Biochar as a building material: Sequestering carbon and strengthening concrete

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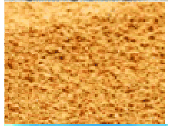
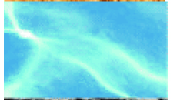
CONCRETE

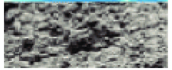
41% Gravel or Crushed Stone (Coarse Aggregate)



26% Sand (Fine aggregate)



16% Water



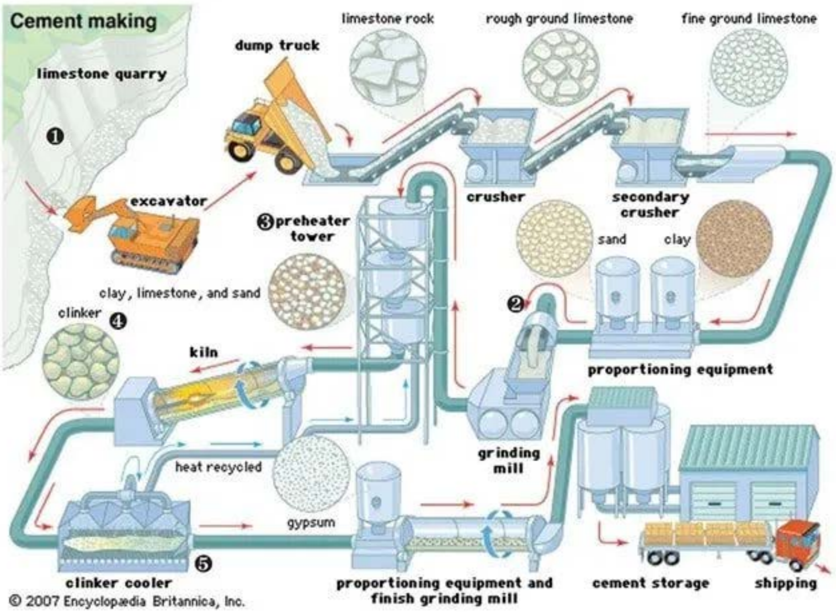
11% Portland cement

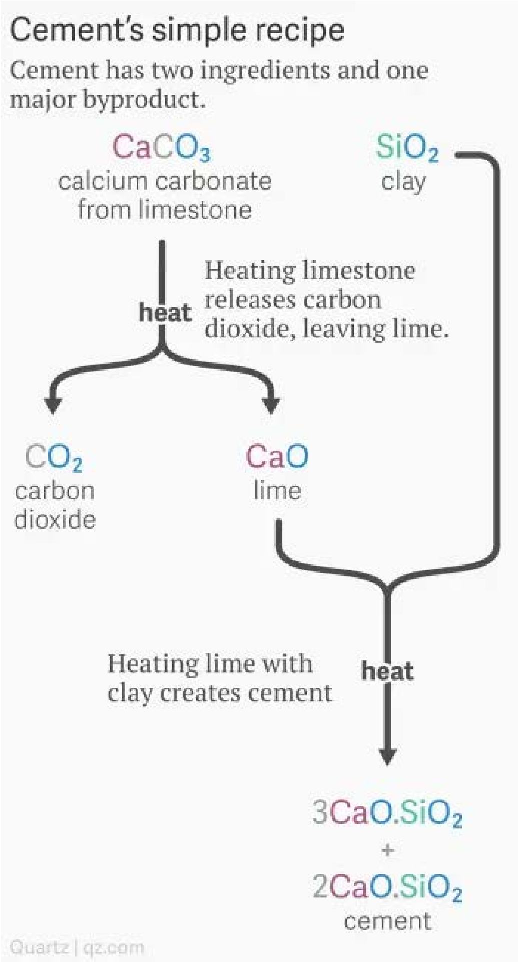
6% Air

0.06-0.6% Super-plasticizer

Energy guzzler, GHG felon

- 10 exa Joules energy (#3 industrial)
- 2.2 Gt CO_2 (#2 industrial)
- ~8% of world's GHG emissions
- 1 t CO_2 / t cement

