage strongly influence fresh, hydration, mechanical, and durability behavior (Chen et al.

2023; Chin et al. 2025; Hylton et al. 2024; Li et al. 2025; Lin et al. 2023; Liu et al. 2022; Maljaee et al. 2021b; Murali and Wong 2024; Tan et al. 2020; Wu et al. 2025; Zaid et al. 2024; Zhang et al. 2023).

Despite this growing literature, limited information is available on coconut shell char produced under one clearly defined high-temperature condition and evaluated over a broad replacement range using a consistent mortar mixture design. In particular, simultaneous assessment of fresh unit weight, flowability, setting behavior, compressive strength, and flexural strength is needed to identify a performance window that is relevant to waste valorization and cement displacement rather than to isolated strength optimization.

Accordingly, this study investigates coconut shell char produced at 750 °C for 2 h as a partial cement-replacement constituent in mortar at nominal levels of 5-30 vol.% of the combined cement-CSC solid phase. The objectives are to (i) characterize the physical, elemental, and morphological properties of CSC; (ii) quantify its effects on fresh unit weight, flowability, and setting time; (iii) evaluate 28-day compressive and flexural strength; and (iv) identify a dosage range that balances engineering performance with resource-efficiency considerations.

The study emphasizes waste valorization and reduced cement use while avoiding unsupported claims of carbon negativity or life-cycle benefit. Environmental implications are therefore discussed in terms of measured cement displacement and material performance, while the need for future life-cycle, durability, and hardened-matrix characterization is stated explicitly.

2. Materials and methods

2.1. Materials and CSC preparation

Ordinary Portland cement (OPC) conforming to ASTM C150/C150M (ASTM International 2024b) was used as the primary binder. Natural river sand was used as fine aggregate; it had a maximum particle size of 4.75 mm, complied with ASTM C33/C33M (ASTM International 2024a), and had a fineness modulus of 2.75 and specific gravity of 2.62. The sand was used in an air-dry condition. Potable tap water was used for mixing and curing. The particle-size distribution of the sand is shown in Fig. 1.

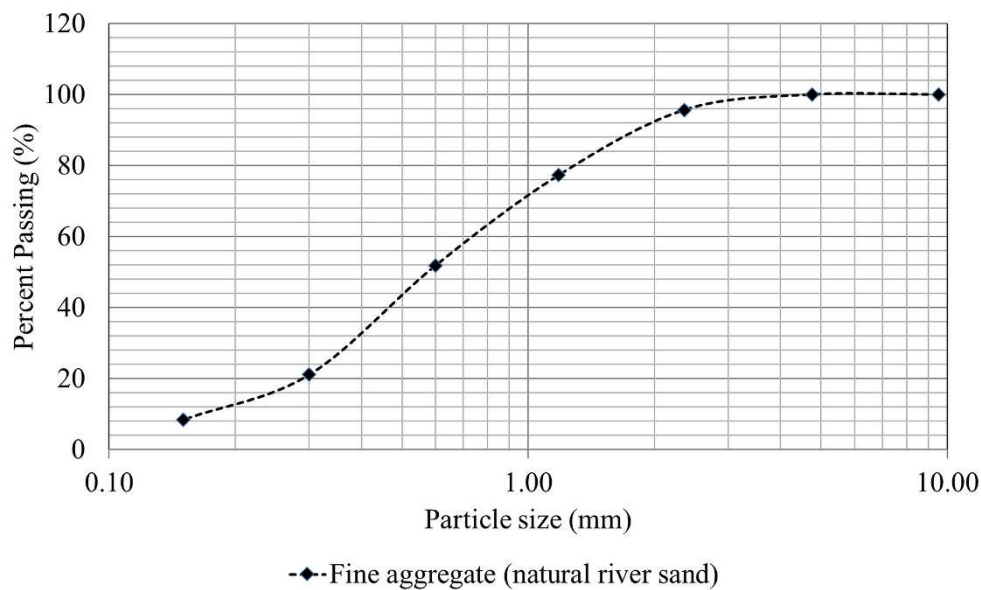


Fig. 1 Particle-size distribution of natural river sand used as fine aggregate

Coconut shells were cleaned and pyrolyzed under limited-oxygen conditions at 750 °C for 2 h to produce CSC (Anoop and Palanisamy 2025; Sarkar and Wang 2020). The resulting material is shown in Fig. 2.

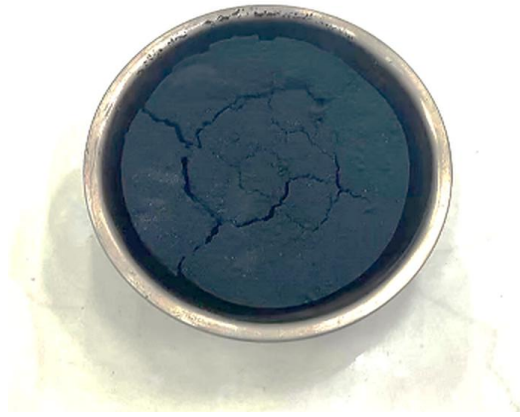


Fig. 2 Coconut shell char produced by pyrolysis at 750 °C for 2 h

After pyrolysis, the CSC was cooled to room temperature, mechanically ground, sieved through a No. 200 sieve, oven-dried at 105 ± 5 °C to constant mass, and stored in sealed containers before use. The processed CSC was therefore introduced as a fine carbon-rich powder rather than as an oxide-rich ash.

Table 1. Physical properties of CSC produced at 750 °C for 2 h.

