

VALORIZATION OF BIODEGRADABLE WASTE BIOCHAR AS SUPPLEMENTARY CEMENTITIOUS MATERIAL: MECHANICAL, DURABILITY AND MICROSTRUCTURAL CHARACTERISTICS

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ABSTRACT

The construction industry around the world needs methods to reduce the production of Ordinary Portland Cement clinker, which's still responsible for about eight percent of human-made CO₂ emissions. Biodegradable waste biochar, created when organic waste from farms forests and cities is heated without oxygen gives a material that can keep carbon out of the air permanently. This review looks at research where waste biochar is added to cement pastes, mortars, ultra-high-performance concrete. It looks at how the kind of waste the heat used to make the biochar and its mineral composition affect how the mix flows how fast it sets, how it holds weight and how long it lasts. Tests show that using 1.0 to 3.0 percent biochar improves the shape of the pores speeds up the hardening of tricalcium silicate by giving spots for crystals to grow boosts bending strength by up to 23.5 percent and makes the mix more resistant when it first cracks by deflecting cracks. If than 4.0 to 5.0 percent biochar is added without treatment the mix becomes difficult to work with as particles clump together and the cement is diluted, leading to more gaps in the structure. In water-tight mixes wet biochar acts as a good internal water source raising the hardening level from 42 percent to 59 percent and keeping compressive strength above 140 MPa without causing shrinkage cracks. Quick carbonation curing of biochar cement also locks carbon by turning CO₂ into calcium carbonate crystals in the tiny pores. Machine learning models show that composite strength reacts in a way to water-to-binder ratio and biochar amount pointing to steps for making consistent biochar reducing alkaline loss and checking long-term weather resistance.

Keywords: Biochar Valorization; Cement Replacement; Hydration Kinetics; Internal Curing; Microstructural Densification; Carbon Mineralization; Ultra-High-Performance Concrete.

1. INTRODUCTION

1.1 Decarbonization Imperatives and Clinker Substitution Challenges

The making of Ordinary Portland Cement (OPC) still supplies a share of global human-made greenhouse gases about 8% of all CO₂ released. Those emissions come from two steps. First limestone CaCO₃ is heated above 1400 °C. Breaks into lime CaO and CO₂. Second

the big furnaces burn fuels to keep the kiln running. At the time more and more crop leftovers, wood scraps and city waste are burned in fields or thrown into landfills releasing lots of methane and carbon.

When the same waste is heated without oxygen it turns into biochar, a tough carbon-rich solid. Adding biochar to cement mixes makes a loop that turns buildings into lasting carbon sinks and cuts the need for new hydraulic clinker. Traditional extra cement materials, like coal fly ash or blast-furnace slag are fading because factories cut emissions. But waste feedstocks that can become biochar stay renewable found everywhere. Fit into a circular economy.

1.2 Mechanistic Role of Biochar in Hydration and Fracture Toughness

When biochar replaces a part of cement it does more than just fill space. If 1.0 to 3.0 wt% of biochar is used the tiny biochar pieces give spots for calcium silicate hydrate C-S-H gels and ettringite to form early on. Siliceous biochars from rice husk or bamboo can react with $\text{Ca}(\text{OH})_2$ to create extra strength hydrates. In mixes with little water like ultra-high-performance concrete (UHPC) the capillary network in biochar supplies water inside the mix helping to keep the mix from drying out and shrinking.

Putting biochar into fresh mix creates problems. Its many cells and large surface area soak up water making the mix thick lowering slump and speeding up setting. If, than 5.0 wt% biochar is added particles clump together and the cement is diluted, creating defects that lower compressive strength.

We review how experiments use waste-derived biochar as a partial replacement for cement. Section 2 builds a map that links where the feedstock comes from and how it is pyrolyzed to the properties of the resulting biochar. Section 3 studies the flow of mixes how strength grows over time how internal curing works in ultra-high-performance concrete (UHPC) how carbonation can be sped up and how machine learning models can predict outcomes. Section 4 pulls together the findings and says what should be done first to get biochar into structural codes. Section 5 lists the institutions that helped.

