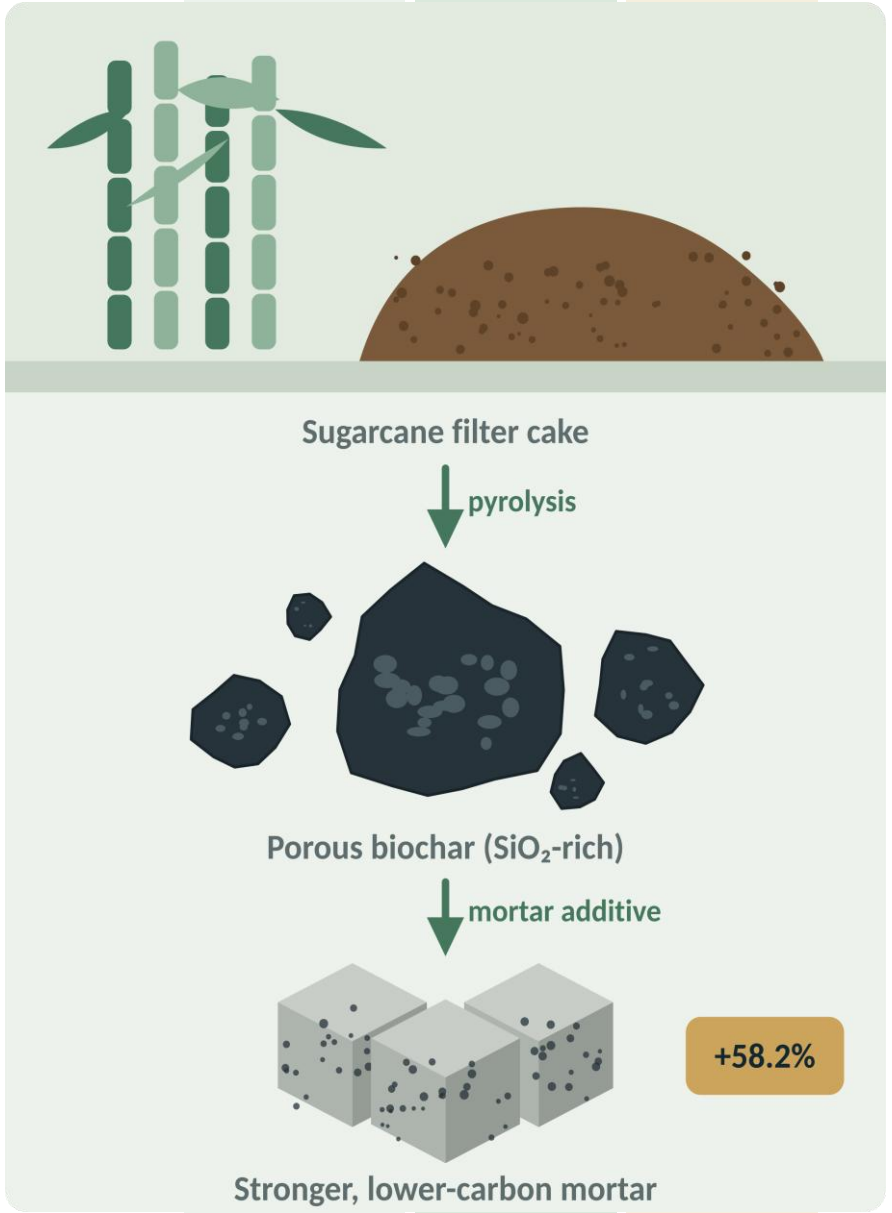
Innovative Upcycling of Biochar and Industrial Waste for Low-Carbon Construction Materials

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Department of Environmental and Sustainable Engineering,
Faculty of Engineering, Chulalongkorn University, Thailand



Academic Profile



Dr. Chitiphon Chuaicham

h-index = 31
publications = 76

Education:

Doctor of Engineering - Earth Resources Engineering — *Kyushu University, Japan*

Master of Science - Chemistry — *Mahidol University, Thailand*

Bachelor of Science - Chemistry — *Mahidol University, Thailand*

Work experience:

Lecturer — ***Dec. 2024 - present***

Department of Environmental and Sustainable Engineering, Faculty of Engineering, Chulalongkorn University, Thailand

Assistant Professor — ***Mar. 2024 – Aug. 2024***

Faculty of Science and Engineering, Waseda University, Japan

Research Assistant Professor — ***Oct. 2020 – Mar. 2024***

Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Japan

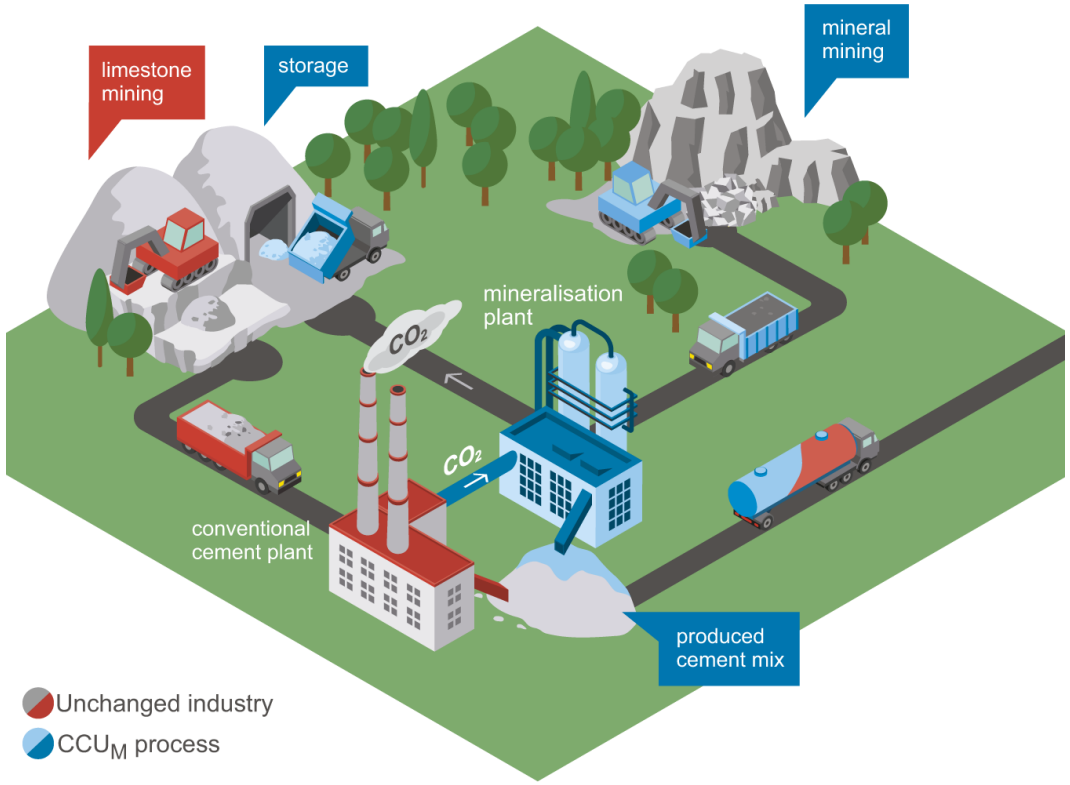
Research fellow — ***Oct. 2019 – Sep. 2020***

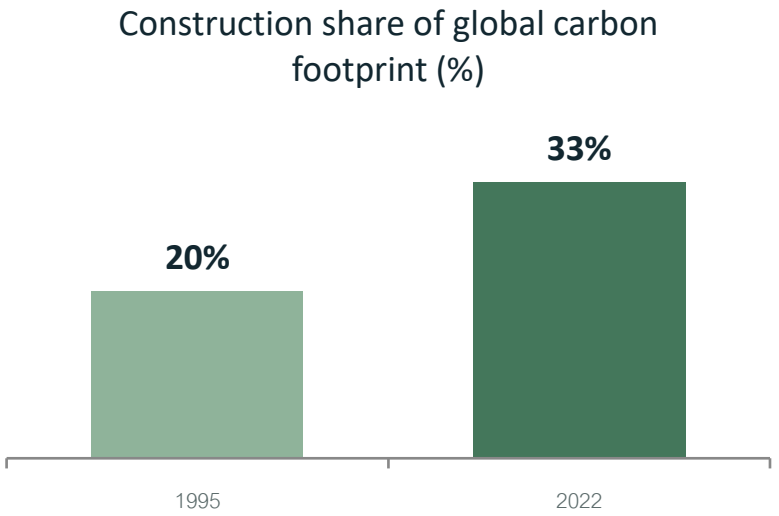
Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Japan

Expertise: **Photocatalysis, Upcycling of waste materials, Material characterizations**, Wastewater treatment, Synchrotron technique, Clean energy

Research interests: **Material chemistry,** Wastewater remediation, Catalyst, **Photocatalyst, Waste utilization, Hydrogen evolution, Carbon dioxide reduction, Supplementary cementitious materials (SCMs)**

Cement and concrete: a CO_2 challenge at scale





Implication: reduce clinker demand with supplementary cementitious materials (SCMs) while maintaining or improving performance.

~8% of global CO_2 emissions come from cement production

0.9–1.0 t of CO_2 emitted for every tonne of cement produced

~33% of the global carbon footprint is attributed to the construction industry (2022)

Low-carbon materials: SCMs and waste valorization

Partially replacing clinker and upcycling low-value waste into functional binder inputs

Conventional SCMs

- Fly ash, GGBFS, silica fume
- Calcined clays (LC3), metakaolin
- Pozzolanic or latent hydraulic reactions
- Better packing and pore refinement

Waste-derived biochar

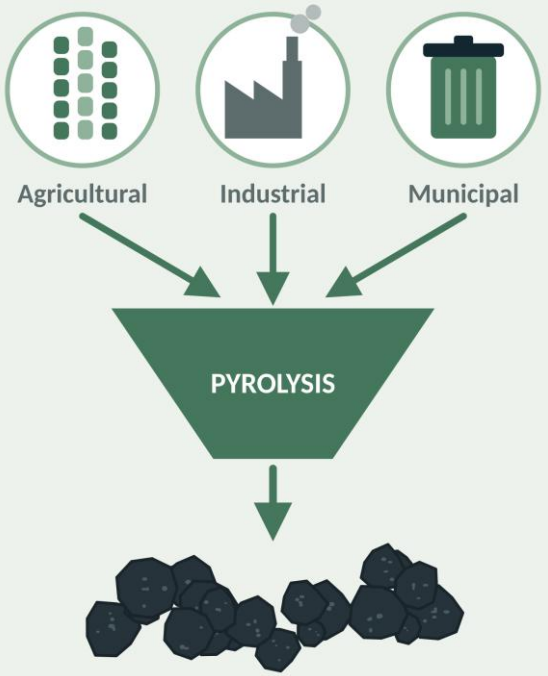
- Carbon-rich pyrolysis product
- From municipal, industrial and agricultural waste
- Internal curing, filler effect, potential pozzolanicity
- Stores carbon, lowering net footprint

Thailand's filter cake

2.1–3.3 Mt

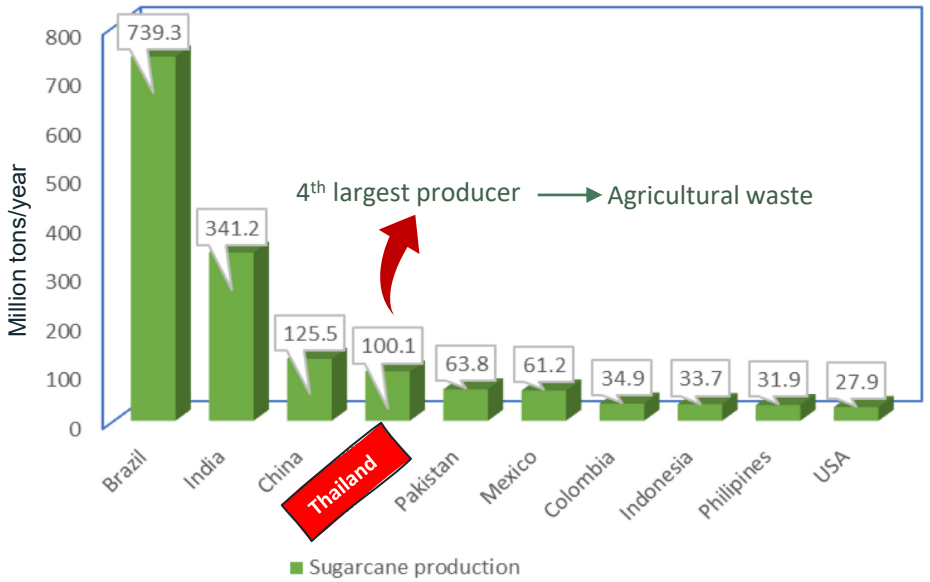
filter cake produced per year

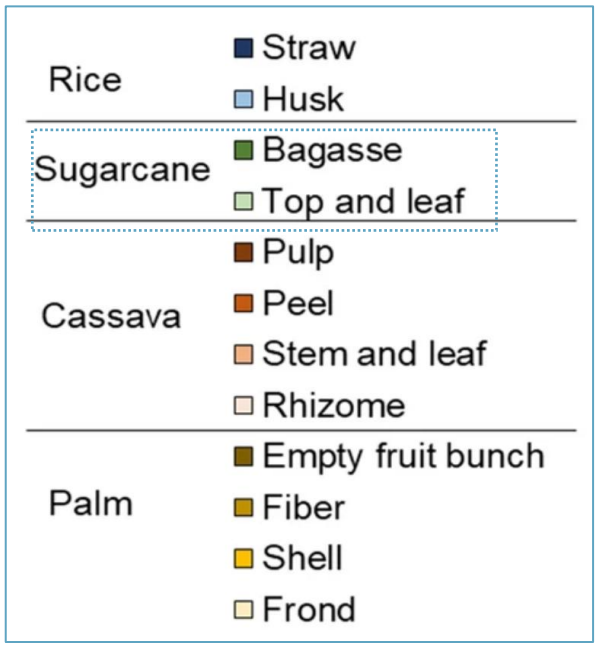
- Landfill causes GHG, odor and leachate
- Biochar turns it into a value-added additive

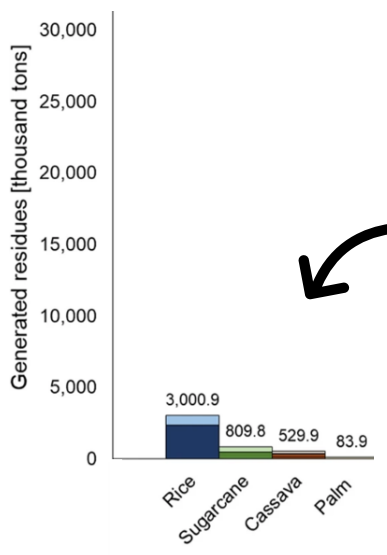


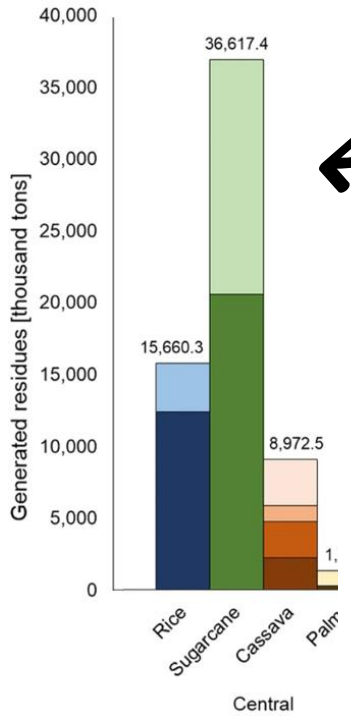
Biochar combines physical, chemical and carbon-storage benefits, not only pozzolanic reactivity.