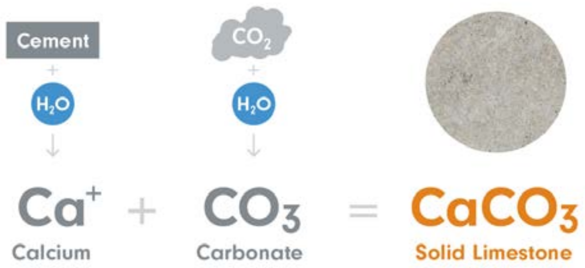




https://www.iea.org/reports/cement

Current activities to reduce cement GHG emissions

1. Green cement manufacturing process
   - High TRL
   - No/minimal impact on product quality
2. Green alternatives to Portland cement
   - Fly ash (supply is decreasing)
   - CarbonCure 25 lbs CO2/cubic yd (7% reduction)
   - Low TRL, new concepts like microbial mineralization
   - Limestone, calcined clay
   - Steel slag
3. Replacement of aggregate with $CaCO_3$



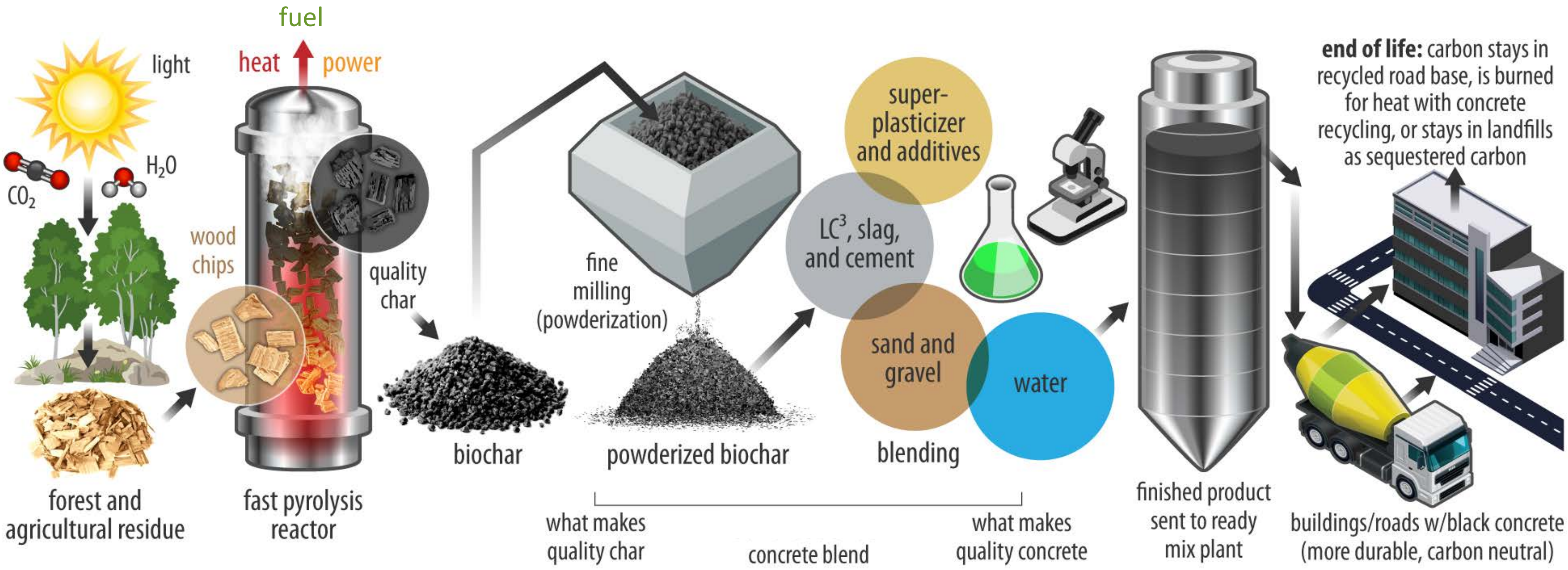
https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry
https://www.cleantech.com/between-a-rock-and-hard-place-commercializing-co2-through-mineralization/

Biochar: The oldest technology

- Biochar is 1 of 5 technologies recognized by the IPCC for carbon sequestration
- 1 ton biochar ≈ 2.2 ton CO_2
- New standards for char released by USDA, CA Air Pollution Control Officers Association, IBI, USBI
- Industrial production (high TRL)
- Can be applied to agriculture, but difficult to make profitable