2.1 Feedstock Provenance and Pyrolysis Regimes

We find that the physical shape, the stability of the carbon and how reactive biochar is all depend a lot on where the feedstock comes from and on the thermochemical conversion settings such as the peak temperature of pyrolysis the rate at which the material is heated and the length of time it is kept hot. Lignocellulosic forestry residues, for example mixed wood sawdust and timber chips make biochars that have an elemental carbon share (usually over 70–85 wt%) low ash content (under 3 wt%) and a neat honeycomb of large pores. These wood-derived chars give a skeleton and can hold a lot of water so they are good for internal curing.

We note that agricultural residues, such as rice husk and bamboo have a lot of silica and other minerals. Rice husk biochar (RHB) can hold up to 13.5% of amorphous SiO_2 while bamboo biochar shows pozzolanic oxide fractions ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) that almost meet the ASTM C618 Class N natural pozzolan standard. When we look at the crystal phases agricultural biochars show two types: a amorphous background and sharp crystalline peaks which means that the carbon framework is stable and that there are reactive mineral parts.

We observe that industrial gasification chars and syngas by-products are made at temperatures above 750–850 °C. These materials are highly graphitized have surface areas and have small particle sizes. Because of these traits they can act as micro-fillers and as templates for crystal growth inside the cement paste.

2.2 Microstructural Geometry and Porosity Dynamics

We see that using field-emission scanning electron microscopy (FE-SEM) and synchrotron X-ray micro-computed tomography we see that biochar particles have a network of pores that connects together over size ranges. Pores from 1 to 10 μm are spread throughout the carbon skeleton and larger channels come from the plant cell walls.

We see that this design gives biochar particles skeletal and outer densities (0.25–0.65 g/cm^3) compared with unhydrated cement particles (about 3.15 g/cm^3). Because the pores are so many biochar particles pull water strongly from the liquid around them. They take in mix water and dissolved ions while the mix is being made. They also act as spots where hydration products can start to form.

Feedstock and process	Physical properties	Reactive mineral phase	Principal matrix interaction
Mixed wood sawdust; slow pyrolysis (500–600 °C)	Carbon 75–85 wt%; surface area 15–45 m ² /g; pores 2–12 µm	Low ash; <2.5% SiO ₂ and CaO reported	Capillary water storage, internal curing and physical nucleation
Rice husk; medium pyrolysis (550–650 °C)	Carbon 50–65 wt%; surface area 50–120 m ² /g; pores 0.5–5 µm	Up to 13.5% amorphous SiO ₂	Portlandite consumption and secondary C–S–H generation
Bamboo; fast pyrolysis (600–700 °C)	Carbon 65–78 wt%; surface area 80–160 m ² /g; pores 1–8 µm	Pozzolanic oxides; combined fraction reported >65%	Crack bridging, micro-interlocking and improved fracture energy
Gasification residues; >800 °C	Carbon 80–90 wt%; surface area >180 m ² /g; pores 0.1–2 µm	Trace alkali and iron silicates	Micro-filler packing and early hydration nucleation
Corn cob or stover; anaerobic pyrolysis (500–550 °C)	Carbon 60–72 wt%; remaining values not reported in source	Not reported in source	Not reported in source

Table 1. Feedstock properties and principal cement-matrix interactions

3. EXPERIMENTAL PERFORMANCE, HYDRATION DYNAMICS, AND COMPARATIVE MECHANICS

3.1 Fresh Rheology and Water Entrainment Dynamics

We notice that adding unconditioned biochar to fresh cementitious pastes, mortars and concretes always makes the mix less workable. Because biochar has pores and a large surface area it can absorb between 1.2 and 2.1 times its own dry weight of water in the first 10 to 15 minutes after it meets the liquid. This quick absorption cuts the water-to-cement ratio makes particles slide against each other harder speeds the slump loss and makes the plastic viscosity higher.