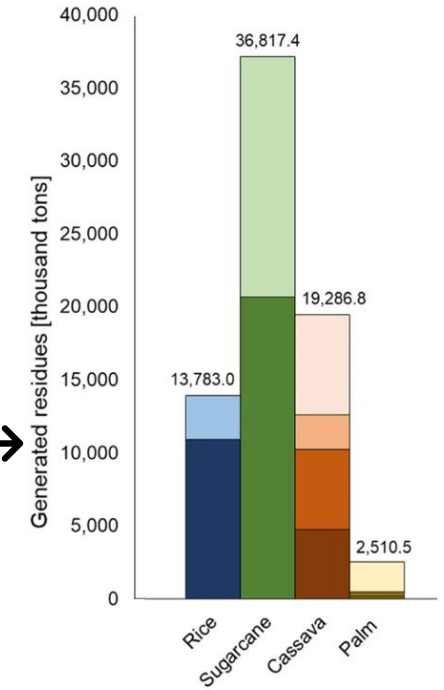
Agricultural waste

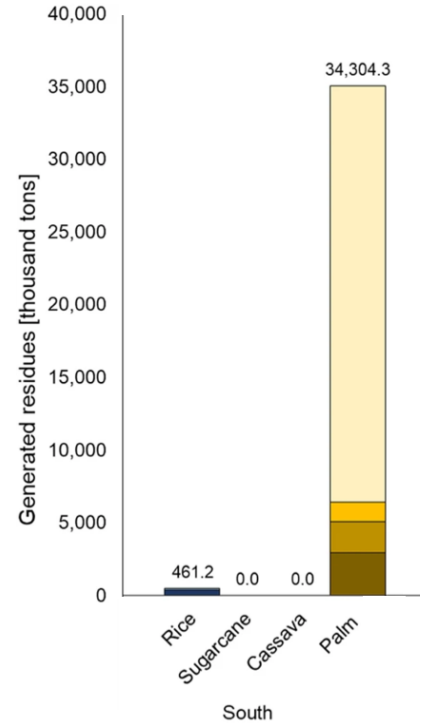












Filter cake waste impacts

Filter cake generated in Thailand

~ **2.1-3.3** million tons year^{-1}

Improper Disposal of FC



Greenhouse gas emissions

Generation of CO_2, CH_4, and N_2O from decomposing organic matter.

Odor generation

Release of odors (e.g., NH_3, H_2S)

Water contamination

Leachate rich in organic matter, nutrients, and dissolved solids can pollute water sources

Soil contamination

Excessive or uncontrolled disposal may cause soil properties

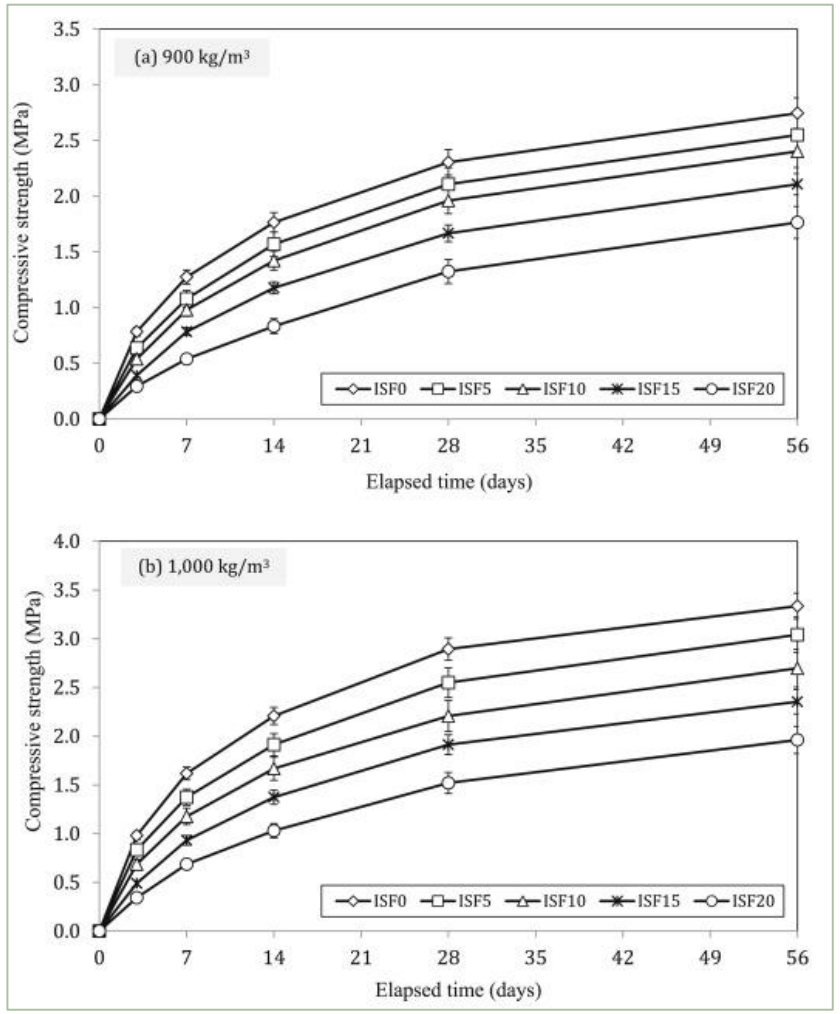
Pest and vector problem

Attracts flies, rodents, and other disease vectors around disposal sites.

Ref: Byakodi & Babu, 2022. EuroBiotech J. 6(1): 32–39, Bano et al., 2025. Cleaner Waste Syst. 10: 100230, https://www.indiamart.com/proddetail/pressmud-2852661137155.
https://www.researchgate.net/figure/Typical-composition-of-filter-cake-from-sugar-industry_tbl1_341682615

Filter cake waste utilization

Incinerated sugarcane filter cake (ISF) for lightweight foam concrete (LFC)



Compressive strength development of LFC mixtures

Replacement of cement by ISF (0%, 5%, 10%, 15%, and 20%) replacement

Reduces compressive strength

Due to **a lower Ca/Si ratio** and increased **air-void effects**

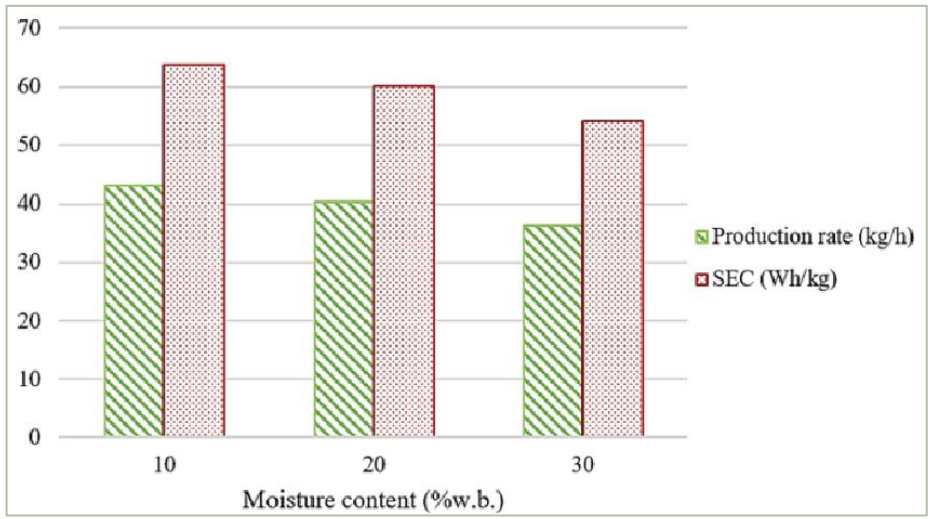
Successfully used incinerated sugarcane filter cake as a cement **replacement in LFC,** but compromised **compressive strength**

Ref: Makul, N., & Sua-iam, G. (2016). Characteristics and utilization of sugarcane filter cake waste in the production of lightweight foamed concrete. Journal of Cleaner Production, 126, 118–133.

Filter cake waste utilization

Filter cake palletization





Effect of initial moisture content on production rate and specific energy consumption (SEC)

Parameters	Calculations	Values
(1) Input sugarcane (million tonnes/year)	131 llion tonnes/ year	
(2) Estimated filter cake (4%) [18]	131 × 0.04	5.24 million tonnes/ year @MC 65%
	5.24(100–65)/ (100–10)	2.04 million tonnes/ year @MC 10%
(3) Heating value (MJ/kg)	12.21	
(4) Heat energy gained	$12.21 \times 2.04 \times 10^9$	2.49×10^{10} MJ/year
(5) Energy output (power plant efficiency 38%)	$0.38 \times 2.49 \times 10^{10}$	9.47×10^9 MJ/year
(6) Electricity production (1 MJ = 0.2778 kWh)	$9.47 \times 10^9 \times$ 0.2778	2.63×10^9 kWh/year
(7) Electrical tariff 4 THB/kWh (0.12 *US dollar*/ kWh)	$2.63 \times 10^9 \times 4$	10.52×10^3 million THB/year (318 million US dollar/ year)

remark: 1 US dollar = 33.082 THB.

Energy and value of filter cake pellets for Thailand (Production year of 2018/ 2019).

High heating value (~12,210 kJ/kg)

↓

Suitable for energy applications

Approach towards a zero-waste solution

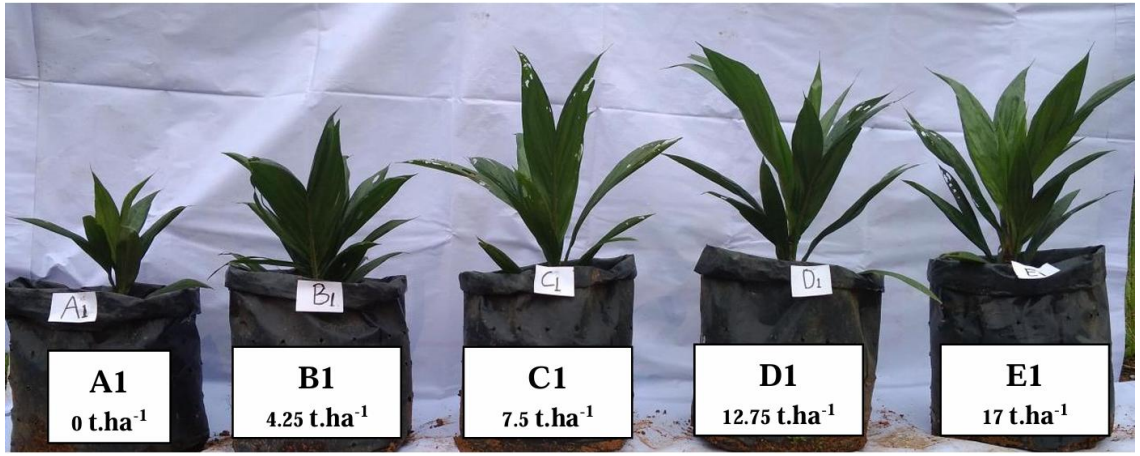
Ref: Pajampa K et al. (2024). Filter cake valorisation as energy pellets for zero-waste sustainability in sugar industries. Ain Shams Eng J, 15(3):102459.

Filter cake waste utilization

ORGANIC FERTILIZER

Compost	Nitrogen (%)	Phosphorus (%)	Potassium (%)
0 $t.ha^{-1}$	3.39^{c}	0.13^{c}	2.37^{c}
4.25 $t.ha^{-1}$	4.79^{b}	0.20^{b}	2.80^{b}
8.50 $t.ha^{-1}$	6.67^{a}	0.24^{b}	3.11^{a}
12.75 $t.ha^{-1}$	5.65^{a}	0.31^{a}	3.81^{a}
17.00 $t.ha^{-1}$	5.55^{a}	0.27^{a}	3.31^{a}

Influence of sugarcane filter cake compost on nutrient absorption in oil palm seedlings in ultisol



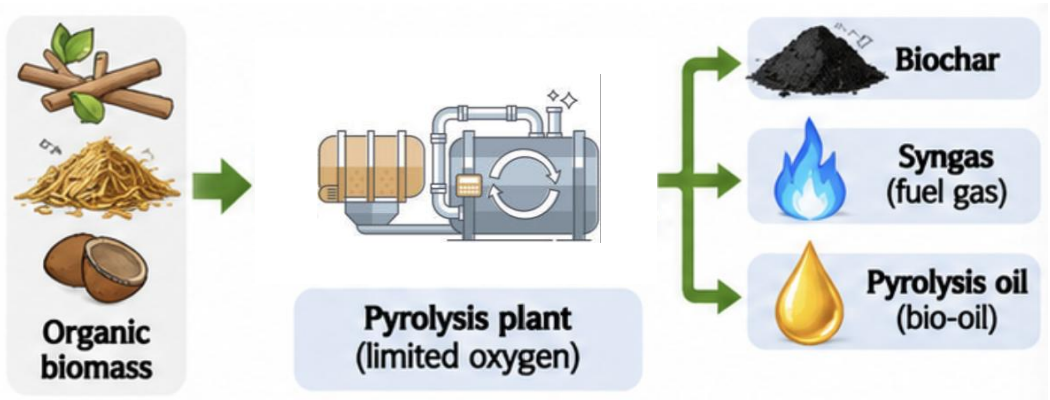
Effects

- ✓ Improved nutrients content
- ✓ Improved Plant growth
- ✓ Optimum dosage 12.75 $t.ha^{-1}$