Carbon transformation

The vision


fuel
light
heat
power
CO_2
H_2O
wood chips
quality char
fine milling (powderization)
super-plasticizer and additives
LC^3, slag, and cement
sand and gravel
water
end of life: carbon stays in recycled road base, is burned for heat with concrete recycling, or stays in landfills as sequestered carbon
forest and agricultural residue
fast pyrolysis reactor
biochar
powderized biochar
blending
what makes quality char
concrete blend
what makes quality concrete
finished product sent to ready mix plant
buildings/roads w/black concrete (more durable, carbon neutral)

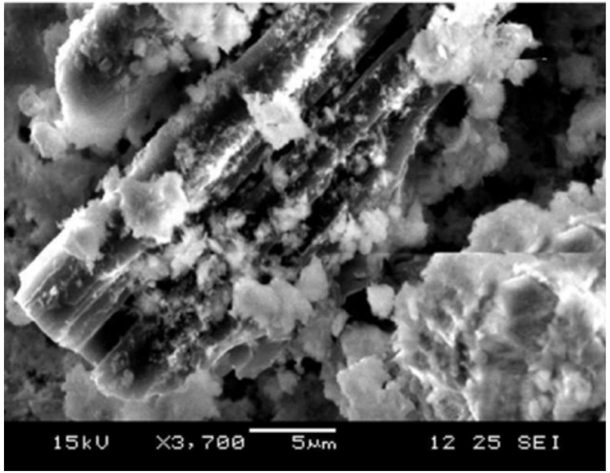
Char *enhances* concrete if it is milled

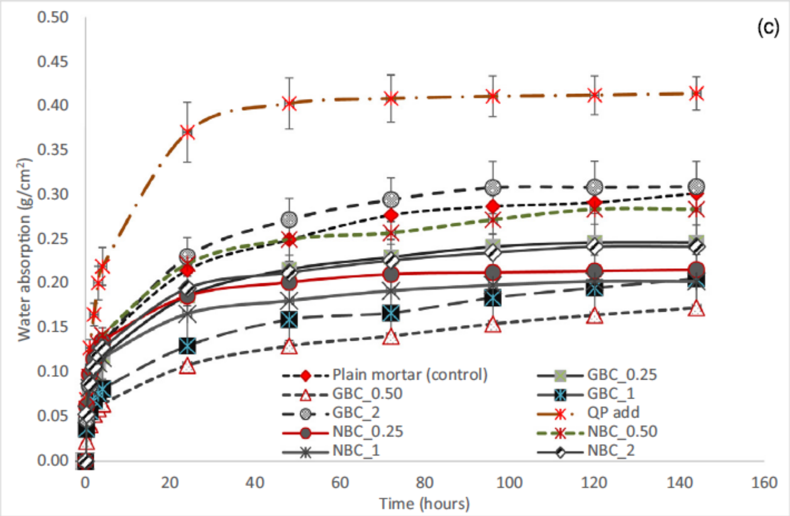
- 2% loading of char:cement **reduces net GHG emissions by 15%**

Table 3
Compressive strength development of mortar with ground and normal biochar under moist curing and air curing.

		Moist curing	Air curing
	1-day strength (MPa)	28-day strength (MPa)	28-day strength (MPa)
Plain mortar (control)	29.74 (1.94)	64.86 (2.63)	53.34 (1.25)
GBC_0.25	40.54 (1.26)	61.78 (2.68)	58.36 (0.46)
GBC_0.50	38.51 (2.42)	69.66 (2.49)	69.61 (2.46)
GBC_1	40.97 (1.20)	70.54 (2.23)	66.04 (4.44)
GBC_2	38.51 (2.10)	70.59 (2.51)	65.76 (1.33)
NBC_0.25	33.57 (0.06)	67.87 (1.56)	60.87 (2.43)
NBC_0.50	35.97 (3.42)	68.00 (2.04)	63.45 (3.10)
NBC_1	35.80 (1.02)	70.30 (1.67)	62.56 (0.98)
NBC_2	30.50 (0.62)	69.40 (2.10)	56.43 (3.90)
QP add	36.48 (0.52)	69.11 (3.10)	54.44 (2.30)