We see that to fix this flow problem without raising the water-to-binder ratio two mixing methods are used: pre-saturation and superplasticizer compensation. In pre-saturation we soak biochar in water before we mix it. It does not pull water from the bulk mix but keeps its own moisture for later curing. In the method we add polycarboxylate ether superplasticizers (0.5 to 1.5 wt% of binder) to spread the particles apart and keep the mix flowing while the effective water-, to-binder ratio stays the same.

3.2 Mechanical Strength Development, Fracture Toughening and Machine Learning Modeling

Experimental investigations across mortars and structural concretes show that adding biochar follows a dosage-dependent performance threshold. When replacement levels are between 1.0 wt % and 3.0 wt % mechanical properties of the mix are consistently better than those of plain OPC control specimens. Aneja, Sharma and Singh showed that concrete with 4 % rice husk biochar had a 2.32 % 28-day compressive strength, a 23.52 % higher flexural strength and a 17.3 % higher durability performance. The increase in strength comes from biochar's ability to keep water inside the mix during curing while fine siliceous particles in biochar react with calcium hydroxide that is released to make secondary calcium silicate hydrates.

Beyond strength biochar also makes mortar tougher and better at absorbing energy during bending. Suarez-Riera and colleagues found that adding 2.0 wt % wood-chip biochar raised mortar fracture energy by much as 70 % and raised flexural strength by 15 %. The wood-chip biochar acts like a reinforcement that pushes crack tips and makes the fracture surface more winding.

When replacement goes beyond 4.0 to 5.0 wt % the mechanical strength of the mix usually falls. The main reason is that the biochar dilutes the cement so there are hydraulic C₃S and C₂S phases and the biochar does not make up for this loss. Light biochar particles also clump together making porous clusters that become points of high stress when the mix is pressed.

To study these trends researchers used machine-learning models such as Random Forests, AdaBoost, Decision Trees and Logistic Regression on large experimental data sets. When modeling biochar-cement mortar composites Random Forest models reached prediction accuracies of up to 96 % (R² > 0.95). This shows that compressive strength is mainly controlled by the non-linear relationship between the water-to-binder ratio and the amount of biochar added.

3.3 Internal Curing and Autogenous Shrinkage Mitigation in Ultra-High-Performance Concrete

Biochar's curing ability is especially useful in ultra-high-performance concrete (UHPC) where very low water-to-binder ratios ($w/b < 0.20$) often cause strong self-drying and shrinkage cracks. Dixit and colleagues studied mixed-wood biochar in three size ranges—fine ($<125 \mu\text{m}$) medium ($125\text{--}250 \mu\text{m}$) and coarse ($250\text{--}500$) and 8 wt % cement replacement. Isothermal calorimetry showed that pre-soaked biochar made the mix set faster producing up to 30 % heat after 96 hours than the control UHPC mix. Thermogravimetric analysis found that the overall hydration level rose from 42 % in the control UHPC to 59 % in mixes with 5 wt % biochar. As the humidity drops water held in biochar's capillary network flows into the drying matrix helping unreacted cement grains to hydrate. Fine biochar mixes reached a 28-day strength of 144 MPa, almost the same as the 150 MPa of the control mix while cutting autogenous shrinkage. Dixit, Verma and Pang also tried a system that mixes wood biochar with calcined marine clay showing that both clinker and fine silica aggregates can be replaced by low-carbon options.

3.4 Accelerated Carbonation Mineralization and Durability Limitations

Biochar-cement composites can. Store carbon efficiently by using accelerated carbonation curing. Sai Praneeth and colleagues studied how biochar speeds up carbonation in ash systems and found that biochar improves how much carbon is captured. The connected pore channels, in biochar let carbon dioxide gas travel into the mix, where it reacts with calcium hydroxide ($\text{Ca}(\text{OH})_2$) and C-S-H to form dense calcium carbonate (CaCO_3) crystals: $\text{Ca}(\text{OH})_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}$. This carbonation process makes the capillary voids tighter and raises the mix's early-age compressive strength. Biochar also tightens the mix's size distribution cutting water permeability by 22 % to 25 % and improving resistance to sulfate and chloride attacks.