Property	Value
Specific gravity	2.20
Dry bulk density (kg/m ³)	750
Loss on ignition (%)	4.6
Median particle size, D50 (μm)	18.4

2.2. Characterization of coconut shell char

2.2.1. Physical and chemical properties

The physical and chemical characteristics of CSC were evaluated after oven drying at 105 ± 5 °C to constant mass. The characterization was intended to establish the material features most relevant to its role as a lightweight carbon-rich filler in mortar (Anoop and Palanisamy 2025; Senadheera et al. 2023).

The specific gravity of CSC was measured with a Le Chatelier flask following ASTM C188 (ASTM International 2025). CSC had a specific gravity of 2.20, compared with 3.15 for OPC, indicating a substantially lighter solid phase. This difference is consistent with the porous carbonaceous structure of biomass-derived char and provides a physical basis for the expected reduction in mortar unit weight (Anoop and Palanisamy 2025; Sarkar and Wang 2020; Senadheera et al. 2023).

Loss on ignition (LOI), determined using a procedure adapted from ASTM C311/C311M (ASTM International 2024e), was 4.6%. The relatively low LOI indicates extensive removal of volatile constituents during pyrolysis, although LOI alone does not quantify the chemical reactivity of CSC in cementitious systems.

Laser-diffraction analysis gave a median particle size (D50) of 18.4 μm, within the same order of magnitude as Portland cement particles. This size range can support a physical filler contribution. Because the material was predominantly carbonaceous and no pozzolanic activity test was performed, CSC is treated in this work primarily as a carbon-rich physical constituent rather than as a conventional supplementary cementitious material.

SEM–EDS was used to examine elemental composition. Table 2 shows that carbon dominated the measured spectrum (88.0 wt.%), whereas oxygen and residual inorganic elements (K, Na, Ca, Mg, Si, P, S, and Cl) were present at much lower levels. The composition supports classification of the processed material as a carbon-rich char rather than a mineral ash.

Table 2. Elemental composition of CSC determined by SEM–EDS.

Element	C	O	K	Na	Ca	Mg	Si	P	S	Cl
Content (wt.%)	88.0	6.0	1.7	1.0	0.6	0.5	0.6	0.6	0.7	0.4

2.2.2. SEM–EDS analysis

SEM observations showed irregular CSC particles with a rough and porous surface texture, typical of biomass-derived char after high-temperature thermal treatment (Anoop and Palanisamy 2025; Sarkar and Wang 2020).

EDS indicated approximately 88.0 wt.% C (92.8 at.%) and 6.0 wt.% O, with minor Na, K, Ca, Mg, Si, P, S, and Cl. These minor elements are attributable to residual mineral matter retained from the coconut shell after pyrolysis. Alkali and alkaline-earth species are commonly present in biomass-derived chars and may influence interfacial chemistry, although their specific role was not isolated in the present study (Anoop and Palanisamy 2025; Arandara et al. 2024; Sarkar and Wang 2020).

The EDS procedure and interpretation followed the general guidance of ASTM E1508 (ASTM International 2019). The high carbon and low oxygen contents are consistent with extensive carbonization; however, SEM–EDS provides local elemental information and should not be interpreted as direct evidence of cementitious reactivity.

2.2.3. SEM morphology

SEM micrographs revealed an irregular porous framework with no dominant smooth, dense morphology. The observed surface and pore features are consistent with thermal decomposition of the original lignocellulosic structure (Anoop and Palanisamy 2025; Sarkar and Wang 2020). These characteristics can affect density, water interaction, and mechanical interlocking in mortar, but the present micrographs characterize the CSC particles only and do not directly demonstrate the microstructure of the hardened cement–CSC interface.

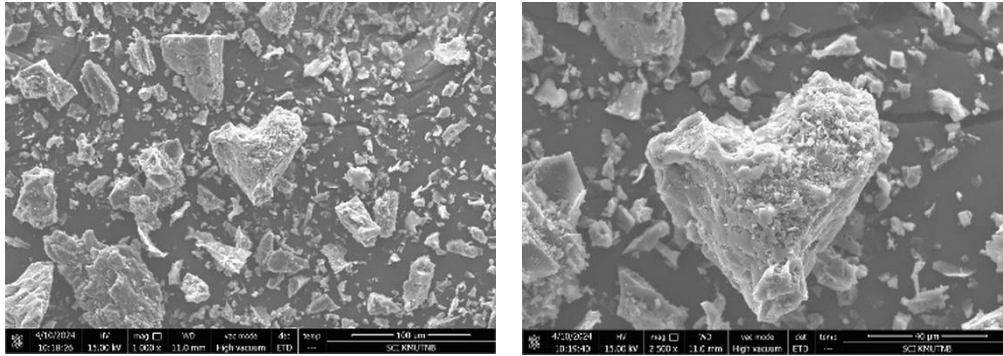


Fig. 3 SEM micrographs showing the irregular morphology and porous surface texture of CSC produced at 750 °C for 2 h

From a materials-design perspective, the combination of low specific gravity, fine particle size, rough texture, and internal porosity suggests competing effects: potential physical filling at low dosage and increasing dilution/water demand as CSC content rises.

2.3. Mix proportions and specimen preparation

Seven mortar mixtures were prepared: an OPC control and six CSC-modified mixtures with nominal CSC fractions of 5, 10, 15, 20, 25, and 30 vol.% of the combined cement–CSC solid phase. The nominal volumetric fractions were calculated from the constituent masses and specific gravities (3.15 for OPC and 2.20 for CSC). The total mass of cement plus CSC was maintained at 450 kg/m³ in the reported mix proportions. The detailed compositions are given in Table 3.

Table 3. Mix proportions of mortar mixtures incorporating CSC.