Gupta, S. and H. W. Kua (2019). "Carbonaceous micro-filler for cement: Effect of particle size and dosage of biochar on fresh and hardened properties of cement mortar." Science of the Total Environment **662: 952-962.**

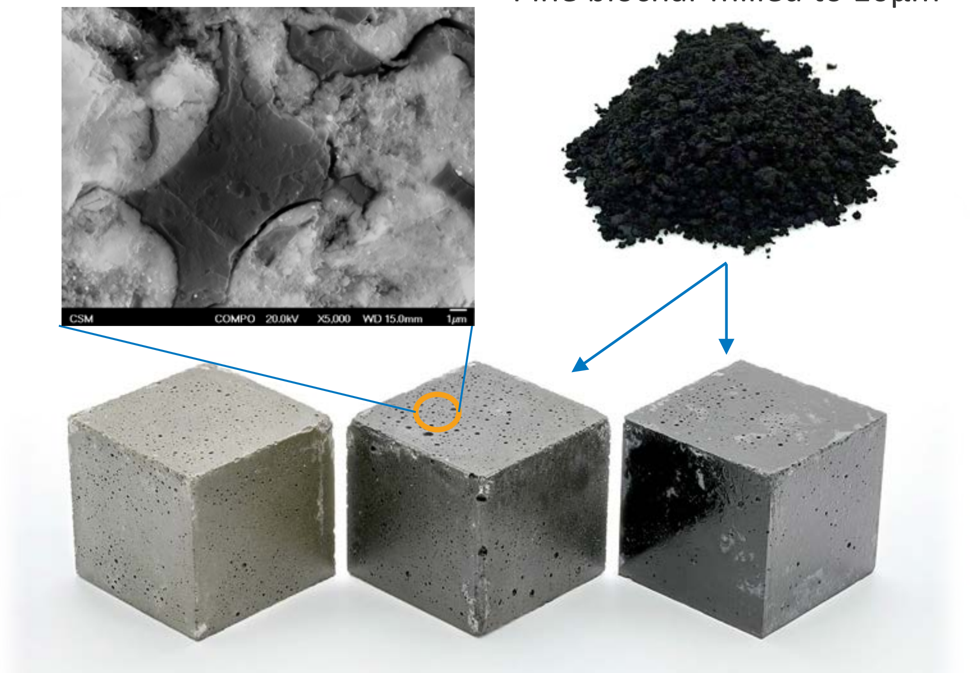




Original hypothesis

Because fast pyrolysis chars have higher surface area + higher water sorption capacity, we can achieve higher cement replacement levels than prior reports

Pine biochar milled to 10µm



Control
(no biochar)

2% Biochar
6% CO_2 reduction

15% Biochar
45% CO_2 reduction

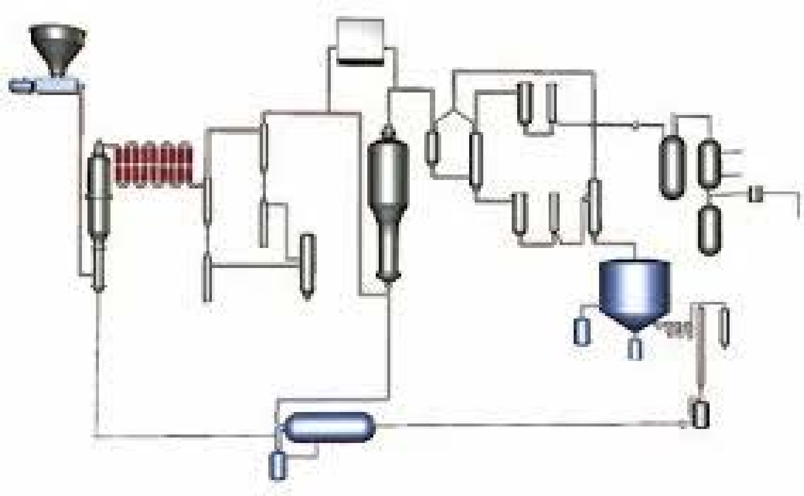
Mortar sample prep

1) Dry mix cement, sand, char in powered mixer
2) Add standard water:cement ratio
3) Adjust flowability (slump) to match control with Sika ViscoCrete superplasticizer following ASTM C1437
4) Cure in cubic forms for compression, elongated forms for tensile (at least triplicate)
5) Compression load testing ASTM C109, flexural ASTM C348