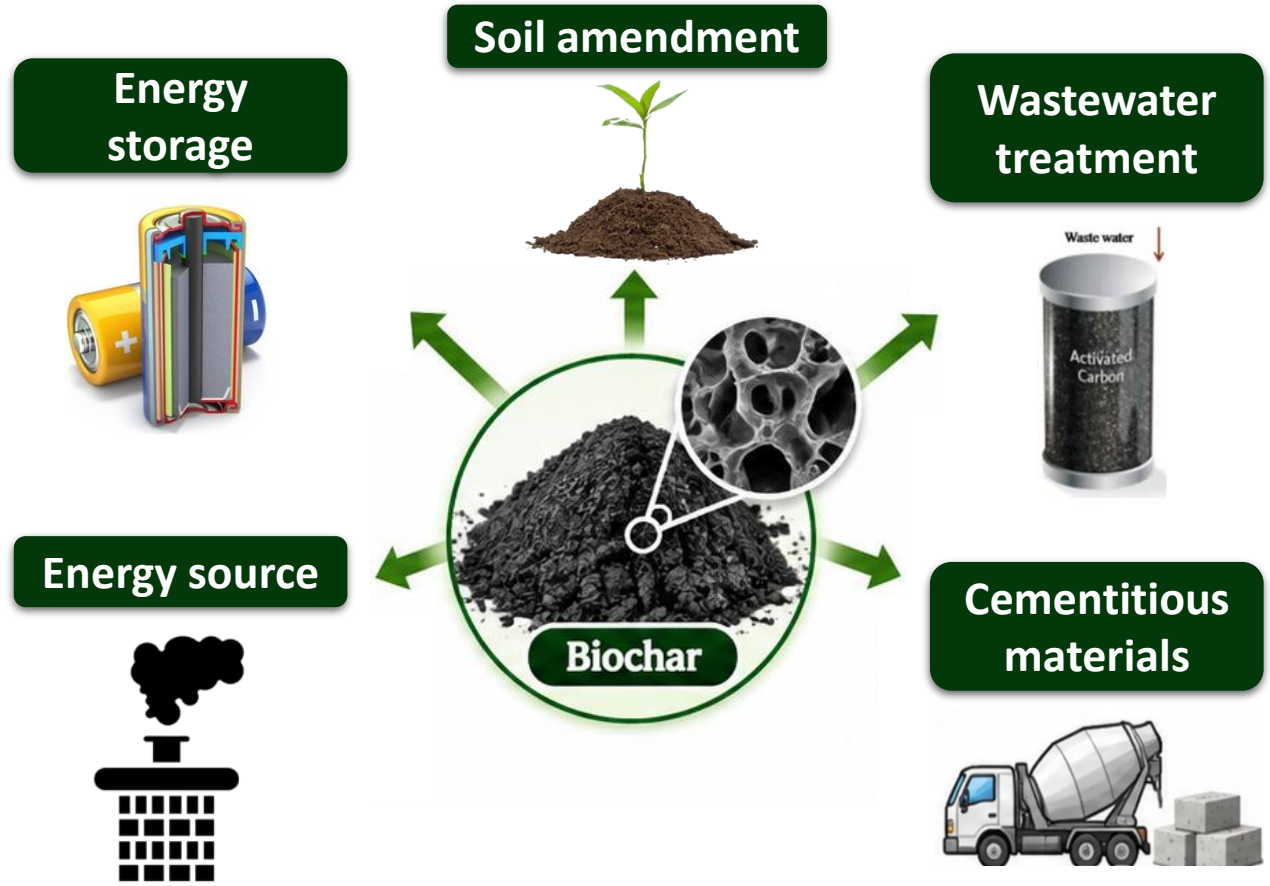
Compost	Stem (cm)	Diameter (mm)	Leaves
0 $t.ha^{-1}$	32.33^{c}	20.20^{c}	8.67^{c}
4.25 $t.ha^{-1}$	40.67^{b}	28.60^{b}	10.00^{b}
8.50 $t.ha^{-1}$	45.67^{a}	30.30^{a}	12.67^{a}
12.75 $t.ha^{-1}$	49.00^{a}	31.00^{a}	12.80^{a}
17.00 $t.ha^{-1}$	45.33^{a}	30.30^{a}	11.67^{a}

Ref: Sehar, A., Aziz, R., Rafiq, M.T. et al. Synthesis of biochar from sugarcane filter-cake and its impacts on physiological performance of lettuce (Lettuce sativa) grown on cadmium contaminated soil. Arab J Geosci 11, 634 (2018). https://doi.org/10.1007/s12517-018-4006-4

Chemical and physical properties of biochar



Parameter	Value
Chemical	
pH	6.8-9.5
Electrical conductivity (ds/m)	3.75-4.00
Organic matter (%)	30-35
C (%)	40-70
Surface area (m^2/g)	36.7-907.4
Physical	
Moisture (%)	3.5-4.0
Ash (%)	1.4-28
Resident material (%)	45-50
Bulk density (g/cm^3)	0.3-0.5



Key Features of Biochar

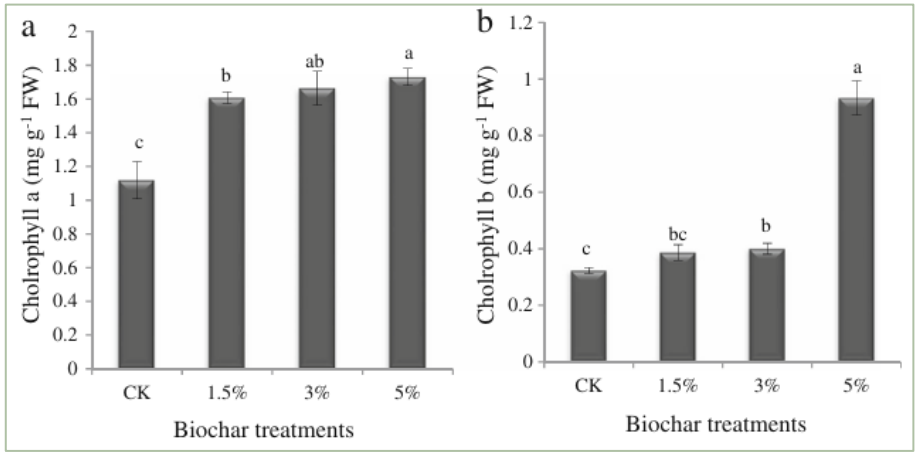
- Carbon-rich and porous structure
- Contains surface functional groups
- Physicochemical properties are tunable

Ref: https://doi.org/10.1016/j.conbuildmat.2019.117338

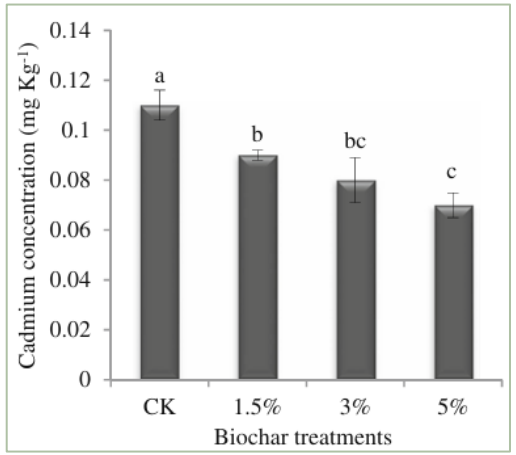
Filter cake biochar utilization

Filter cake biochar as fertilizer

Biochar levels (%w/w)	Root length (cm)	Leaf length (cm)	Root fresh weight (g)	Leaf fresh weight (g)	Root dry weight (g)	Leaf dry weight (g)
CK	11.73 ± 0.62 a	4.5 ± 0.53 a	6.6 ± 0.31 a	13.8 ± 0.21 a	2.8 ± 2.78 a	2.8 ± 0.31 a
1%	9.5 ± 2.56 b	5.6 ± 0.59 ab	7.4 ± 0.21 ab	45.8 ± 0.12 a	0.24 ± 3.21 b	3.6 ± 0.38 a
3%	7.4 ± 3.08 c	6.7 ± 0.6 bc	8.3 ± 0.29 bc	76.2 ± 0.80 b	0.56 ± 1.31 c	5.3 ± 0.09 b
5%	6.5 ± 4.46 c	11.3 ± 0.63 c	12.3 ± 0.31 c	103.5 ± 0.87 b	0.57 ± 1.39 c	5.8 ± 0.1 b



Effects of different treatments of biochar on chlorophyll a (a) and chlorophyll b (b)



Concentrations of cadmium at different levels of biochar in lettuce leaves



- ✓ **Reduces heavy metal risks in crops**
- ✓ **Improved Plant growth**

Ref: Sehar A., Aziz R., Rafiq M.T. et al. (2018). Synthesis of biochar from sugarcane filter-cake and its effects on lettuce grown in cadmium-contaminated soil. Arabian Journal of Geosciences, 11:634.

Filter cake biochar utilization

Filter cake biochar for cementitious materials

Physicochemical properties of FCB

Attribute	Value
Moisture %	1.8
pH	8.50
CE (mS cm^{-1})	0.323
Ashes (Silica) %	46.86
Total C (g kg^{-1})	287.9
Total N (g kg^{-1})	1.84
P (g kg^{-1})	0.48
K (g kg^{-1})	3.55
Ca (g kg^{-1})	115.56
Mg (g kg^{-1})	2.84
Zn (mg kg^{-1})	0.017
Cu (mg kg^{-1})	0.051

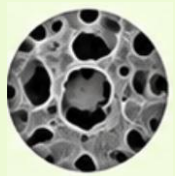


High silica content

Potential Pozzolanic reaction

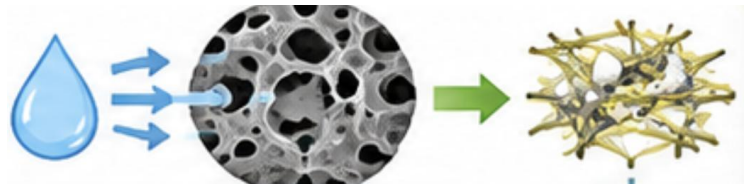


SiO_2 (from FCB) + $Ca(OH)_2$ → C-S-H (additional)



Porous structure

Promote hydration and C-S-H formation



Water absorption (internal curing) — Porous FCB — C-S-H formation

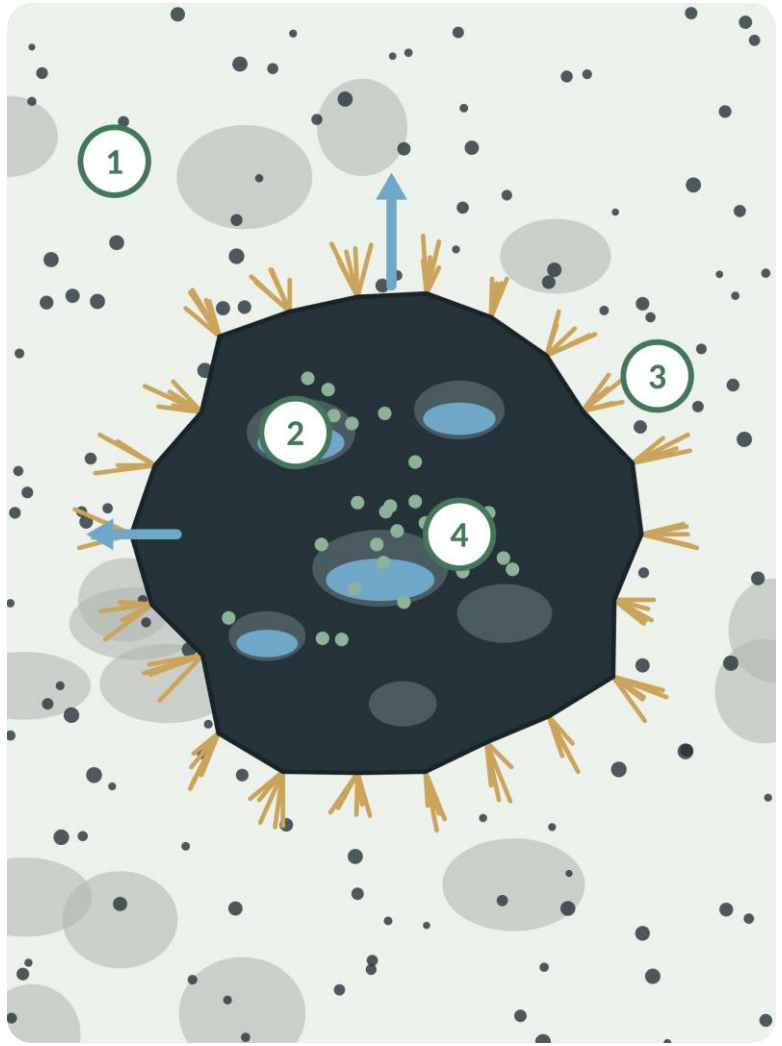


Utilization in concrete/mortar to improve its mechanical strength?

Ref: http://dx.doi.org/10.1590/2179-8087-floram-2022-0075, http://dx.doi.org/10.5418/cee-2020-0029

How biochar enhances compressive strength

Four synergistic mechanisms make biochar a reactive additive, not an inert filler



1 Micro-filling

Fine particles fill voids and raise packing density

2 Internal curing

Pores store mixing water and release it during curing

3 Heterogeneous nucleation

Surfaces seed early C–S–H and ettringite growth

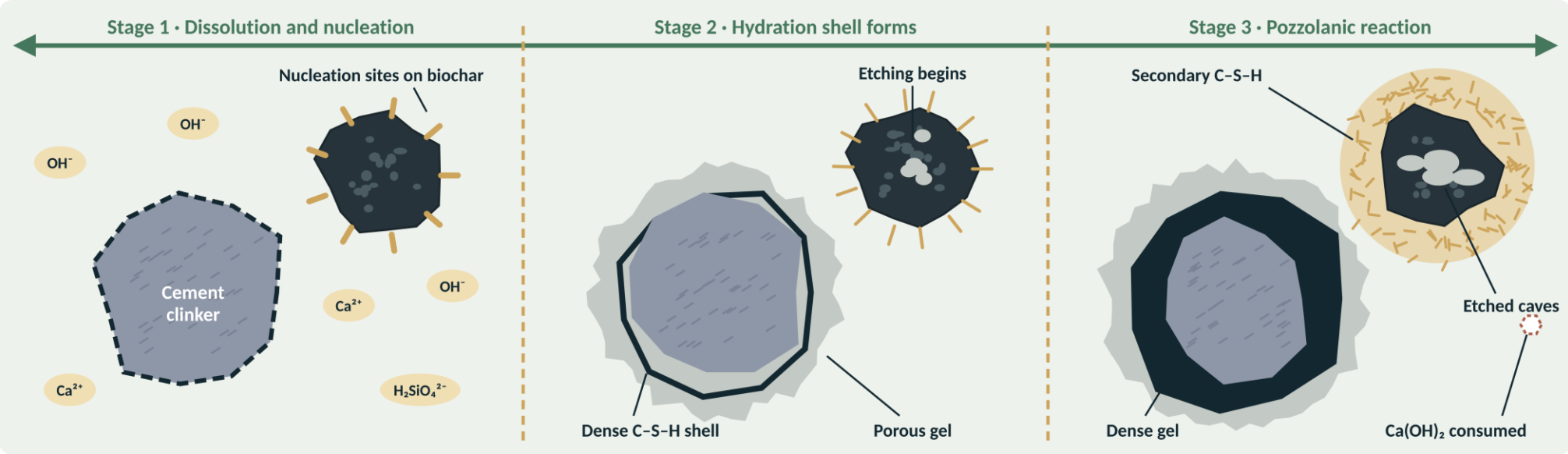
4 Pozzolanic reaction

Reactive silica consumes $Ca(OH)_2$ to form extra C–S–H

Pozzolanic reaction: SiO_2, $Ca(OH)_2$ and C–S–H

Reactive silica in biochar converts portlandite into additional strength-giving gel as mortar cures

$SiO_2 + Ca(OH)_2 + H_2O \rightarrow$ C–S–H gel



1 Dissolution and nucleation
C_3S and C_2S dissolve, releasing Ca^{2+}, OH^- and silicates; biochar surfaces act as nucleation sites.

2 Hydration shell forms
A C–S–H shell grows on clinker; hydration becomes diffusion-controlled and $Ca(OH)_2$ accumulates.

3 Pozzolanic reaction
Reactive SiO_2 in biochar consumes $Ca(OH)_2$, forming secondary C–S–H that fills pores.

Biochar utilization in concrete/mortars

Comparison of different biochar in mortar

Biochar source	Challenges	Effects	Optimal dosage (wt%)
Waste Wood	Agglomeration at high dosages(>5%) Excessive dosage increases porosity	Improves compressive strength (CS) by 8-10%	1-3
Mixed Wood Sawdust	Water absorption by porous structure Requires optimal w/c ratio adjustment.	Up to 20% increase in CS 60% reduction in water penetration.	1-2
Date Palm Fronds	Requires precise dosage control Excessive addition reduces strength	Increases CS by 29%	1.5
Rice Husk	High SiO_2 content (66.4%), requires careful proportioning.	Increases CS by 4% Better performance in durability than strength enhancement	1-3

Ref: Ling et al., 2023 (Materials), Khan et al., 2022 (Materials), Pravina Kamini et al., 2023 (AIMS Mat. Sci.)