Mix ID	Cement (kg/m ³)	CSC (kg/m ³)	Sand (kg/m ³)	Water (kg/m ³)
OPC	450.0	0.0	1237.5	225.0
5CSC	434.0	16.0	1237.5	225.0
10CSC	417.6	32.4	1237.5	225.0
15CSC	400.6	49.4	1237.5	225.0

Mix ID	Cement (kg/m ³)	CSC (kg/m ³)	Sand (kg/m ³)	Water (kg/m ³)
20CSC	383.1	66.9	1237.5	225.0
25CSC	365.0	85.0	1237.5	225.0
30CSC	346.3	103.7	1237.5	225.0

OPC = control mixture; CSC = coconut shell char. Nominal CSC percentage denotes the volumetric fraction of the combined cement-CSC solids calculated from constituent masses and specific gravities.

Mortar was mixed mechanically following ASTM C305 (ASTM International 2020a). Cement, sand, and the specified quantity of CSC were first dry blended to promote uniform distribution; water was then added gradually and mixing continued until a visually homogeneous mortar was obtained.

Fresh mortar was cast into 50 × 50 × 50 mm cubes for compressive strength testing in accordance with ASTM C109/C109M (ASTM International 2024c) and 40 × 40 × 160 mm prisms for flexural strength testing in accordance with ASTM C348 (ASTM International 2021). Specimens were compacted in three layers and the top surfaces were leveled after casting.

After casting, specimens were covered or sealed to limit early moisture loss. They were demolded after 24 ± 2 h and water cured at 28 °C until testing at 28 days (ASTM International 2021; ASTM International 2024c).

2.4. Test methods

2.4.1. Flowability

Flowability was measured with a standard flow table following ASTM C1437 (ASTM International 2020b). The flow value was calculated as the percentage increase in spread diameter relative to the mold base diameter. The test setup is shown in Fig. 4.

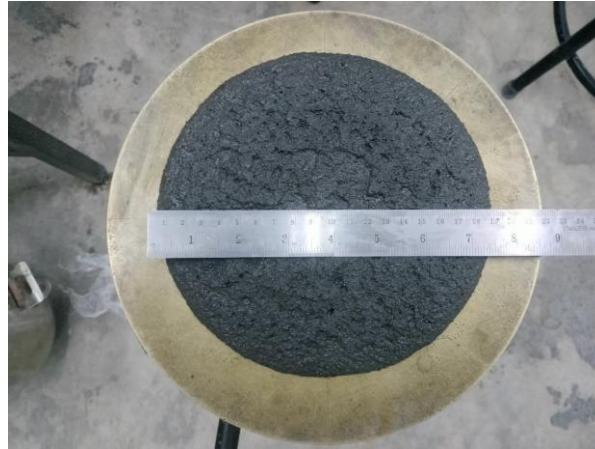


Fig. 4 Flow-table test setup for fresh mortar

2.4.2. Setting time

Initial and final setting times were determined using the penetration-resistance principle of ASTM C403/C403M (ASTM International 2023). Penetration resistance was measured at regular intervals after mixing and the corresponding setting times were obtained from the resistance–time relationship. The setup is shown in Fig. 5.



Fig. 5 Penetration-resistance setup used to determine initial and final setting times

2.4.3. Fresh unit weight

Fresh unit weight was determined using a gravimetric procedure adapted from ASTM C138/C138M (ASTM International 2024d). A container of known volume was filled with compacted fresh mortar and weighed; unit weight was calculated as mass divided by container volume.

2.4.4. Compressive strength

Compressive strength was measured at 28 days on 50 mm cubes following ASTM C109/C109M (ASTM International 2024c). Three specimens were tested for each mixture and the mean value was reported. The test setup is shown in Fig. 6.

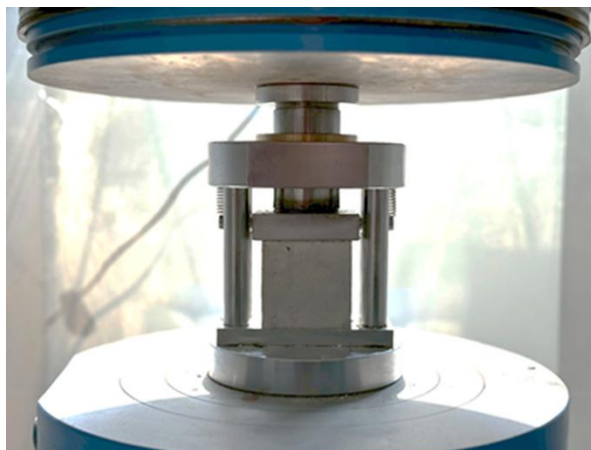


Fig. 6 Compressive-strength test setup for 50 mm mortar cubes

2.4.5. Flexural strength

Flexural strength was measured at 28 days on $40 \times 40 \times 160$ mm prisms under three-point bending following ASTM C348 (ASTM International 2021). Three specimens were tested for each mixture and the mean value was reported. The setup is shown in Fig. 7.

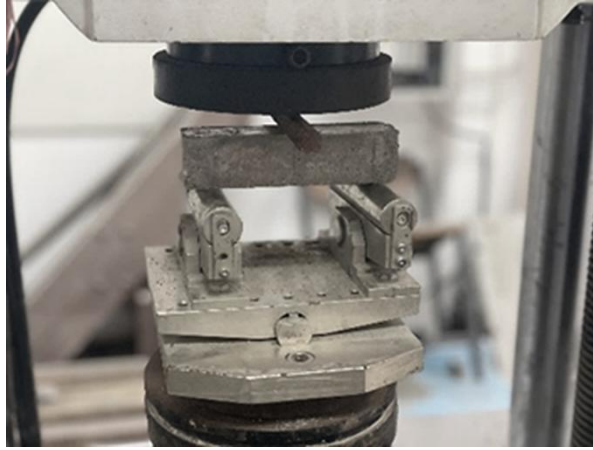


Fig. 7 Flexural-strength test setup for 40 × 40 × 160 mm mortar prisms

Unless otherwise stated, tests were conducted in triplicate. Results are reported as mean ± standard deviation and the error bars in Figs. 8–12 represent the standard deviation of three measurements ($n = 3$). No inferential significance test was reported; comparisons are therefore interpreted descriptively.