Mix Name	Water/Cement	Cement (kg/m3)	Sand (kg/m3)	Water (kg/m3)	Biochar (kg/m3)	SP:cement
Control	0.4	646.5	1440.8	258.6	0	0.3%
2% Biochar	0.4	640.9	1428.4	256.1	13.4	0.4%
6% Biochar	0.4	629.4	1402.7	250.8	41.1	0.7%
10% Biochar	0.4	617.3	1375.7	245.3	70.2	1.1%
15% Biochar	0.4	601.3	1340.1	238.0	108.7	1.5%
32% Biochar	0.55	498.3	1110.5	268.4	240.1	12.3%
32% Biochar	0.61	483.9	1078.3	289.7	233.2	8.0%

Biochar preparation

- Local collaborator Lori Tunstall at Mines
- NREL TCPDU 500 ^{o}C char
- 60% air-classified forest residues, 30% clean pine and 10% hybrid poplar
- Milled char to 10 um (RockLabs RM2000)



10”

10”

Biochar characterization

Proximate (% dry)	
ash	3.66
volatile	18.87
fixed C	77.47
Ultimate (% dry)	
carbon	83.91
hydrogen	3.3
nitrogen	0.29
sulfur	0.032
ash	3.66
oxygen	8.81

Elemental analysis of ash (% of ash)	
SiO_2	49.41
Al_2O_3	8.52
TiO_2	0.28
Fe_2O_3	2.13
CaO	10.44
MgO	4.10
Na_2O	0.56
K_2O	9.63
P_2O_5	2.32
SO_3	6.42
Cl	0.02
CO_2	3.39