Biochar utilization in concrete/mortars

Comparison of different biochar in mortar

Biochar source	Challenges	Effects	Optimal dosage (wt%)
Bamboo	Significantly reduced workability. Porous structure increases water demand	7% increase in 28-day strength. Acts as a nucleation site Effective CO_2 adsorption for carbon sequestration.	5
Corn cob	Feedstock variability affects consistency High specific surface area (483 m^2/g) requires careful mixing	17% increase in 7-day CS Effective nucleation sites	1-3
Filter cake	Very high moisture raw material Requires drying pre-pyrolysis. >3M tons/year produced every year	Potential: Enhance CS (pozzolanic reaction) Improve microstructure through pore refinement. Internal curing Carbon sequestration in construction materials	xx

Ref: Ling et al., 2023 (Materials), Khan et al., 2022 (Materials), Pravina Kamini et al., 2023 (AIMS Mat. Sci.)

Comparison of different biochars with filter cake biochar

Biomass Source	Optimal dosage (%)	Compressive Strength improvement
Waste Wood	1-3%	10%
Mixed Wood Sawdust	1-2%	20%
Date Palm Fronds	1.5%	29%
Rice Husk	3%	4%
Bamboo	5%	7%
Corn cob	3%	17%
Filter cake	**xx %**	**xx %**

An integrated circular-economy research concept

One agricultural waste stream, two value chains: cleaner water and lower-carbon mortar

01

Sugarcane filter cake

Sugar-mill by-product, 2.1–3.3 Mt/yr in Thailand

02

Pyrolysis

300–700 °C; porous carbon with SiO_2 and Ca phases

03

Wastewater adsorption

BC700 removes methylene blue; Qmax 136.37 mg/g

04

Mortar incorporation

Fresh or spent biochar added at 5–7.5 wt.%

05

Low-carbon mortar

More C–S–H, denser matrix, higher strength



Environmental value

Diverts filter cake from landfill, removes cationic dye and locks carbon in biochar.

Material value

Up to +58.2% strength at 28 d; spent MB-loaded biochar still matches or beats control.

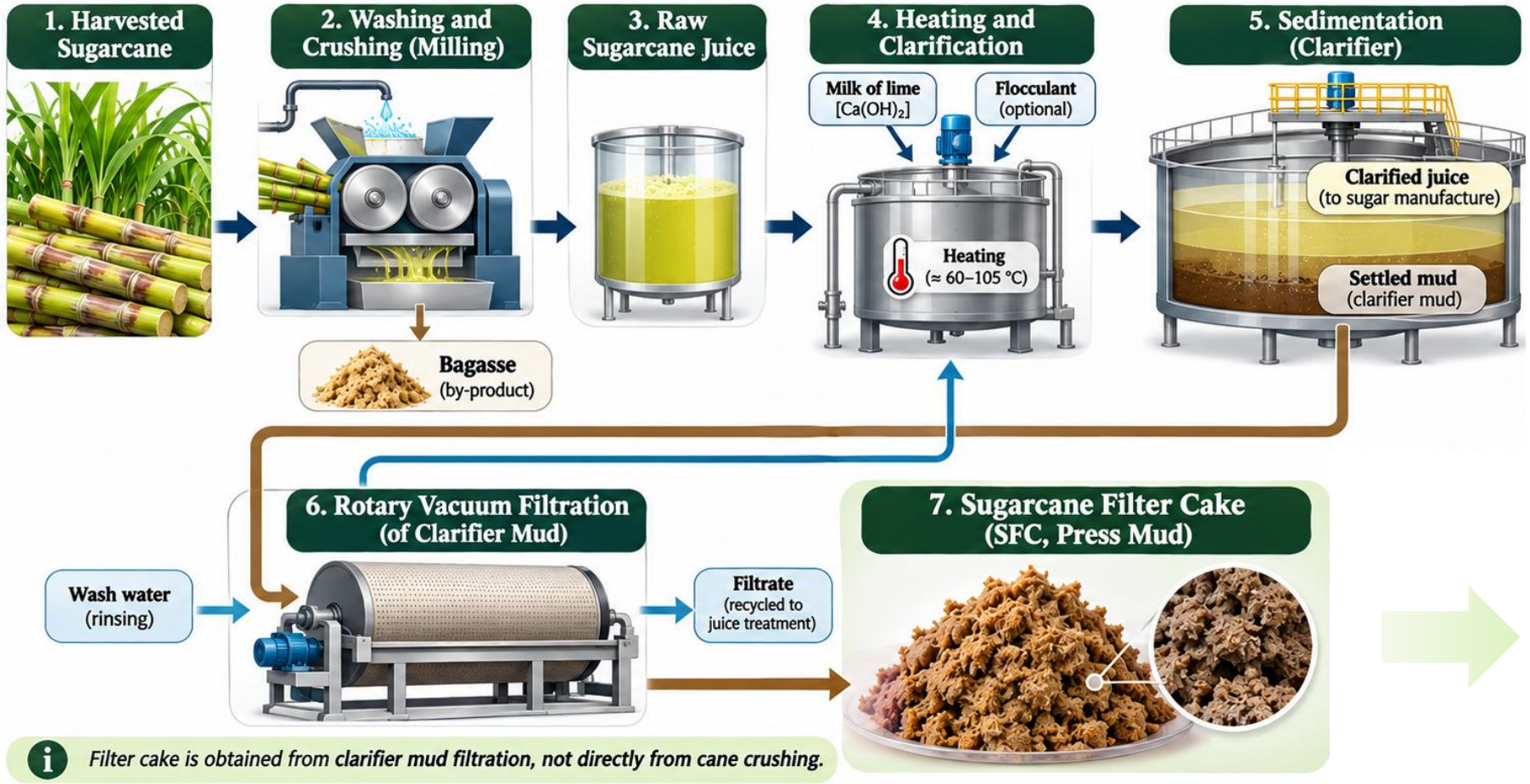
Research gap

FCB dosage optimization and sequential wastewater-to-mortar reuse are rarely reported.

Upcycling of Sugarcane Filter Cake to Biochar for Improving the Mechanical Properties of Cement Mortar

From Agricultural Waste to Sustainable Construction

Sugarcane Filter Cake A solid, moisture-rich residue generated during sugar production



Key characteristic

Composition
Rich in calcium carbonate ($CaCO_3$) and silica (SiO_2) compounds

Physical nature
Highly porous structure with a large surface area

Biomass origin
Renewable, abundant, and derived from agro-industrial waste

Methodology

Biochar Production



sugarcane filter cake

1. Dried at 105 °C for 24 h
2. Crushed and sieved



Raw sugarcane filter cake (RFC)



Pyrolysis under N_2 at **500** °C
- Heating rate (5, **10**, and 15 °C·min^{-1})
- holding time (30, **75**, and 120 min)



Filter cake biochar (FCB)

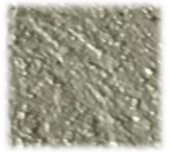
Mortar Preparation and Curing (ASTM C109)



Cement : Sand : Water : FCB

1 : 2.75 : 0.60 : 0.0, 2.5, 5.0, 7.5, and 10.0 wt.% (by cement mass)

1. Dry mixed (cement, sand, and FCB) for 2 min
2. Gradually added water for 30 s
3. Mixed at low speed for 2 min
4. Mixed at high speed for 2 min
5. Rested for 1 min
6. Mixed at high speed for 1 min



Fresh mortar

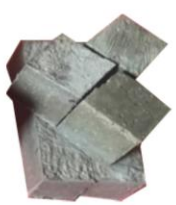
Casted into 50 mm cubic molds



1. Covered with plastic
2. Stored at 23±2°C for 24±2 hours
3. Demoled
4. Added in a 7.5 wt.% $Ca(OH)_2$



Cured in a 7.5 wt.% $Ca(OH)_2$ solution at 20 ± 2 °C for 7, 14, 28, and 56 days



CM



FCB-CM

Model Experiments for Pozzolanic Activity Assessment



$Ca(OH)_2$



Water

$Ca(OH)_2$: Water

1 : 0.60

1. Mixed $Ca(OH)_2$ and water
2. Added FCB (0, 7.5 wt.% of $Ca(OH)_2$)
3. Stirred for 2 h
4. Casted into mold
5. Cured at 20 ± 2 °C
6. Collected samples (7 and 28 d)



ME



7.5FCB-ME

Optimizing slow pyrolysis for filter cake biochar

A fixed temperature of 500 °C was used to evaluate the effects of heating rate and holding time.

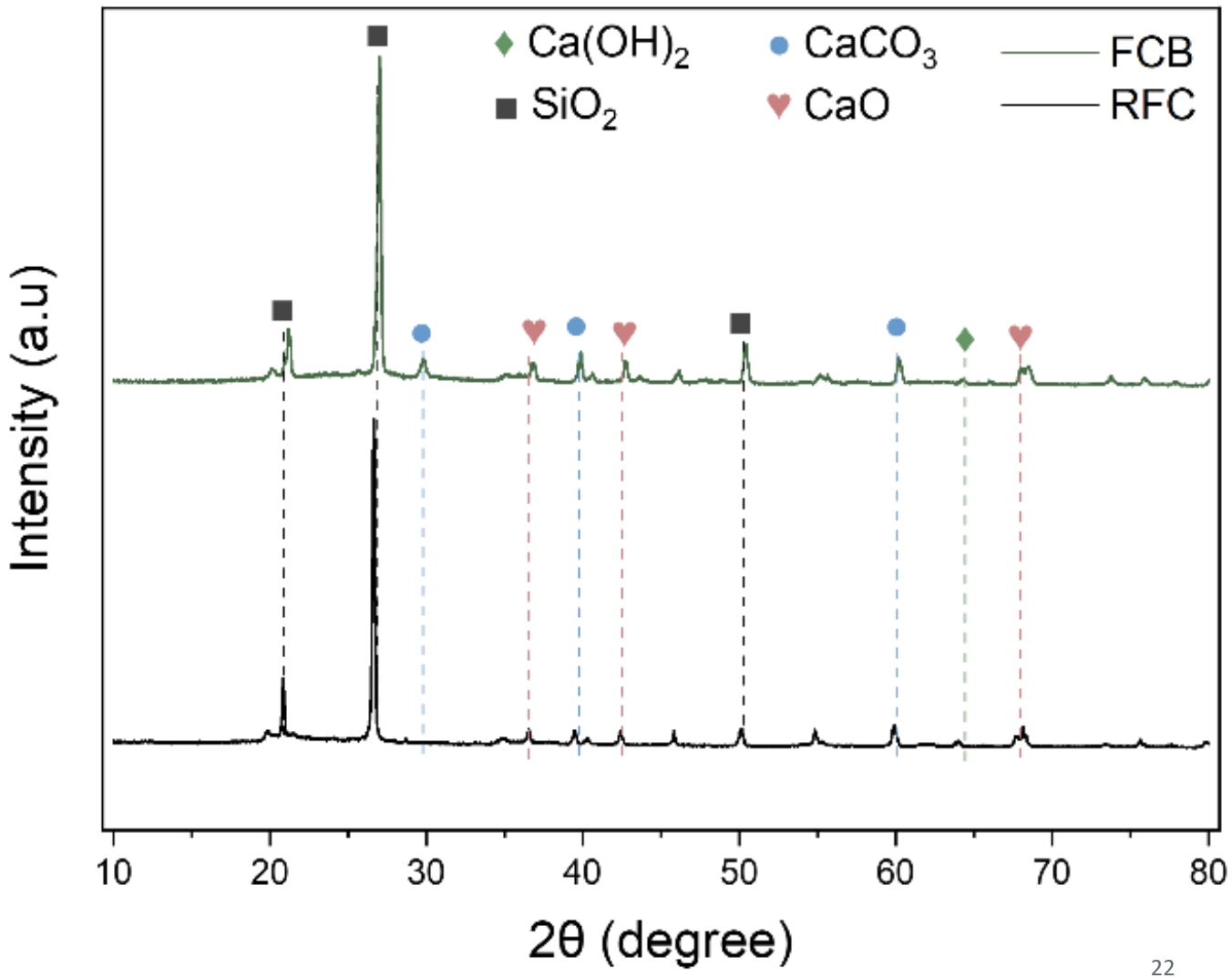
Sample	Temperature (°C)	Time (minutes)	Heating Rate ($°C \cdot min^{-1}$)	Biochar Yield (%)	Initial weight (g)	After weight (g)	Carbon Content (%)
1	500	30	5	58.50	8.00	4.68	98.18
2	500	120	5	57.13	8.00	4.57	87.73
3	500	30	15	59.50	8.00	4.76	98.19
4	500	120	15	59.38	8.00	4.75	98.19
5	500	75	10	60.38	8.00	4.83	98.25
6	500	75	10	57.50	8.00	4.60	87.72
7	500	75	10	57.63	8.00	4.61	93.80

Selected condition

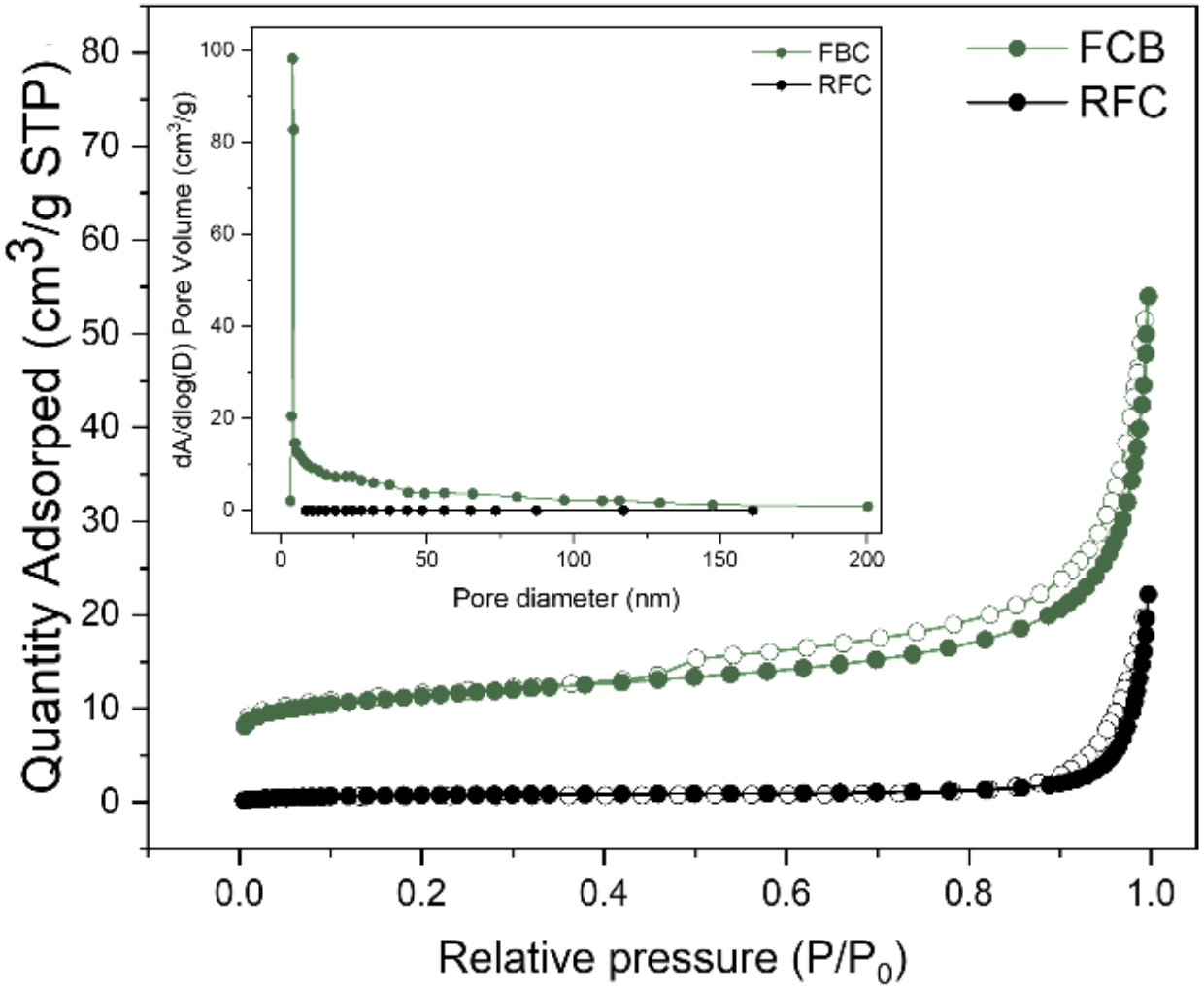
Elemental composition, phase identification of RFC and FCB