3. Results and discussion

3.1. CSC characteristics and mechanistic relevance

CSC produced at 750 °C for 2 h combined a low specific gravity (2.20), fine median particle size (18.4 μm), high carbon content (88.0 wt.%), and a rough porous morphology. These characteristics are consistent with a lightweight carbonaceous filler rather than an oxide-rich reactive SCM (Anoop and Palanisamy 2025; Sarkar and Wang 2020; Senadheera et al. 2023). The low density is expected to lower mortar unit weight, while the rough porous surface can increase water demand and interparticle friction.

At low dosage, the fine CSC fraction may improve local packing and provide additional solid surface within the binder matrix. At higher dosage, the increasing volume of porous, largely non-reactive particles reduces the proportion of hydraulic cement and can interrupt matrix continuity. Because the hardened mortar was not examined by SEM, XRD, TGA, MIP, or other pore-structure techniques, these explanations are mechanistic interpretations of the measured trends rather than direct microstructural evidence.

3.2. Fresh unit weight

Fresh unit weight decreased monotonically from 2282.8 kg/m³ for the OPC control to 2267.7, 2245.5, 2226.9, 2207.5, 2186.1, and 2177.3 kg/m³ for 5CSC through 30CSC, respectively (Fig. 8). The net reduction at 30CSC was approximately 4.6%.

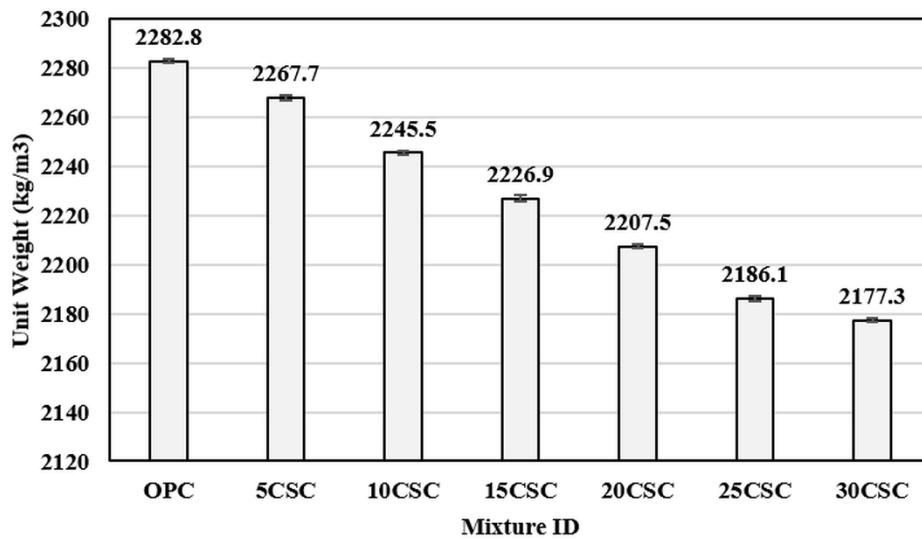


Fig. 8 Fresh unit weight of CSC-modified mortars. Error bars represent standard deviation ($n = 3$)

The reduction is consistent with replacement of part of the denser cement phase by CSC with lower specific gravity and internal porosity. Similar density reductions have been reported for biochar-modified cementitious materials (Anoop and Palanisamy 2025; Chin et al. 2025; Lin et al. 2023; Maljaee et al. 2021a; Maljaee et al. 2021b; Murali and Wong 2024; Senadheera et al. 2023; Tan et al. 2020; Wu et al. 2025). The result confirms that CSC can reduce material mass per unit volume, although the magnitude is moderate and must be evaluated together with changes in flow and strength.

The near-linear density response across the dosage series provides a useful practical indicator of the increasing char fraction, but it does not by itself demonstrate particle dispersion or pore refinement in the hardened matrix.

3.3. Flowability

Flow decreased from 114.0% for the control to 100.0%, 96.0%, 92.0%, 90.5%, 87.5%, and 84.0% as CSC increased from 5% to 30% (Fig. 9). The 30CSC mixture therefore exhibited a 26.3% reduction relative to the control.

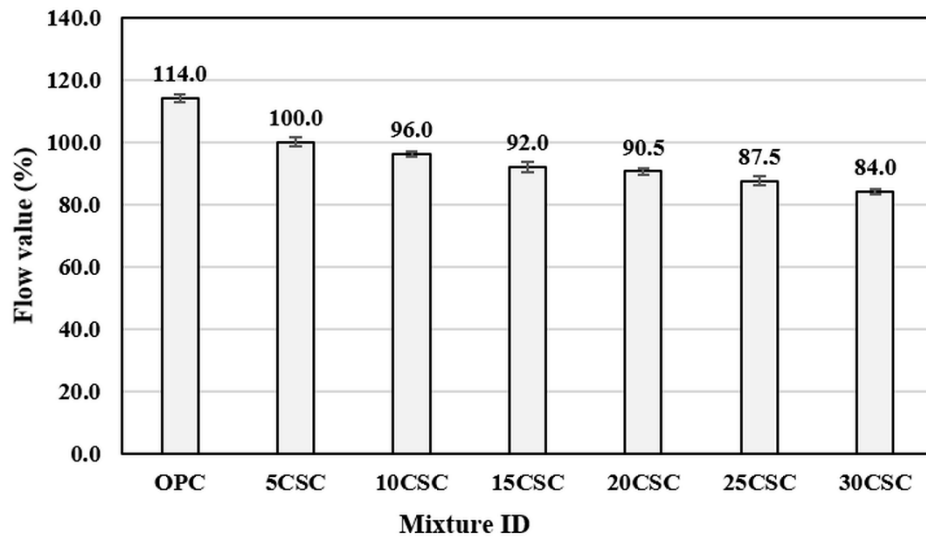


Fig. 9 Flow values of CSC-modified mortars. Error bars represent standard deviation (n = 3)