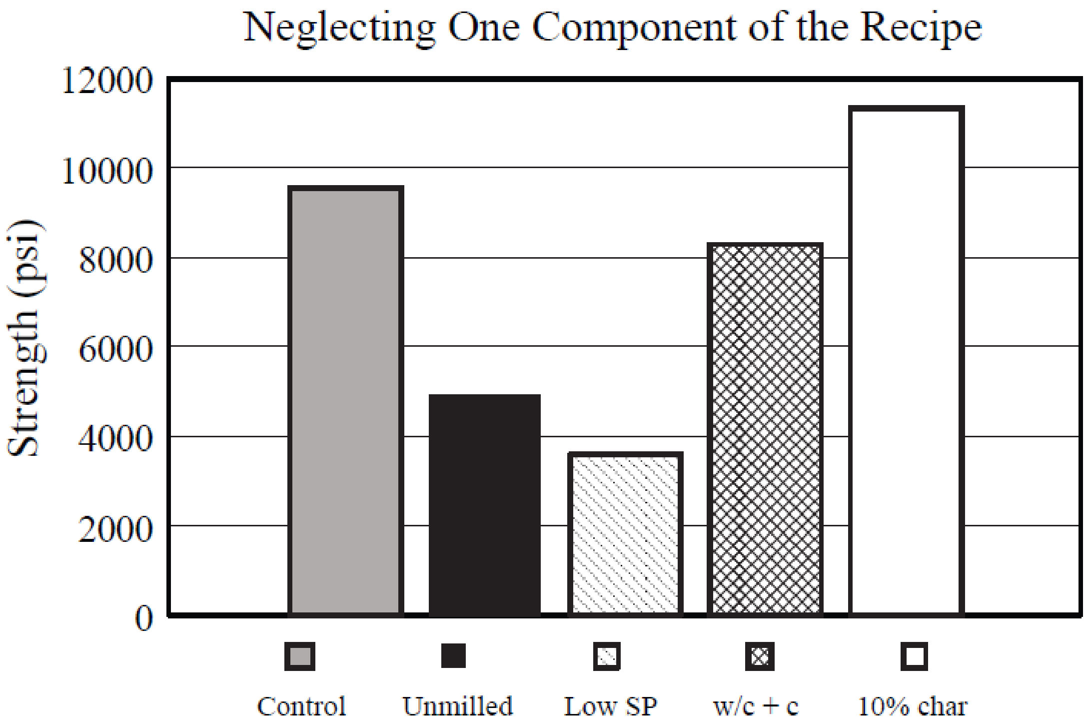
Biochar characterization

We are using high surface area fast pyrolysis char

Study	Feed-stock	Pyrolysis process	Surface area	D50	Ash content	SiO_2 + Al_2O_3 + Fe_2O_3	H_2O adsorption capacity	Max. Char % [a]	28 day mortar strength gain
Gupta [2]	Pine	T = 300 °c T = 70 min Rate = 10 °c/min	0.83 m^2/g	< 10 µm	N/r	N/r	2.5 %	**2**	**7 %**
Choi [6]	Hardwood	T = 500 °c T = 1 – 2 s Rate = 10^4 °c/min	9 m^2/g [b]	< 10 µm [c]	34.7 %	25 %	N/r	**5**	**6.4 %**
This work	Pine	T = 500 °c T = 1 – 2 s Rate = 10^4 °c/min	233 m^2/g	< 10 µm	3.7 %	60 %	8.0 %	**15**	**38 %**

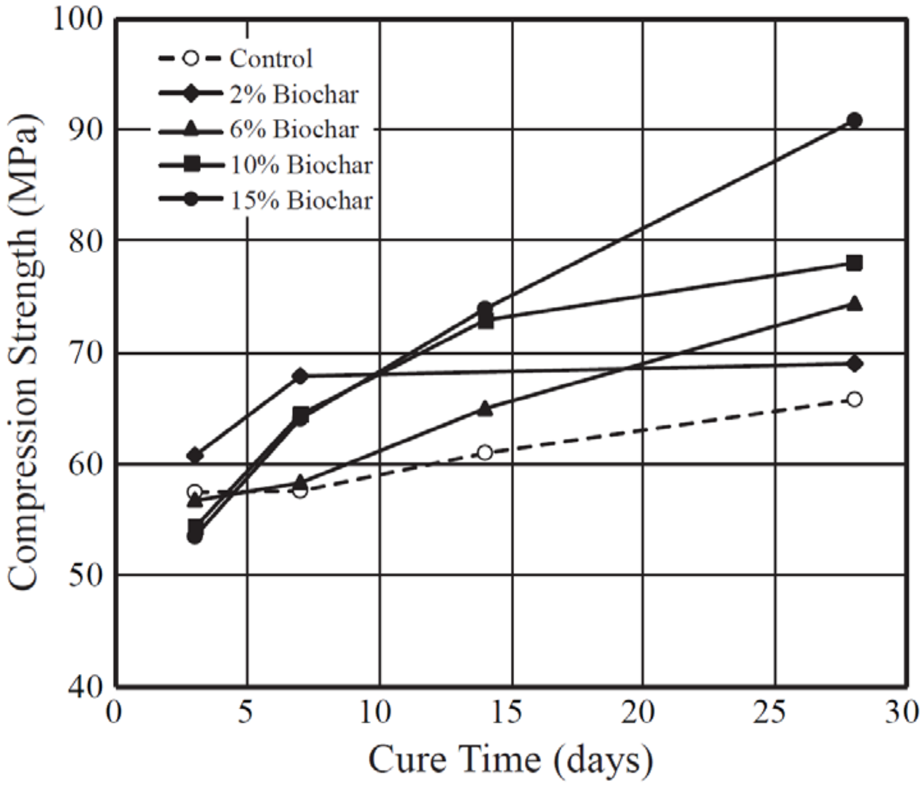
Results: Why are we able to achieve the strength at such high loadings?