Oxide composition	RFC (%)	FCB (%)
SiO_2	51.1	57.5
Al_2O_3	9.23	11.5
CaO	18.0	11.3
Fe_2O_3	9.43	8.32
P_2O_5	4.22	4.06
K_2O	2.81	2.46
MgO	1.58	1.74
TiO_2	1.16	1.03
SO_3	1.14	0.587
MnO	0.47	0.419

77.3 wt.% (SiO_2+Al_2O_3+Fe_2O_3)



Surface properties of RFC and FCB

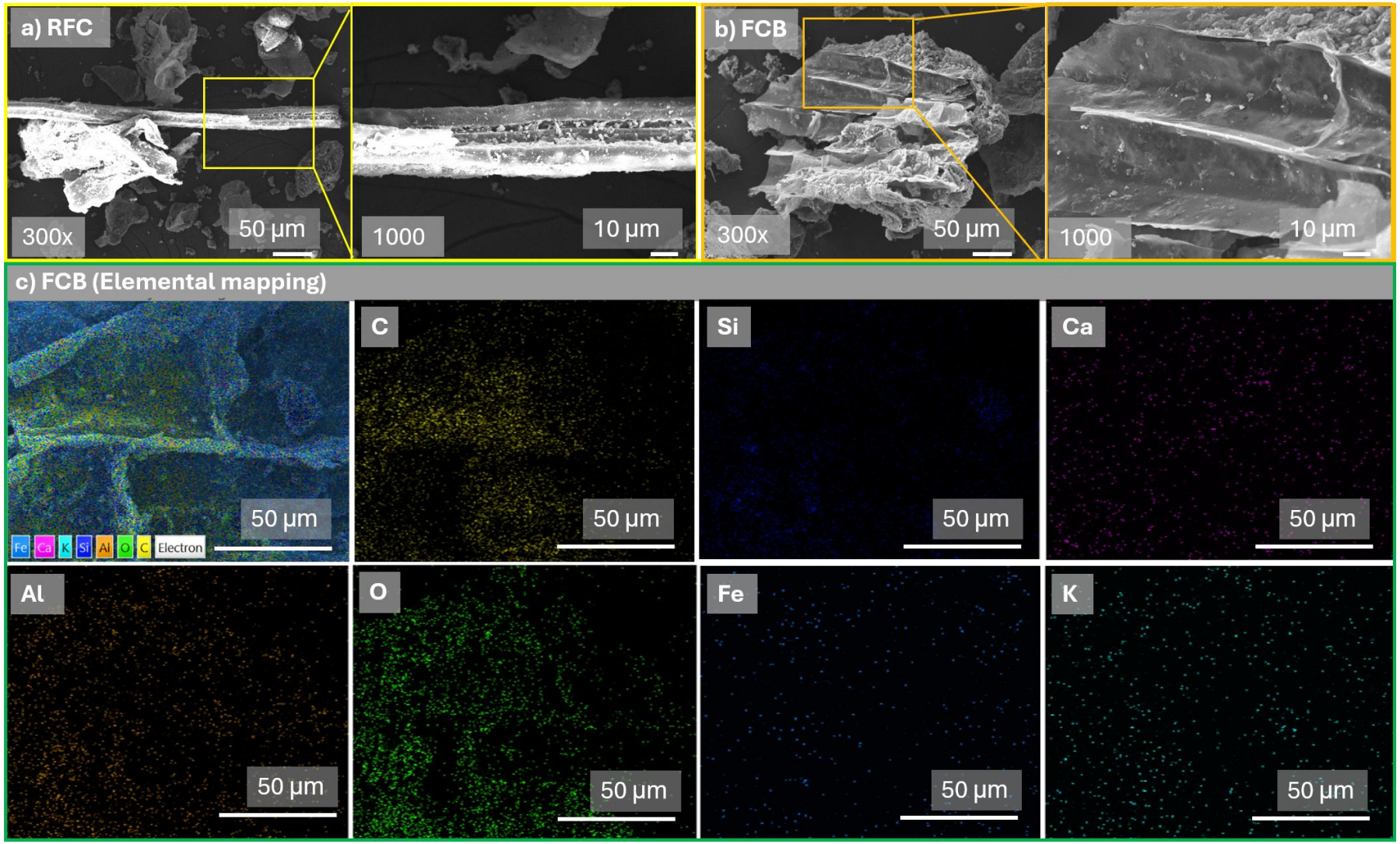


Sample	S_{BET} (m^2g^{-1})	Pore volume (cm^3g^{-1})	Average pore diameter (nm)
RFC	3.5	0.0057	36.7
FCB	6.2	0.0117	25.2

Surface area and pore volume increased

Type IV isotherm with H3 hysteresis –characteristic of mesoporous materials

Morphological characterization of RFC and FCB



FCB shows a rough, granular, and porous surface with broadly distributed C, O, Si, Al, Ca, Fe, and K

Mortar Mix Design



Mortars	Cement (g)	Water (g)	Sand (g)	FCB (g)	W/C	S/C	FCB (%)
CM	100	60	275	0	0.60	2.75	0.0
2.5FCB-CM	100	60	275	2.5	0.60	2.75	2.5
5.0FCB-CM	100	60	275	5.0	0.60	2.75	5.0
7.5FCB-CM	100	60	275	7.5	0.60	2.75	7.5
10.0FCB-CM	100	60	275	10.0	0.60	2.75	10.0

Specimen

50x50x50mm

Curing

7.5 wt.% $Ca(OH)_2$ solution at 20 ± 2 °C

Ages

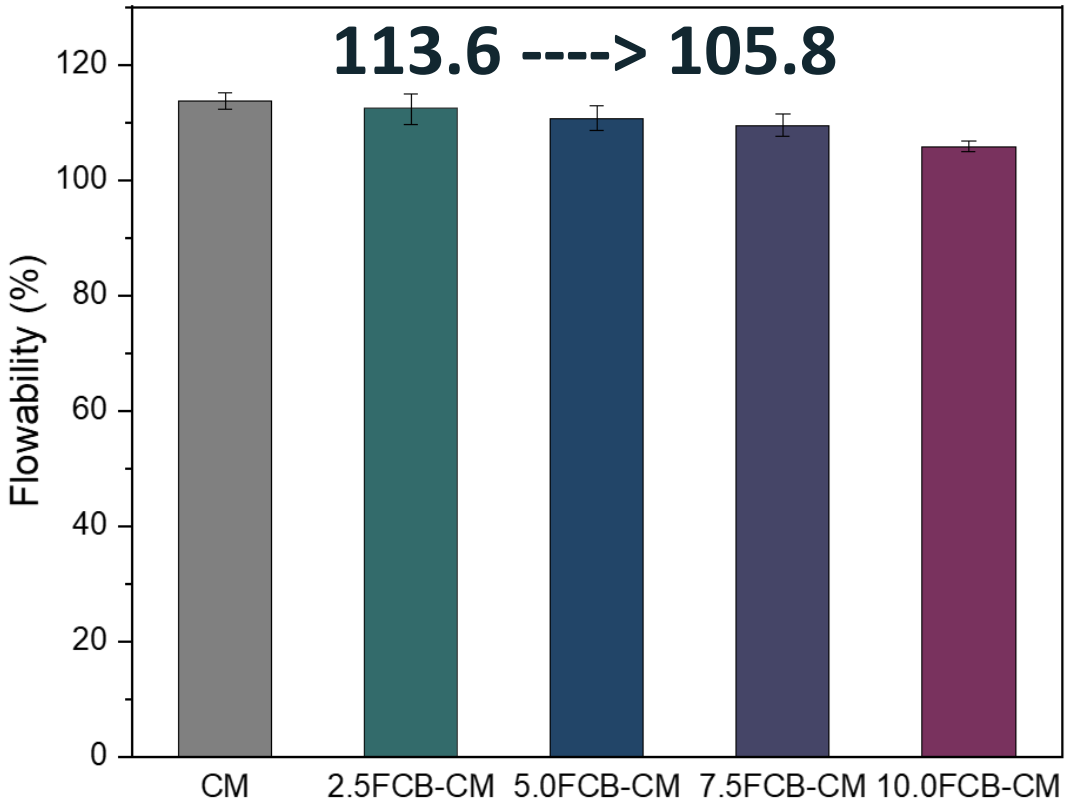
7,14,28, 56 days

Test

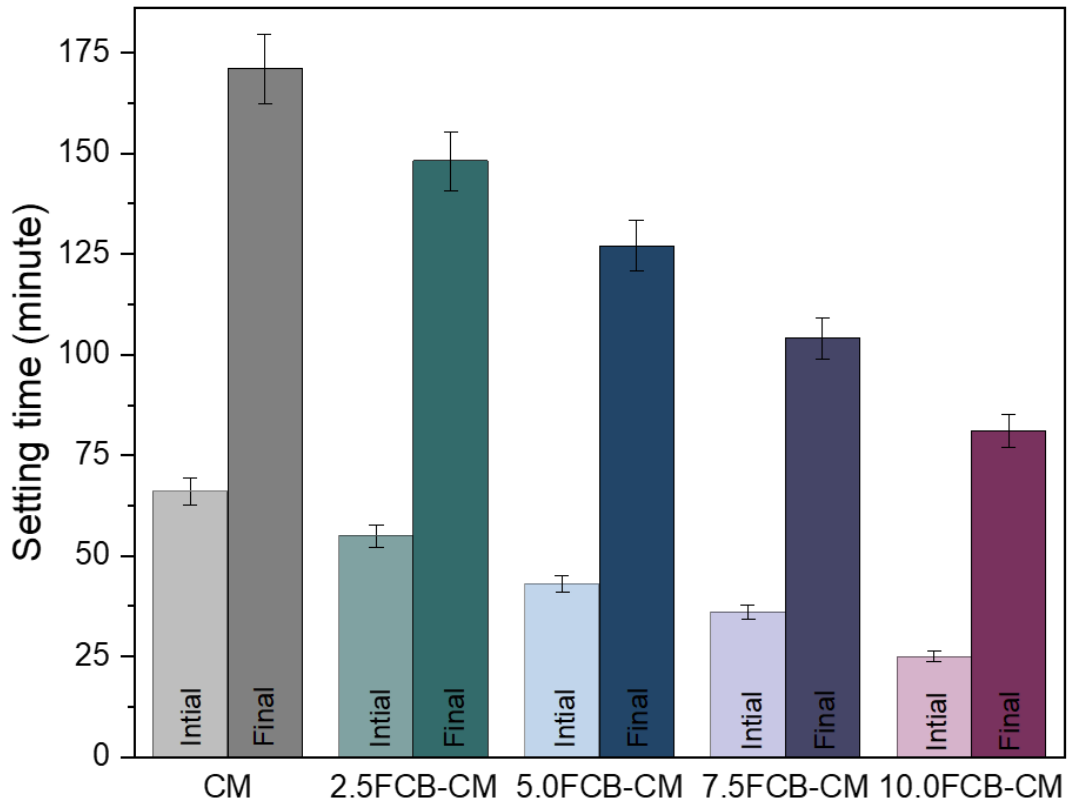
Workability, Setting Time, Compressive Strength

Mechanical Properties of FCB-Modified Mortars

Flowability

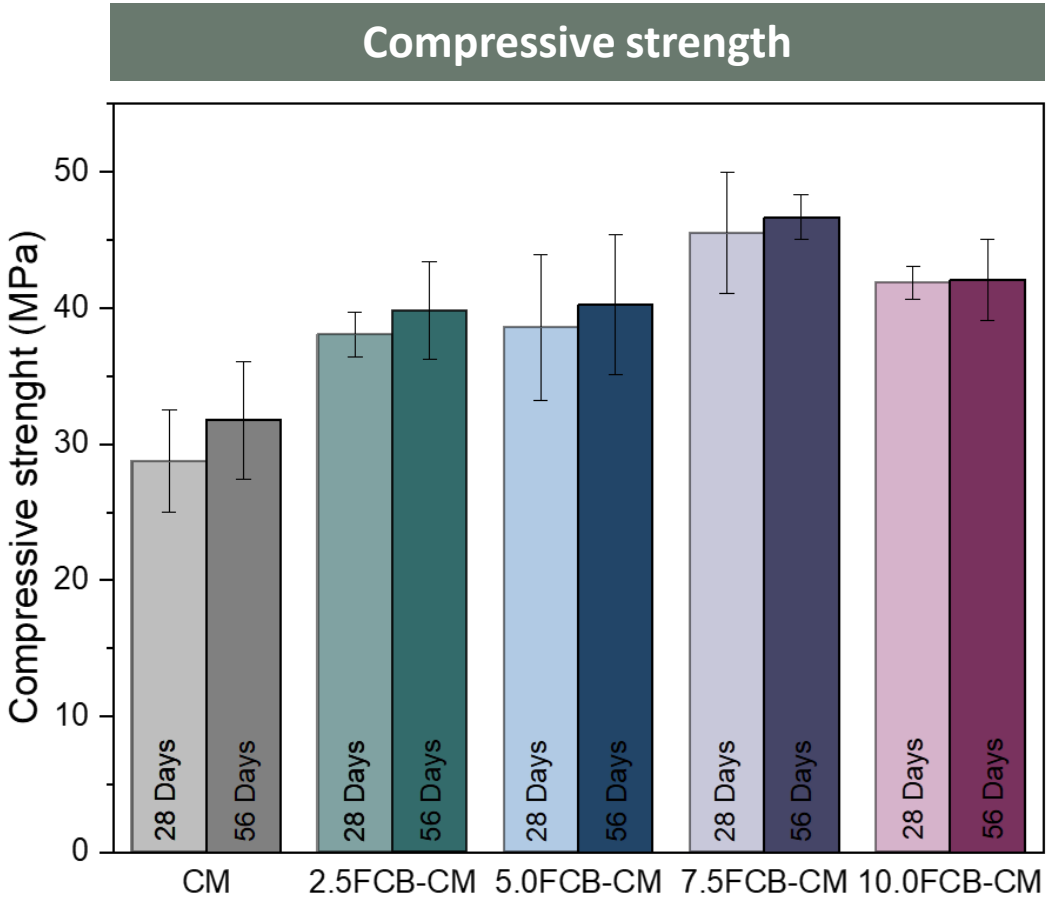


Seting Time



FCB water uptake can reduce workability, while its fine-particle filling and water-holding behavior are associated with faster setting