The workability loss is attributed primarily to the rough surface, irregular geometry, and porous structure of CSC. These features increase friction and the effective surface area that must be wetted, while internal pores can retain part of the mixing water. Under the fixed water-to-binder ratio used here, less free water is consequently available for lubrication as CSC dosage increases.

This interpretation is consistent with studies showing that biochar influences fresh-state behavior through water entrainment, surface texture, dosage, and moisture availability (Chen et al. 2023; Gupta and Kua 2018; Hylton et al. 2024; Salem and Fen-Chong 2025; Senadheera et al. 2023; Tan et al. 2020). The progressive flow reduction also identifies workability as a key constraint on using CSC at high dosage unless moisture conditioning or admixture optimization is introduced.

3.4. Setting time

The control mortar had initial and final setting times of 185 and 228 min, respectively. With CSC incorporation, initial setting increased to 230–270 min and final setting to 291–339 min (Fig. 10). At 30CSC, the increases relative to the control were approximately 46% and 49% for initial and final setting, respectively.

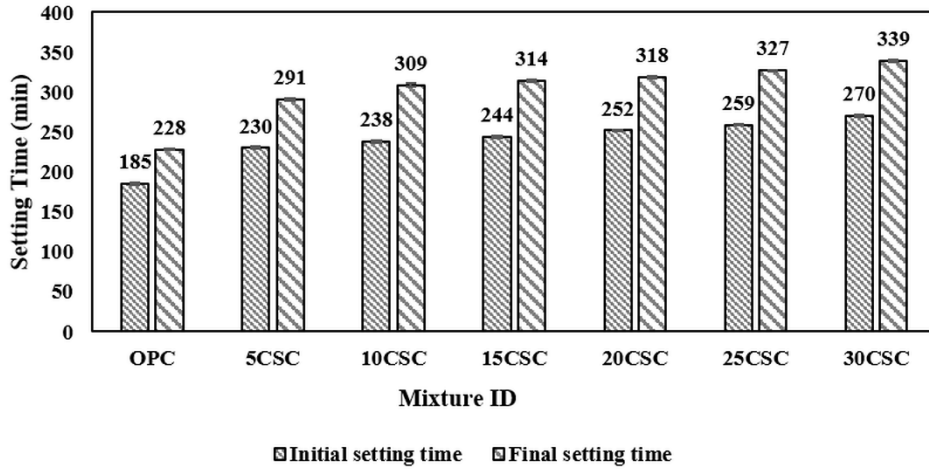


Fig. 10 Initial and final setting times of CSC-modified mortars. Error bars represent standard deviation ($n = 3$)

The dominant explanation is binder dilution: increasing CSC content reduces the fraction of reactive clinker available to generate early hydration products. Because CSC was treated as a predominantly carbonaceous, non-pozzolanic constituent in this study, increasing dosage delays the development of a continuous rigid skeleton.

Water interaction may provide an additional contribution. Porous char can adsorb or retain mixing water, modifying short-term water availability and the local hydration environment (Chen et al. 2023; Li et al. 2025; Maljaee et al. 2021b; Salem and Fen-Chong 2025; Tan et al. 2020). The present experiment did not directly measure sorption kinetics or heat evolution, so the relative contribution of dilution and water retention cannot be separated.

From an application perspective, the systematic retardation increases the available working time but also delays finishing and early strength development. The effect is modest at low CSC dosage and becomes progressively more pronounced as the replacement level increases.

3.5. Compressive strength

The 28-day compressive strength of the OPC mortar was 31.6 MPa. Strength increased to 38.1 MPa at 5CSC (+20.6%), 35.1 MPa at 10CSC (+11.1%), and 32.8 MPa at 15CSC (+3.8%), before falling to 26.7, 25.3, and 22.5 MPa at 20CSC, 25CSC, and 30CSC, respectively (Fig. 11). The response therefore shows a clear low-dosage optimum followed by dilution-controlled deterioration.

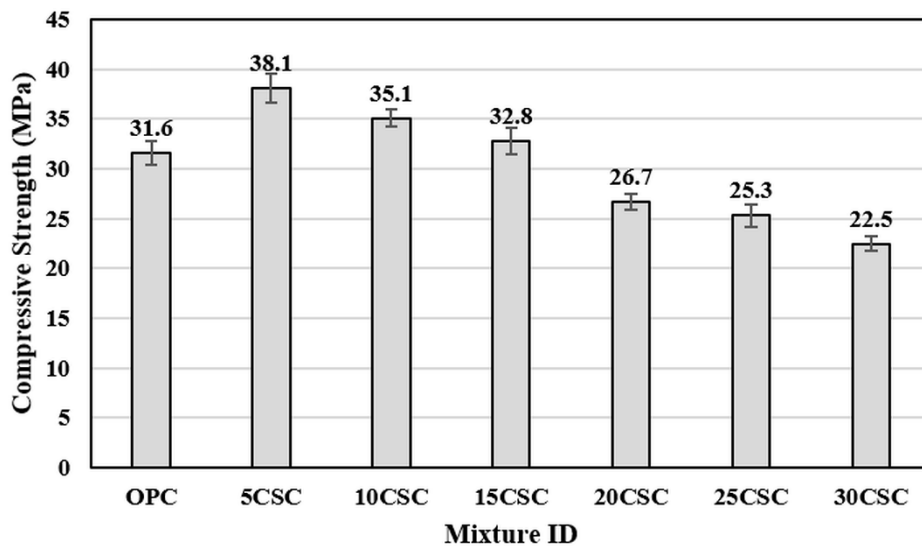


Fig. 11 Compressive strength of CSC-modified mortars at 28 days. Error bars represent standard deviation ($n = 3$)