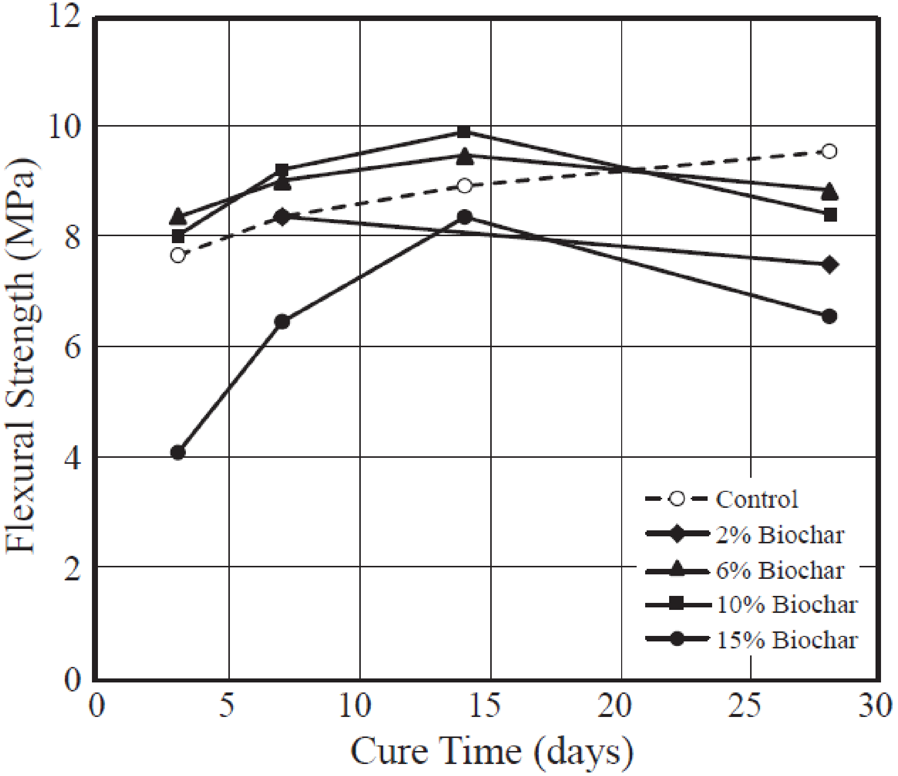
1. Milling- sub 20 μm
2. Modulate flowability
3. Do not add excess water
4. Fast pyrolysis char