Mechanical Properties of FCB-Modified Mortars



45.5 MPa 28-day compressive strength

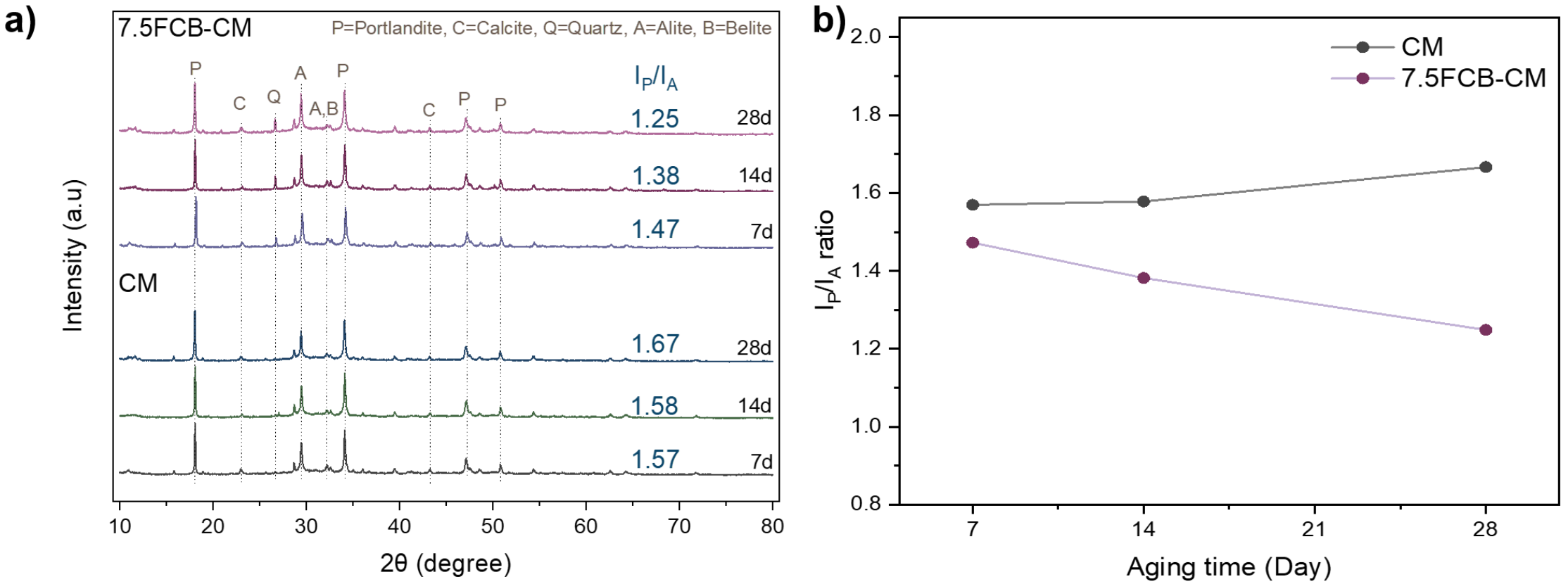
Highest among all investigated mortar mixtures

- The 7.5 wt.% mixture also remained the strongest at 56 days
- Increasing FCB to 10 wt.% reduced strength by about 8% relative to 7.5 wt.%

The optimum balance the benefits of pore filling and hydration promotion against excessive particle agglomeration.