At low dosage, fine CSC particles may contribute a micro-filling effect and improve local packing, while the rough surface can promote mechanical interlocking with surrounding hydration products. These explanations are consistent with prior biochar studies (Anoop and Palanisamy 2025; Chen et al. 2022; Chen et al. 2023; Gupta and Kua 2018; Hylton et al. 2024; Maljaee et al. 2021b; Murali and Wong 2024; Tan et al. 2020; Zhao et al. 2024), but they remain inferential here because the hardened matrix and interfacial zones were not directly characterized.

The observed optimum agrees with the broader dosage-dependent behavior of biochar–cement composites: limited incorporation can be beneficial, whereas excessive substitution tends to reduce strength (Chen et al. 2023; Chin et al. 2025; Gupta and Kua 2018; Hylton et al. 2024; Maljaee et al. 2021b; Murali and Wong 2024; Salem and Fen-Chong 2025; Tan et al. 2020; Zaid et al. 2024; Zhao et al. 2024). The 5CSC result is therefore best interpreted as a balance between physical particle effects and retention of sufficient reactive cement.

Beyond 15% CSC, cement dilution and the increasing fraction of porous char dominate. Reduced hydration-product volume, higher susceptibility to internal voids, and weaker matrix continuity provide plausible explanations for the decline. The data identify 5–10% as the most favorable range for compressive performance under the fixed mixture conditions used here.

3.6. Flexural strength

Flexural strength followed the same general dosage response as compressive strength. The control reached 3.2 MPa, while 5CSC achieved the maximum value of 3.5 MPa (+9.4%). Values then decreased to 3.2, 3.0, 2.5, 2.1, and 1.8 MPa for 10CSC through 30CSC (Fig. 12).

The modest improvement at 5CSC is consistent with a limited filler/packing contribution and possible enhanced mechanical interaction between the rough CSC surface and the hydrated matrix. Direct evidence of crack bridging or interfacial strengthening is not available because crack paths and the hardened interface were not imaged.

The sharp decline at higher CSC contents is consistent with increasing matrix discontinuity and cement dilution, both of which are critical for flexural resistance. Similar dosage-dependent trends have been reported in biochar-modified cementitious systems (Anoop and Palanisamy 2025; Chen et al. 2023; Chin et al. 2025; Hylton et al. 2024; Li et al. 2025; Lin et al. 2023; Liu et al. 2022; Maljaee et al. 2021b; Murali and Wong 2024; Senadheera et al. 2023; Tan et al. 2020; Wu et al. 2025; Zaid et al. 2024; Zhang et al. 2023).

The parallel compressive and flexural responses reinforce the interpretation that the useful CSC dosage is governed by a balance between low-dosage physical benefits and high-dosage loss of continuous load-bearing cement paste.

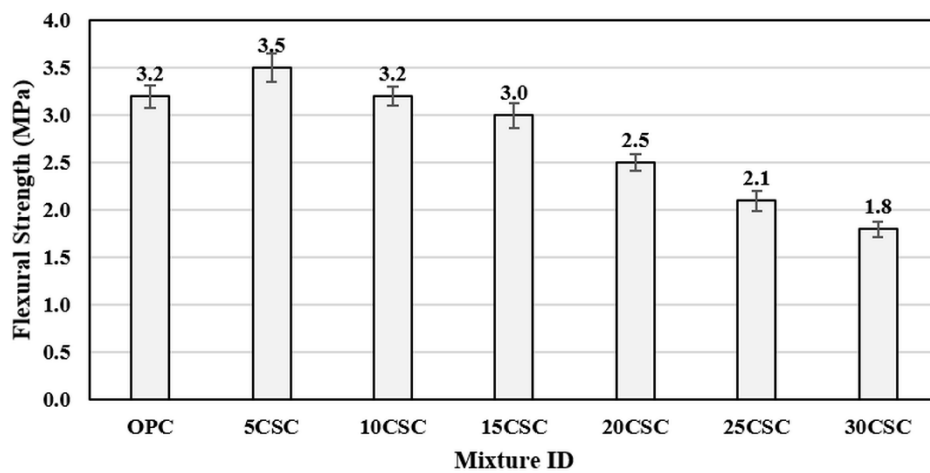


Fig. 12 Flexural strength of CSC-modified mortars at 28 days. Error bars represent standard deviation (n = 3)

3.7. Performance window and practical implications

Across the measured properties, increasing CSC consistently reduced fresh unit weight and flowability and extended setting time, while mechanical performance exhibited a distinct optimum at low dosage. These trends are consistent with the low density and porous morphology of biomass-derived char and with the dosage-dependent behavior reported for biochar-cement systems (Anoop and Palanisamy 2025; Chen et al. 2023; Hylton et al. 2024; Lin et al. 2023; Liu et al. 2022; Maljaee et al. 2021b; Murali and Wong 2024; Sarkar and Wang 2020; Senadheera et al. 2023; Tan et al. 2020; Wu et al. 2025; Zaid et al. 2024; Zhang et al. 2023).

The 5CSC mixture provided the strongest overall mechanical response, whereas 5-10% CSC represented the most balanced range when cement displacement, workability, setting, density, and strength are considered together. Above 15%, the negative effects of cement dilution and porous-particle incorporation outweighed the low-dosage physical benefits.