Despite these benefits several long-term durability trade-offs require evaluation. Both pozzolanic reactions and accelerated carbonation consume free portlandite lowering the solution pH below the depassivation threshold ($\text{pH} \approx 11.5$) necessary to maintain the protective passive film on steel reinforcement. This reduction in alkalinity increases the risk of steel corrosion in concrete exposed to moisture and chlorides. Additionally biochar can alter the air-void system of concrete. Saturated biochar particles that remain filled with water may undergo hydraulic dilation during cyclic freezing and thawing initiating internal micro-cracks. Furthermore biochars produced at pyrolysis temperatures ($<450^\circ\text{C}$) can retain volatile organic fractions, polycyclic aromatic hydrocarbons (PAHs) and mobile salts which may leach out under acidic groundwater exposure and compromise matrix integrity over time.

3.5 Comparative Literature Matrix

Study	Material and dosage	Reported finding	Limitation or bottleneck
Sai Praneeth et al. (2020)	Corn and wood-waste biochar (500°C), fly ash-cement; 1–3 wt% replacement or 1–2 wt% addition	Accelerated CO_2 sequestration and dense CaCO_3 precipitation in capillary pores; increased micro-hardness	Strength falls at higher additions; specialized carbonation chamber required
Aneja, Sharma and Singh (2022)	Rice-husk biochar (550°C), structural concrete; 0–5 wt% replacement	Source reports +2.32% compressive strength, +23.52% flexural strength and +17.3% durability at 2–4 wt%	Water absorption can reduce workability; mix adjustment needed
Dixit, Gupta, Pang and Kua (2019)	Mixed-wood sawdust (500°C), UHPC; 2, 5 and 8 wt% replacement	At 5 wt% fine biochar ($<125 \mu\text{m}$), hydration rose from 42% to 59%; 144 MPa strength; up to 30% more heat at 96 h	Coarse fractions reduce fracture energy; pre-saturation needed
Dixit, Verma and Pang (2021)	Wood biochar and calcined marine clay in UHPC; 2–5 wt% replacement	Combined clinker replacement and aggregate valorization; dense microstructure observed by micro-CT	Toughness reported about 20% below plain control UHPC

Study	Material and dosage	Reported finding	Limitation or bottleneck
Sobuz, Khan and Kabbo et al. (2024)	Biomass-residue biochar in cement mortar; 0.5–4 wt% replacement	Random Forest models reached up to 96% accuracy ($R^2 > 0.95$) for compressive-strength prediction	Models need broader validation across regional feedstocks
Lorenzoni, Bruno et al. (2024)	Wood-biomass biochar in micro-paste	Study is cited in the source reference list; comparative performance details were not supplied	Details not reported in source

Table 2. Comparative findings reported in the reviewed studies

4. CONCLUSIONS

The experimental literature confirms that biodegradable waste-derived biochar provides a viable carbon-negative mineral modifier for cementitious composites across standard and ultra-high-performance matrices. Systematic evaluation establishes a cement replacement window of 1.0 to 3.0 wt%, where micro-filler packing, heterogeneous nucleation and pozzolanic reactions from reactive silica improve flexural strength by up to 23.5 % and compressive strength by 2 % to 18 %. Exceeding this replacement threshold generally degrades properties due to clinker dilution, workability loss and particle agglomeration that creates stress concentrations. In water-to-binder systems such as UHPC, pre-saturated biochar mitigates self-desiccation increasing the degree of cement hydration from 42 % to 59 % while preserving compressive strengths exceeding 140 MPa. Furthermore biochar's interconnected pore network facilitates accelerated carbonation curing, binding gaseous CO_2 as stable crystalline CaCO_3 polymorphs that densify the pore architecture and reduce water permeability. Machine learning models, Random Forest architectures successfully capture these non-linear composite behaviors with predictive accuracies up to 96 % identifying effective w/b ratios and substitution dosage as primary design parameters. To transition this technology into building codes future research must focus on standardizing conversion regimes developing targeted chemical admixtures to manage rheology without manual pre-soaking assessing long-term steel passivation and corrosion risks and conducting comprehensive cradle-to-gate life cycle assessments.

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