Hydration and phase evolution

SiO_2 (from FCB)+CH (P) +H → C-S-H

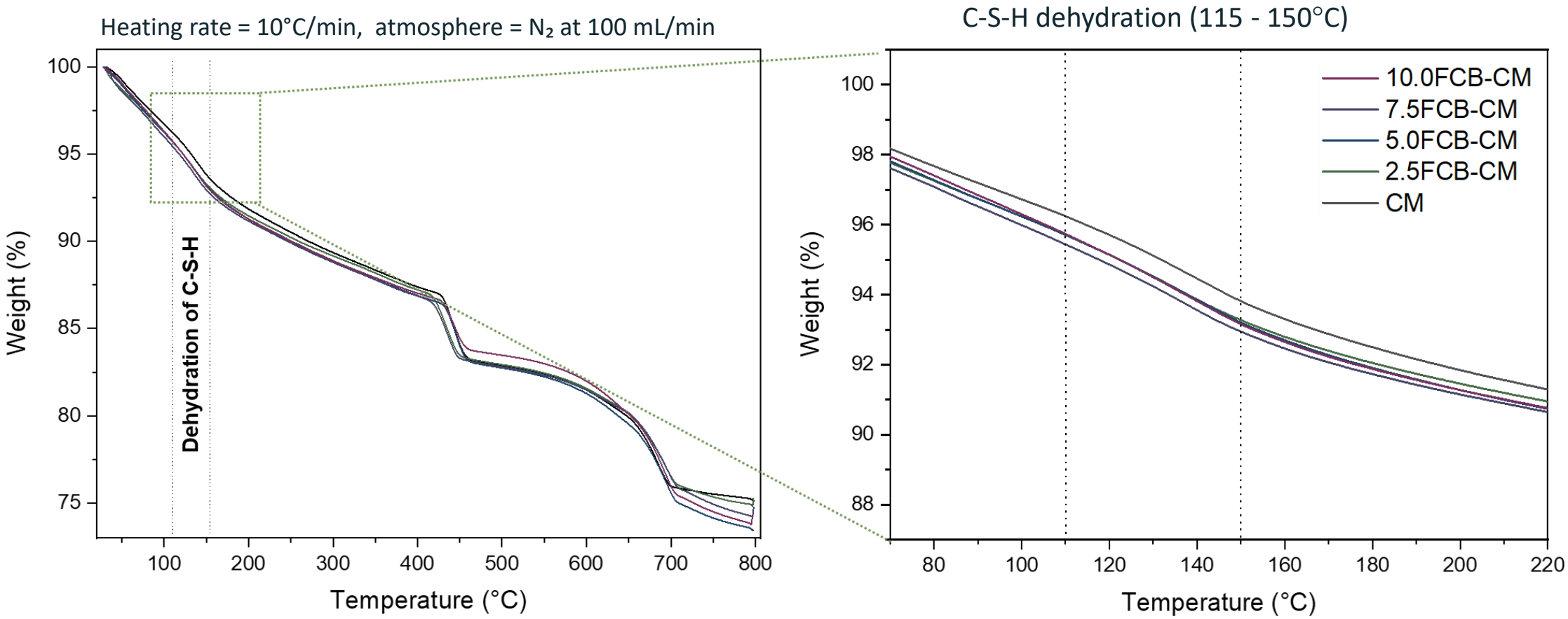


I_P/I_A Control : 1.57 -> 1.67

7.5% FCB : 1.47 -> 1.25

A decreasing ratio indicates progressive CH consumption

Hydration product evaluation

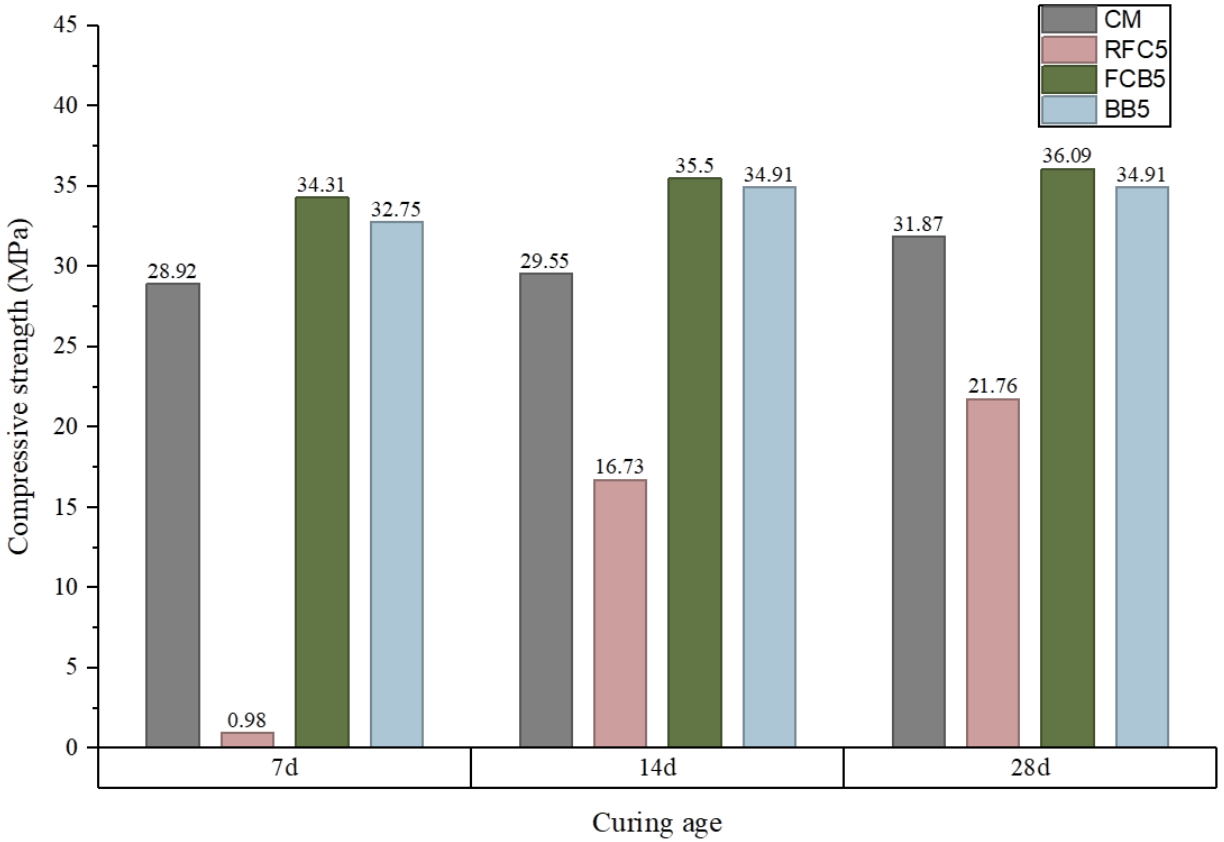


↑ Highest dehydration in FCB7.5
↓ Lowest dehydration in CM

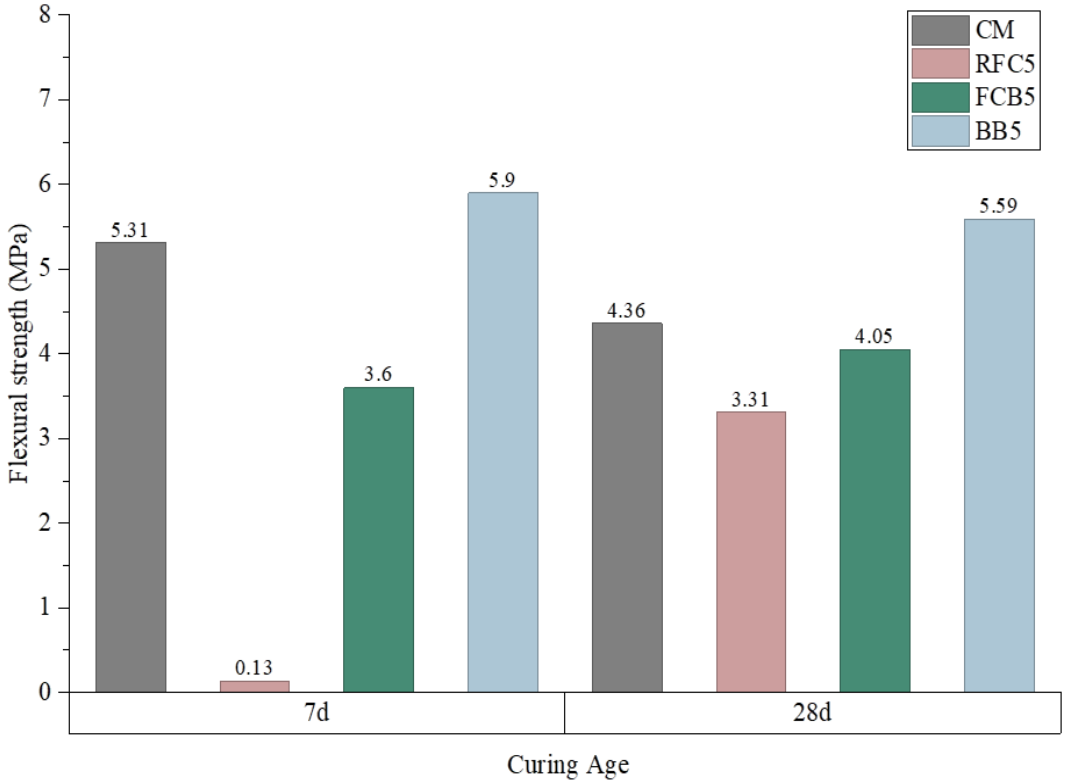
More C-S-H formation in biochar Samples

Mechanical Properties

Compressive strength

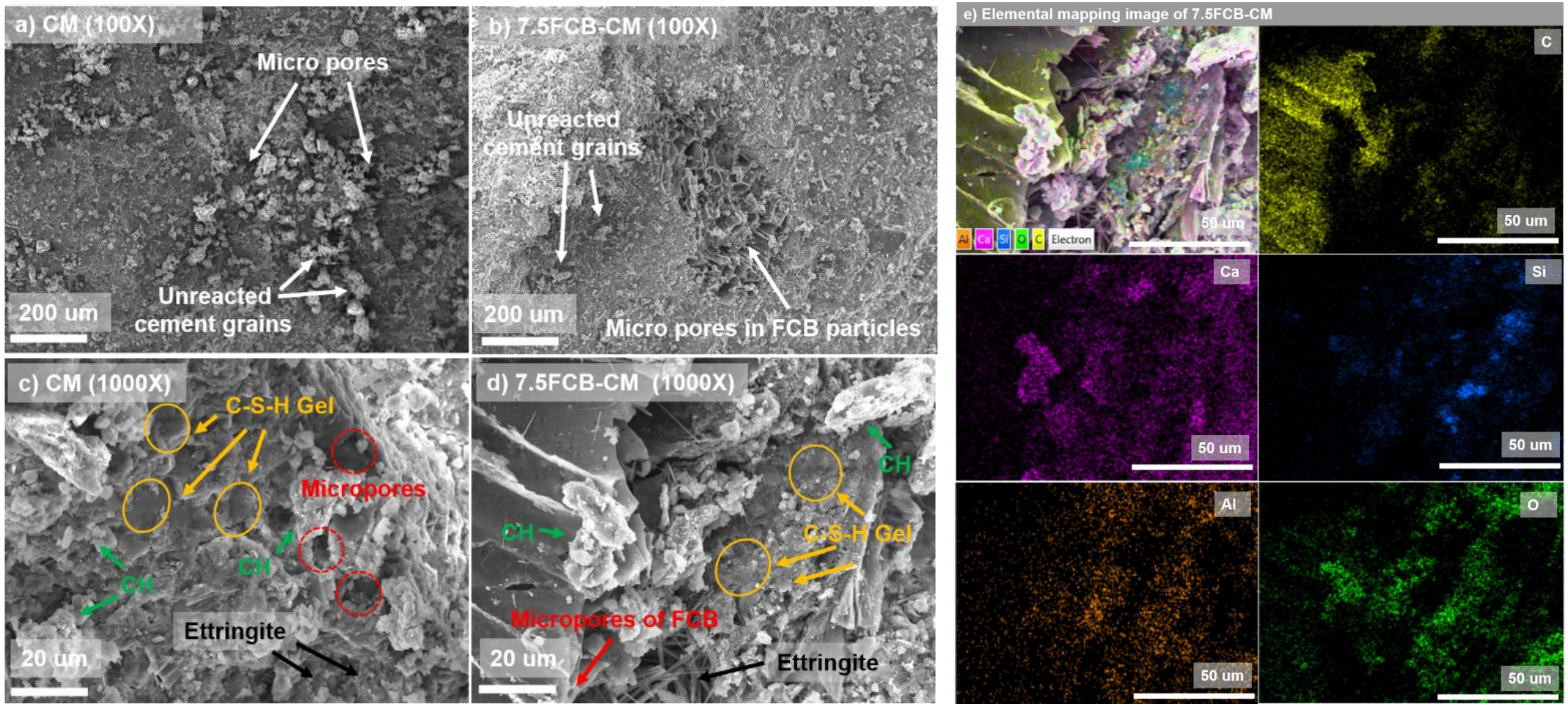


Flexural strength of mortars



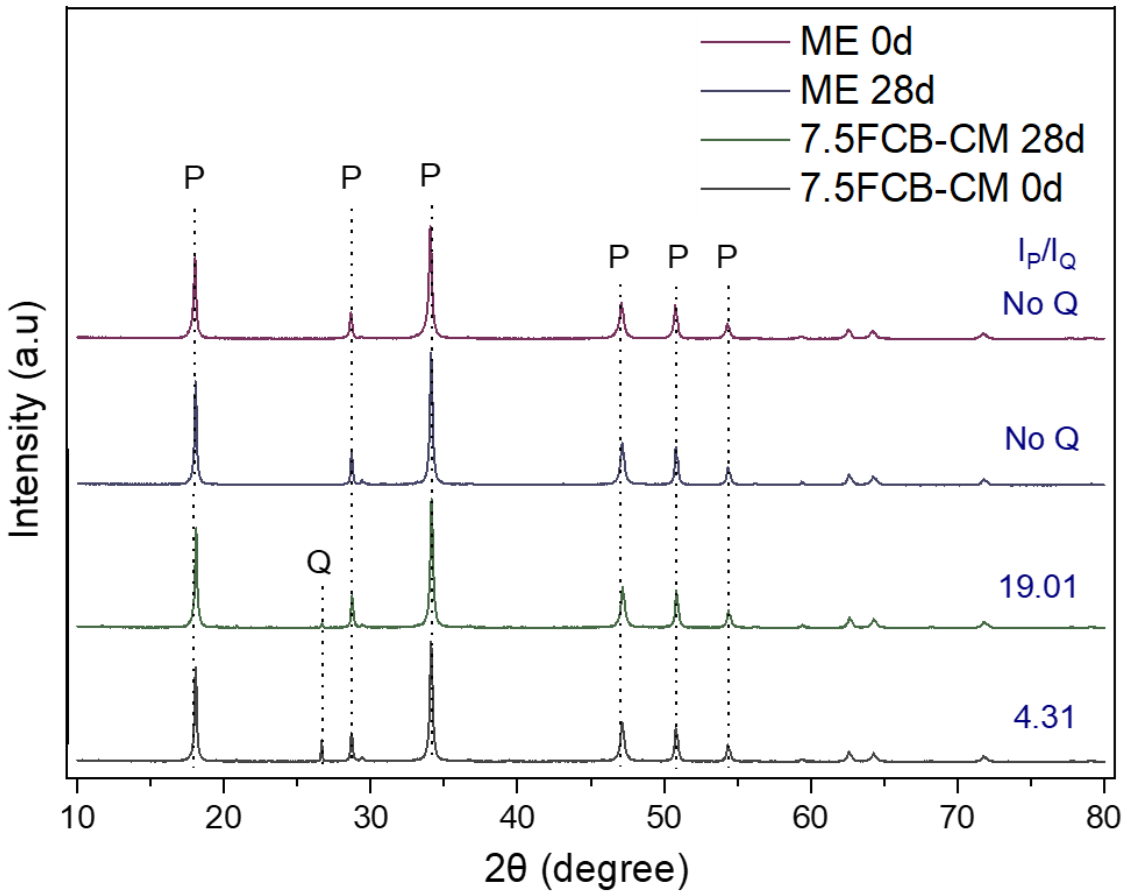
Filter cake biochar exhibited good results as compared to other additives.

Microstructure results



FCB mortar: fewer visible capillary pores, well-dispersed biochar, compact C-S-H, and local Si enrichment near the FCB-matrix interface.

Pozzolanic verification



Quartz peak intensity decreases from 0 to 28 days in FCB-CM

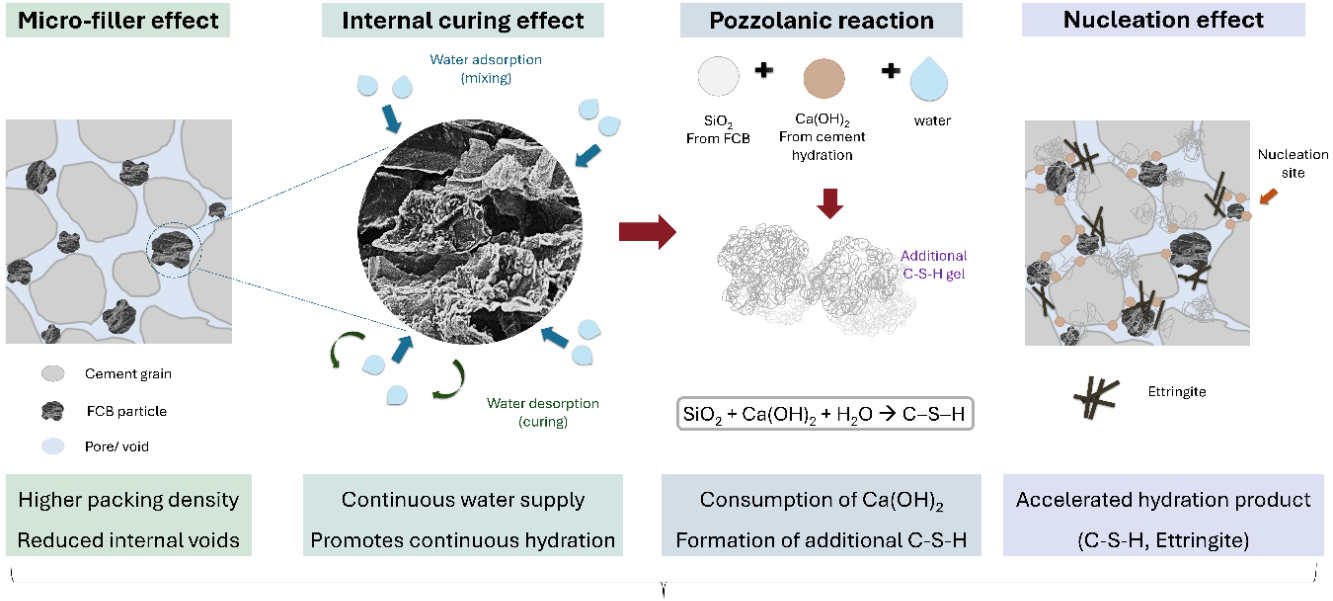
4.31 -> **19.01**

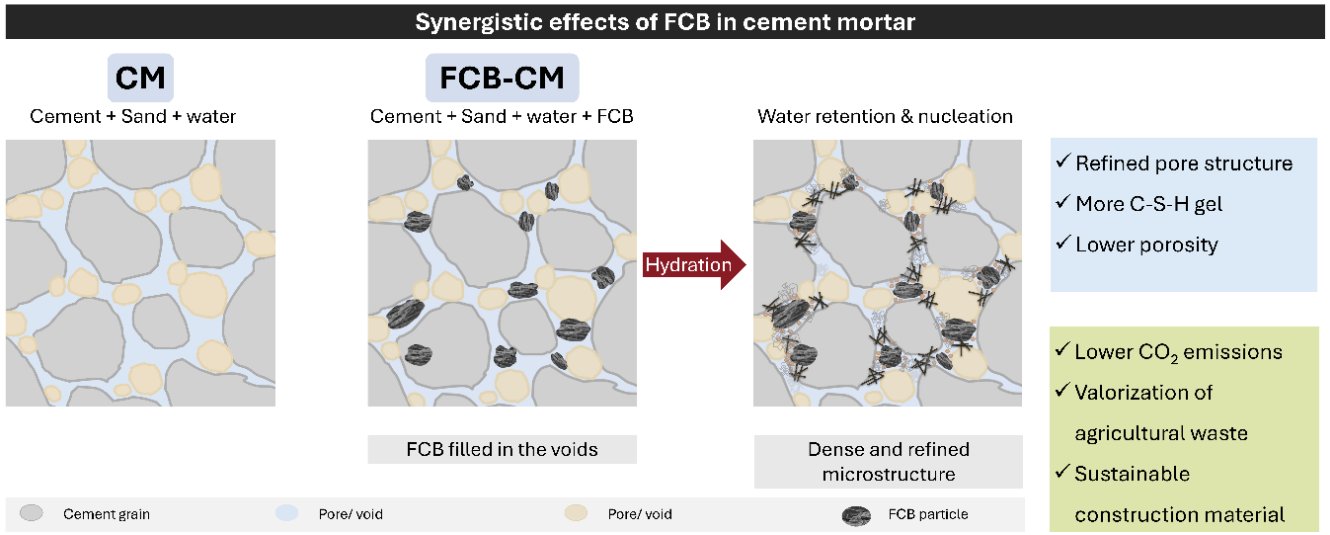
0 days 28 days

- The quartz peak becomes progressively weaker, indicating silica dissolution and consumption.
- The increase in I_P/I_Q confirms continued reaction of FCB silica with $Ca(OH)_2$.

Evidence supports secondary C-S-H generation through the pozzolanic reaction.

Proposed mechanism





Synergistic effects explain the strength enhancement

01 Micro-filler effect

Fine FCB particles fill voids and improve packing density.

02 Internal curing

Porous FCB absorbs mixing water and releases it during curing.

03 Pozzolanic reaction

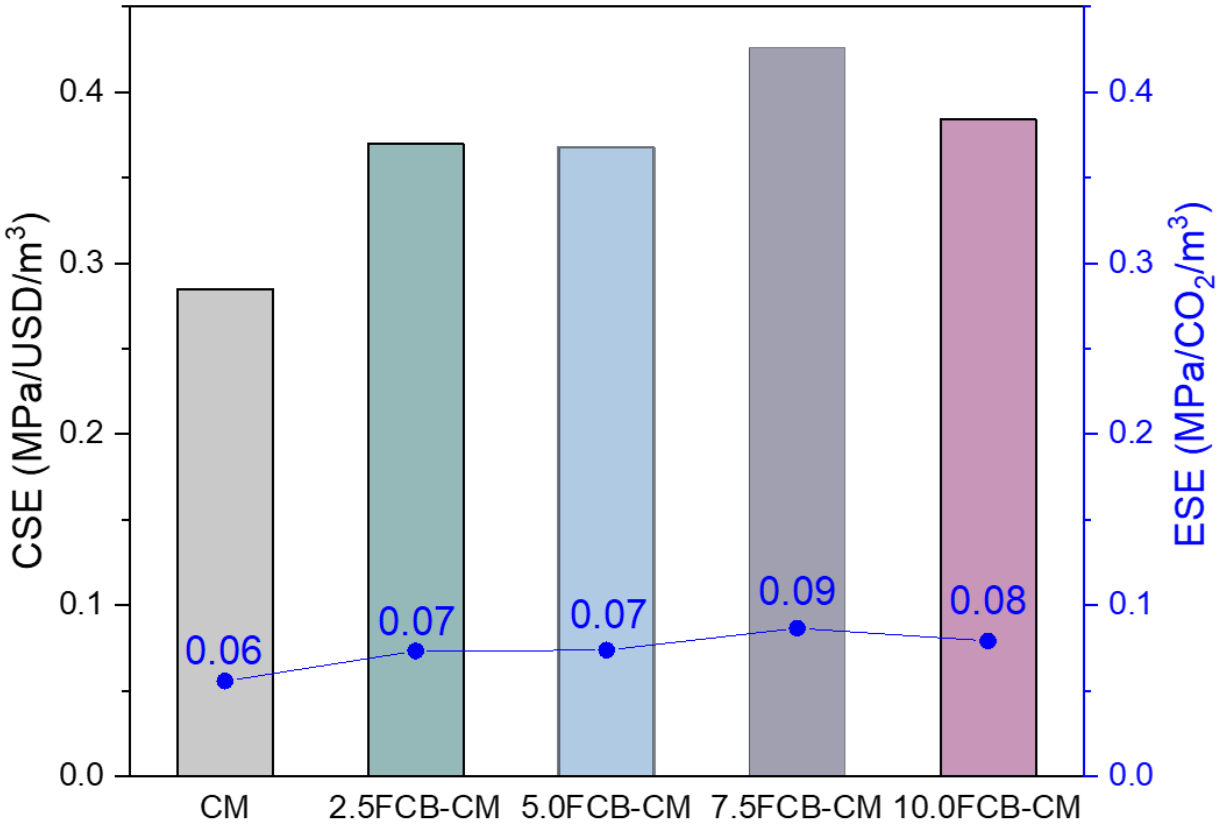
Reactive SiO_2 consumes $Ca(OH)_2$ and forms additional C-S-H.

04 Heterogeneous nucleation

FCB surfaces promote precipitation of C-S-H and ettringite.

Sustainability and conclusions

$$ESE = \frac{Compressive\ strength\ at\ 28\ days}{T\text{-}CO_2E} \qquad CSE = \frac{compressive\ strength\ at\ 28\ days}{\mathrm{TCP}}$$



- Optimized FCB was produced at 500 °C, 10 °C/min, and 75 min (60.38% yield; 98.25% carbon).
- At 7.5 wt.% FCB, 28-day strength reached 45.5 MPa (+58.2% versus control) and remained highest at 56 days.
- XRD, TGA, SEM-EDS, and model tests show CH consumption, additional C-S-H formation, and matrix densification.
- FCB acts as a reactive multifunctional additive - not merely an inert carbon filler - while valorizing agricultural waste.

Utilization of 2nd biochar-based waste as cementitious materials



Sugarcane fields



Sugar factory



Filter cake



The sugarcane filter cake obtained from the sugar mill was ground and dried.



Pyrolysis process designed using Minitab with 15 experimental conditions.



Biochar from filter cake



Analyze 15 biochar conditions to determine the best one for mortar mixing."



Test biochar for methylene blue adsorption.