The results support CSC valorization as a carbon-rich constituent for mortar, but they do not establish carbon negativity, long-term durability, or a chemical contribution to hydration. Those outcomes require direct environmental assessment and hardened-matrix characterization rather than inference from fresh and mechanical properties alone.

3.8. Resource-efficiency and environmental implications

The mix design progressively displaced Portland cement with CSC. Relative to the control cement content of 450.0 kg/m³, cement content decreased to 434.0 kg/m³ at 5CSC and 417.6 kg/m³ at 10CSC, corresponding to reductions of approximately 3.6% and 7.2% by mass per cubic metre, respectively. These two mixtures still exceeded the control compressive strength by 20.6% and 11.1%. This combination of cement displacement and maintained or improved mechanical performance is the strongest resource-efficiency outcome supported directly by the present data.

At higher CSC contents, additional cement displacement was accompanied by substantial loss of strength and workability, illustrating that waste incorporation alone is not an adequate sustainability criterion. The present results demonstrate a technically viable valorization pathway for coconut-shell-derived char, but the net environmental effect cannot be quantified without accounting for pyrolysis energy, grinding, transport, avoided waste handling, service-life performance, and end-of-life scenarios. Future work should therefore combine durability testing with life-cycle assessment or an equivalent carbon and resource-accounting framework.

4. Conclusions

Coconut shell char produced at 750 °C for 2 h was a low-density, fine, porous, carbon-dominated material with a specific gravity of 2.20, D50 of 18.4 µm, and carbon content of 88.0 wt.%. These characteristics support its use primarily as a carbon-rich physical constituent rather than as a conventional reactive supplementary cementitious material.

Increasing CSC dosage reduced fresh unit weight by up to 4.6%, reduced flow by up to 26.3%, and prolonged initial and final setting. Mechanical performance was optimized at low dosage: 5CSC achieved 38.1 MPa compressive strength and 3.5 MPa flexural strength, corresponding to increases of 20.6% and 9.4% over the control. At 10CSC, compressive strength remained 11.1% above the control. Strength decreased once CSC exceeded 15%, consistent with increasing cement dilution and matrix discontinuity.

Under the fixed mixture conditions used here, 5-10% CSC provides the most practical performance window. Within this range, cement content was reduced by approximately 3.6-7.2% by mass per cubic metre while compressive strength was maintained above the control, demonstrating a credible resource-efficiency pathway for coconut-shell waste valorization. The inferred filler/packing mechanisms require direct verification in hardened mortar, and any claim of net environmental benefit should be supported by durability testing and life-cycle assessment.

References

- Anoop PP, Palanisamy T (2025) Coconut shell biochar-Bacillus cereus DKBovi-5 based biocomposite as a sustainable additive for cement mortar: Effect of pyrolysis temperature on characterization, strength, hydration, and healing. *Sustain Chem Pharm* 46:102112. <https://doi.org/10.1016/j.scp.2025.102112>
- Arandara KP, Paravithana GN, Priyadarshana ST, Pitawala HMTGA, Dissanayake R (2024) Evaluation of coconut shell biochar on recycled aggregate concrete through petrographic studies. *Constr Build Mater* 428:136342. <https://doi.org/10.1016/j.conbuildmat.2024.136342>
- ASTM International (2019) Standard guide for quantitative analysis by energy-dispersive spectroscopy, ASTM E1508-12a(2019). ASTM International, West Conshohocken, PA, USA
- ASTM International (2020a) Standard practice for mechanical mixing of hydraulic cement pastes and mortars of plastic consistency, ASTM C305-20. ASTM International, West Conshohocken, PA, USA
- ASTM International (2020b) Standard test method for flow of hydraulic cement mortar, ASTM C1437-20. ASTM International, West Conshohocken, PA, USA
- ASTM International (2021) Standard test method for flexural strength of hydraulic-cement mortars, ASTM C348-21. ASTM International, West Conshohocken, PA, USA