Mix biochar with mortar mixture.

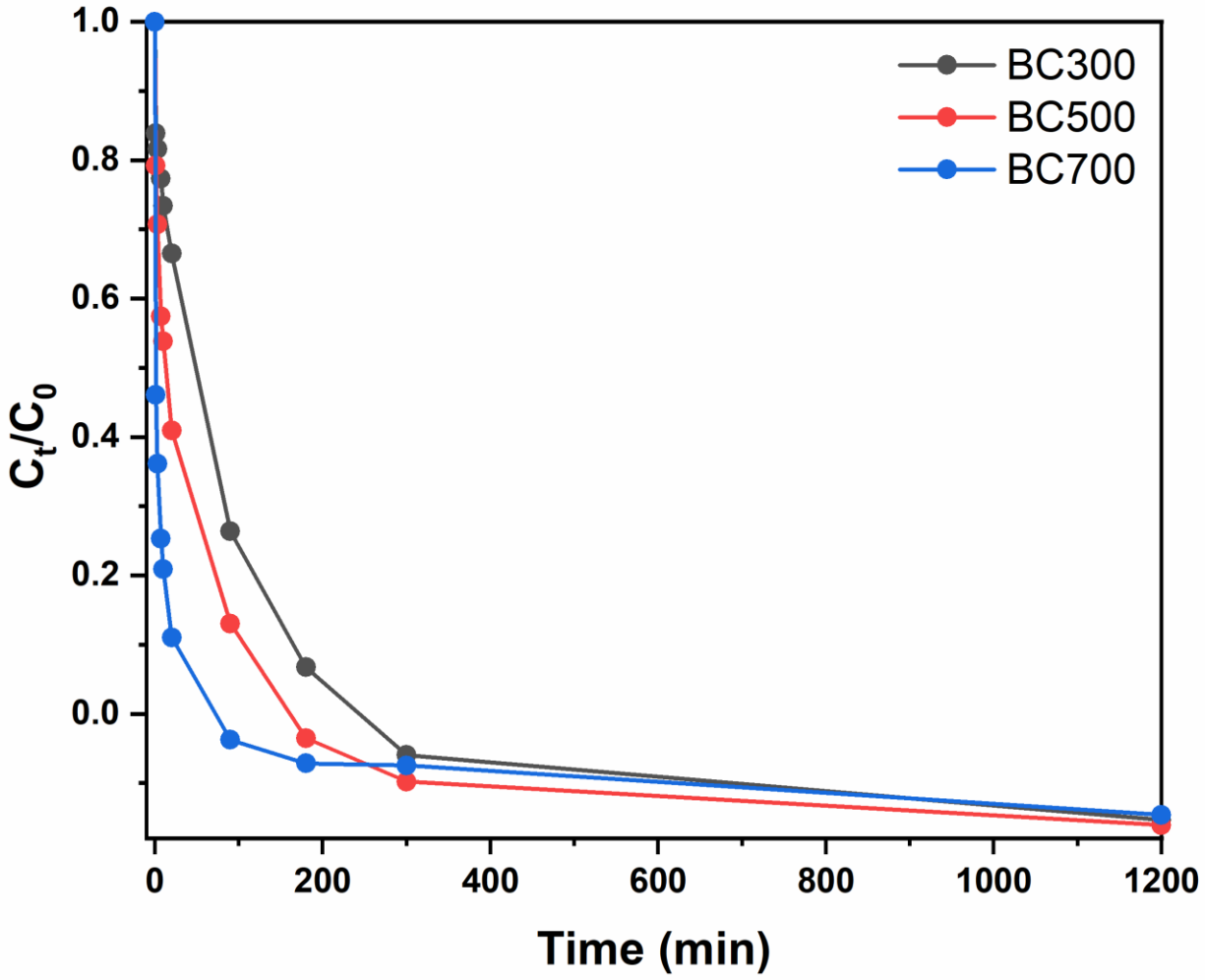


Cast mortar samples into molds.

SiO_2

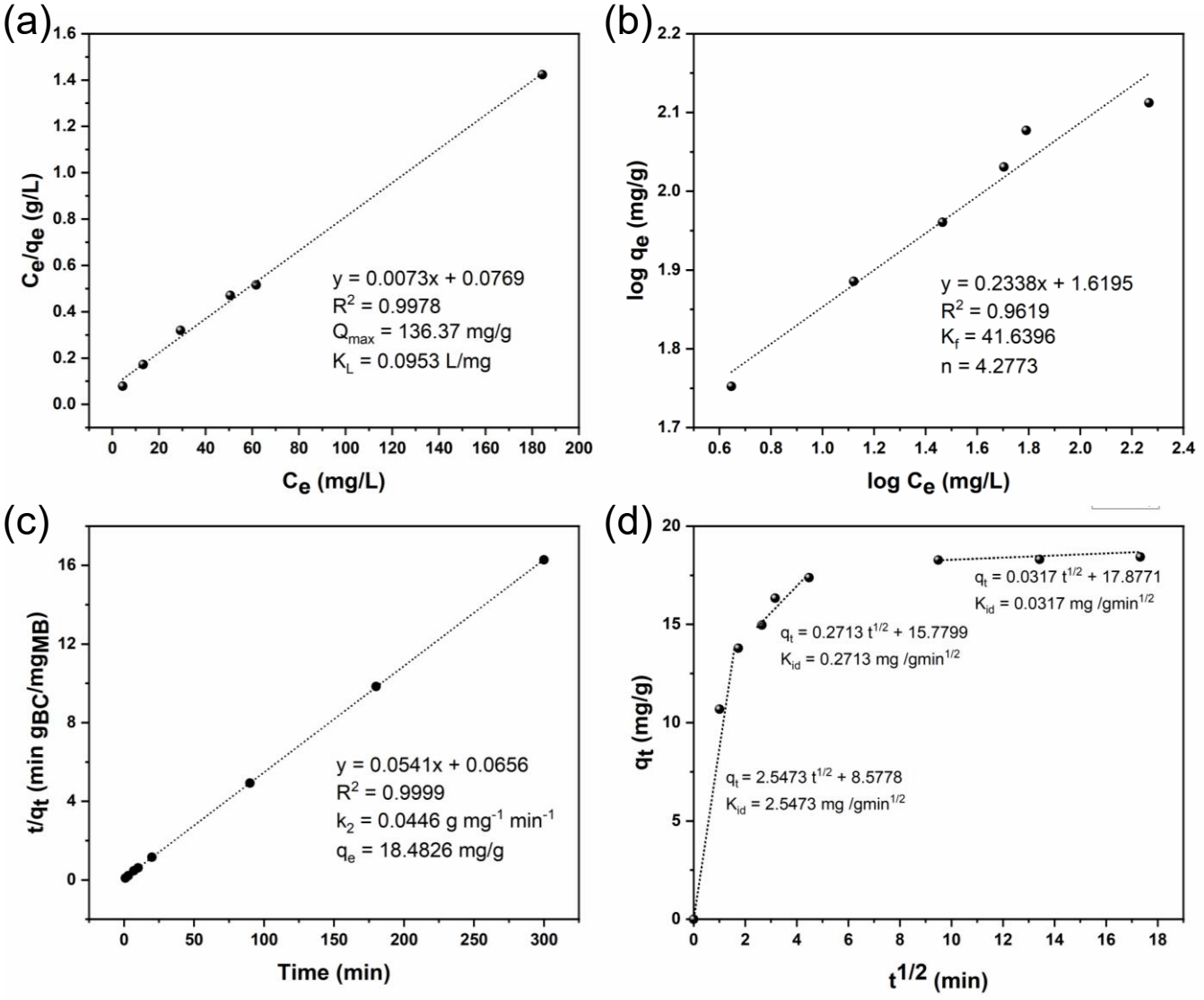
"SiO_2 in biochar reacts pozzolanically with $Ca(OH)_2$ to form C–S–H, which increases strength, reduces porosity, and improves the durability of mortar."

MB adsorption capacities of FCB



BC700 showed the fastest adsorption and highest removal efficiency among BC300, BC500 and BC700.

MB adsorption capacities of FCB



Isotherm interpretation

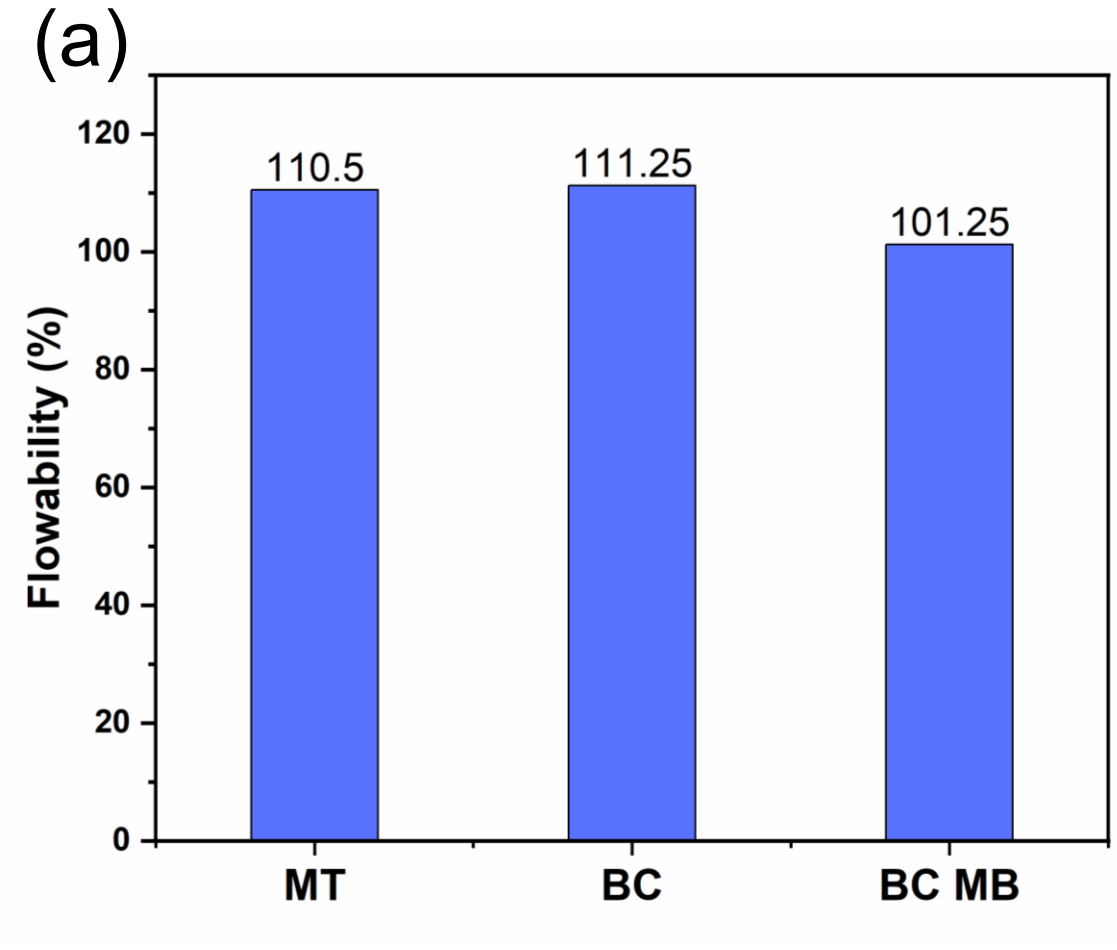
Langmuir (R^2 = 0.9978) fitted better than Freundlich (R^2 = 0.9619), supporting predominantly monolayer adsorption.

Kinetic interpretation

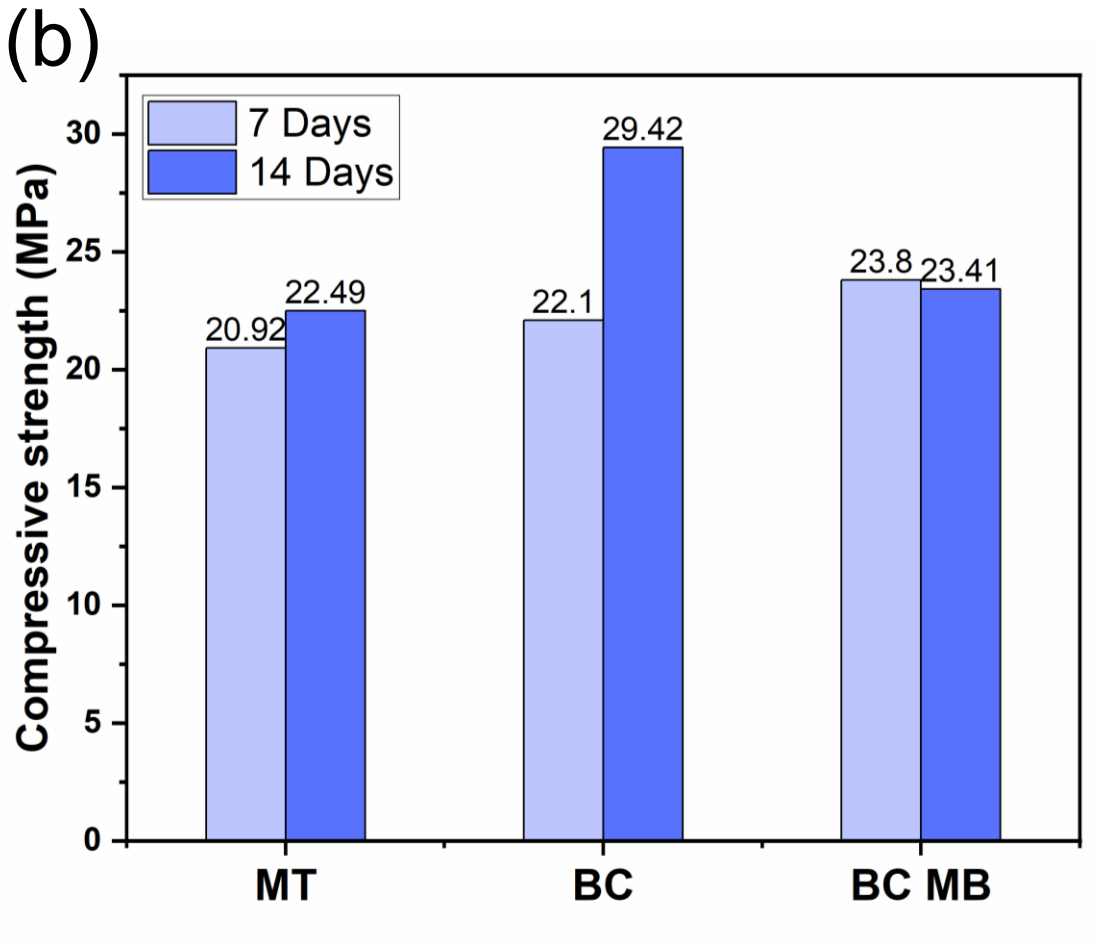
Pseudo-second-order fit: q_e = 18.48 mg g^{-1}; k_2 = 0.0446 g mg^{-1} min^{-1}. IPD analysis indicated three diffusion stages.

Mechanical Properties

Flowability



Compressive strength





Prof. Siwaporn Meejoo Smith

CCC Lab

WASTE TO WEALTH & SUSTAINABLE MATERIALS LABORATORY





Prof. Pitcha Jongvivatsakul





Dr. Napat Kaewtrakulchai

Thank you for your attention