- ASTM International (2023) Standard test method for time of setting of concrete mixtures by penetration resistance, ASTM C403/C403M-23. ASTM International, West Conshohocken, PA, USA
- ASTM International (2024a) Standard specification for concrete aggregates, ASTM C33/C33M-24. ASTM International, West Conshohocken, PA, USA
- ASTM International (2024b) Standard specification for Portland cement, ASTM C150/C150M-24. ASTM International, West Conshohocken, PA, USA
- ASTM International (2024c) Standard test method for compressive strength of hydraulic cement mortars (using 50 mm [2 in.] cube specimens), ASTM C109/C109M-24. ASTM International, West Conshohocken, PA, USA
- ASTM International (2024d) Standard test method for density (unit weight), yield, and air content (gravimetric) of concrete, ASTM C138/C138M-24a. ASTM International, West Conshohocken, PA, USA
- ASTM International (2024e) Standard test methods for sampling and testing coal ash or natural pozzolans for use in concrete, ASTM C311/C311M-24. ASTM International, West Conshohocken, PA, USA
- ASTM International (2025) Standard test method for density of hydraulic cement, ASTM C188-25. ASTM International, West Conshohocken, PA, USA
- Chen L, Zhou T, Yang J, Qi J, Zhang L, Liu T, Dai S, Zhao Y, Huang Q, Liu Z, Li B (2023) A review on the roles of biochar incorporated into cementitious materials: Mechanisms, application and perspectives. *Constr Build Mater* 409:134204. <https://doi.org/10.1016/j.conbuildmat.2023.134204>
- Chen T, Zhao L, Gao X, Li L, Qin L (2022) Modification of carbonation-cured cement mortar using biochar and its environmental evaluation. *Cem Concr Compos* 134:104764. <https://doi.org/10.1016/j.cemconcomp.2022.104764>
- Chin SC, Gunasekaran PK, Che J, Anand N, Gimbin J (2025) Bamboo biochar and carbonation enhanced the compressive and flexural strength of cement mortar. *Next Mater* 9:100959. <https://doi.org/10.1016/j.nxmater.2025.100959>
- Gupta S, Krishnan P, Kashani A, Kua HW (2020) Application of biochar from coconut and wood waste to reduce shrinkage and improve physical properties of silica fume-cement mortar. *Constr Build Mater* 262:120688. <https://doi.org/10.1016/j.conbuildmat.2020.120688>
- Gupta S, Kua HW (2018) Effect of water entrainment by pre-soaked biochar particles on strength and permeability of cement mortar. *Constr Build Mater* 159:107-125. <https://doi.org/10.1016/j.conbuildmat.2017.10.095>
- Hylton J, Hugen A, Rowland SM, Griffin M, Tunstall LE (2024) Relevant biochar characteristics influencing compressive strength of biochar-cement mortars. *Biochar* 6:87. <https://doi.org/10.1007/s42773-024-00375-6>
- Li S, Jin L, Chen X, Hu M, Geng Y, Li K, Liu Y, Hu Q, Zhang S (2025) Effect and mechanisms of biochar particle size and dosage on the hydration process and mechanical properties of cementitious materials. *Constr Build Mater* 472:140931. <https://doi.org/10.1016/j.conbuildmat.2025.140931>
- Lin X, Li W, Guo Y, Dong W, Castel A, Wang K (2023) Biochar-cement concrete toward decarbonisation and sustainability for construction: Characteristic, performance and perspective. *J Clean Prod* 419:138219. <https://doi.org/10.1016/j.jclepro.2023.138219>
- Liu J, Liu G, Zhang W, Li Z, Xing F, Tang L (2022) Application potential analysis of biochar as a carbon capture material in cementitious composites: A review. *Constr Build Mater* 350:128715. <https://doi.org/10.1016/j.conbuildmat.2022.128715>
- Maljaee H, Madadi R, Paiva H, Tarelho LAC, Ferreira VM (2021b) Incorporation of biochar in cementitious materials: A roadmap of biochar selection. *Constr Build Mater* 283:122757. <https://doi.org/10.1016/j.conbuildmat.2021.122757>
- Maljaee H, Paiva H, Madadi R, Tarelho LAC, Morais M, Ferreira VM (2021a) Effect of cement partial substitution by waste-based biochar in mortars properties. *Constr Build Mater* 301:124074. <https://doi.org/10.1016/j.conbuildmat.2021.124074>
- Murali G, Wong LS (2024) A comprehensive review of biochar-modified concrete: Mechanical performance and microstructural insights. *Constr Build Mater* 425:135986. <https://doi.org/10.1016/j.conbuildmat.2024.135986>
- Salem T, Fen-Chong T (2025) Clarifying the effect of biochar on the hydration, setting, workability, and mechanical strength of cementitious materials. *Constr Build Mater* 485:141892. <https://doi.org/10.1016/j.conbuildmat.2025.141892>

- Sarkar JK, Wang Q (2020) Different pyrolysis process conditions of South Asian waste coconut shell and characterization of gas, bio-char, and bio-oil. *Energies* 13(8):1970. <https://doi.org/10.3390/en13081970>
- Senadheera SS, Gupta S, Kua HW, Hou D, Kim S, Tsang DCW, Ok YS (2023) Application of biochar in concrete - A review. *Cem Concr Compos* 143:105204. <https://doi.org/10.1016/j.cemconcomp.2023.105204>
- Tan K, Pang X, Qin Y, Wang J (2020) Properties of cement mortar containing pulverized biochar pyrolyzed at different temperatures. *Constr Build Mater* 263:120616. <https://doi.org/10.1016/j.conbuildmat.2020.120616>
- Wu F, Zhang Q, Dong S, Cai Y, Yang S, Xu F, Luo P, Jiang J (2025) Biochar modification enhances mechanical and durability properties of cement-based materials. *Sci Rep* 15:22174. <https://doi.org/10.1038/s41598-025-06968-w>
- Zaid O, Alsharari F, Ahmed M (2024) Utilization of engineered biochar as a binder in carbon negative cement-based composites: A review. *Constr Build Mater* 417:135246. <https://doi.org/10.1016/j.conbuildmat.2024.135246>
- Zhang Q, Feng P, Shen X, Lu J, Ye S, Wang H, Ling TC, Ran Q (2023) Utilization of solid wastes to sequester carbon dioxide in cement-based materials and methods to improve carbonation degree: A review. *J CO2 Util* 72:102502. <https://doi.org/10.1016/j.jcou.2023.102502>
- Zhao Z, El-Naggar A, Kau J, Olson C, Tomlinson D, Chang SX (2024) Biochar affects compressive strength of Portland cement composites: A meta-analysis. *Biochar* 6:21. <https://doi.org/10.1007/s42773-024-00309-2>

Statements and Declarations

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Authors' Contributions

Phattharachai Pongsopha, Buchit Maho, Tanapat Namjan, and Darrakorn Intarabut contributed to the research and manuscript preparation. All authors read and approved the final manuscript.

Ethical Approval

Ethical approval was not required for this study because the research did not involve human participants, human biological materials, animals, or personally identifiable data.

Consent to Participate

Not applicable. This study did not involve human participants.

Consent to Publish

Not applicable. This manuscript does not contain any individual person's data, images, or other material requiring consent for publication.

Competing Interests

The authors declare that they have no relevant financial or non-financial interests to disclose.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author on reasonable request.