United States Patent & Trademark Office (USPTO)
Application No. 17/698,569

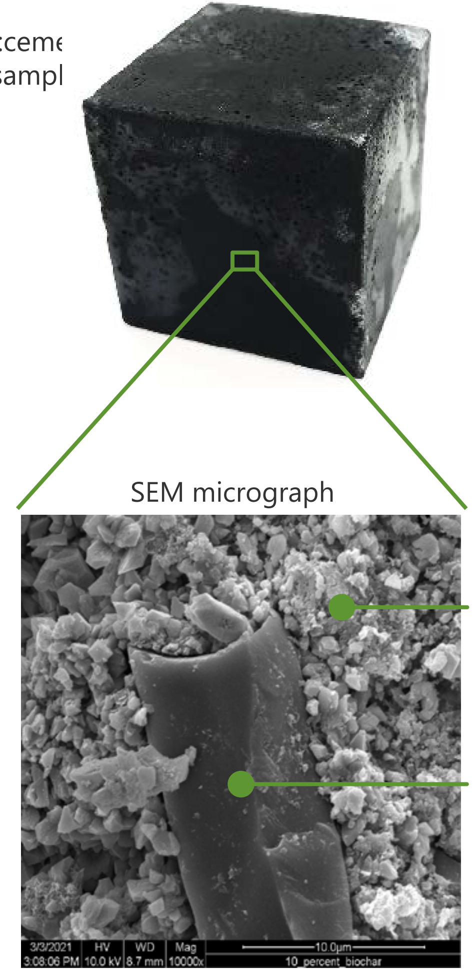
Results: Compression vs time





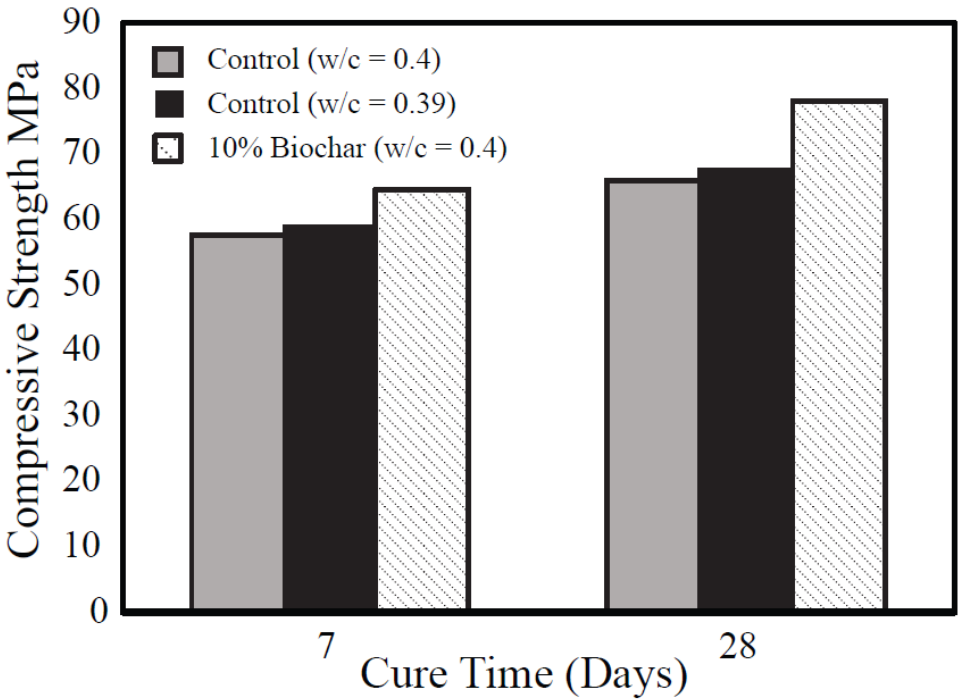
Mechanisms for strength enhancement

1. Water sorption capacity imbues internal curing through slow release of moisture
2. Biochar surface has nucleation sits for dispersed formation of calcium silicate hydrate (as opposed to calcium hydroxide)
3. Biochar itself is a supplemental cementitious material (SCM)



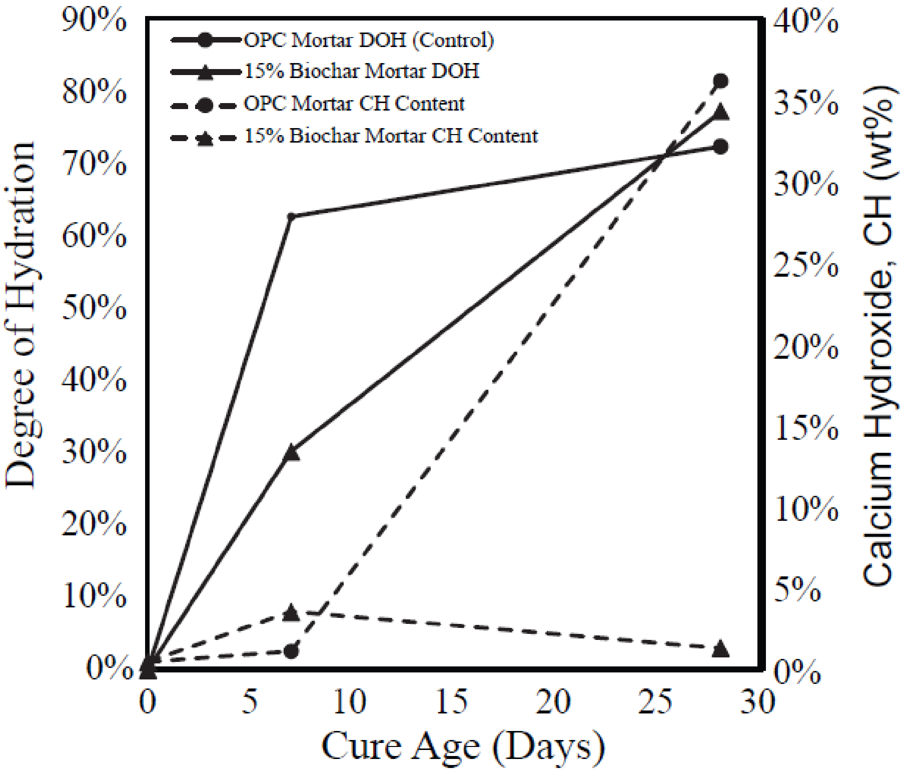
Mechanism 1: Internal curing

Biochar can absorb 8% water by weight, but removing this amount of water from control only accounts for small strength gains



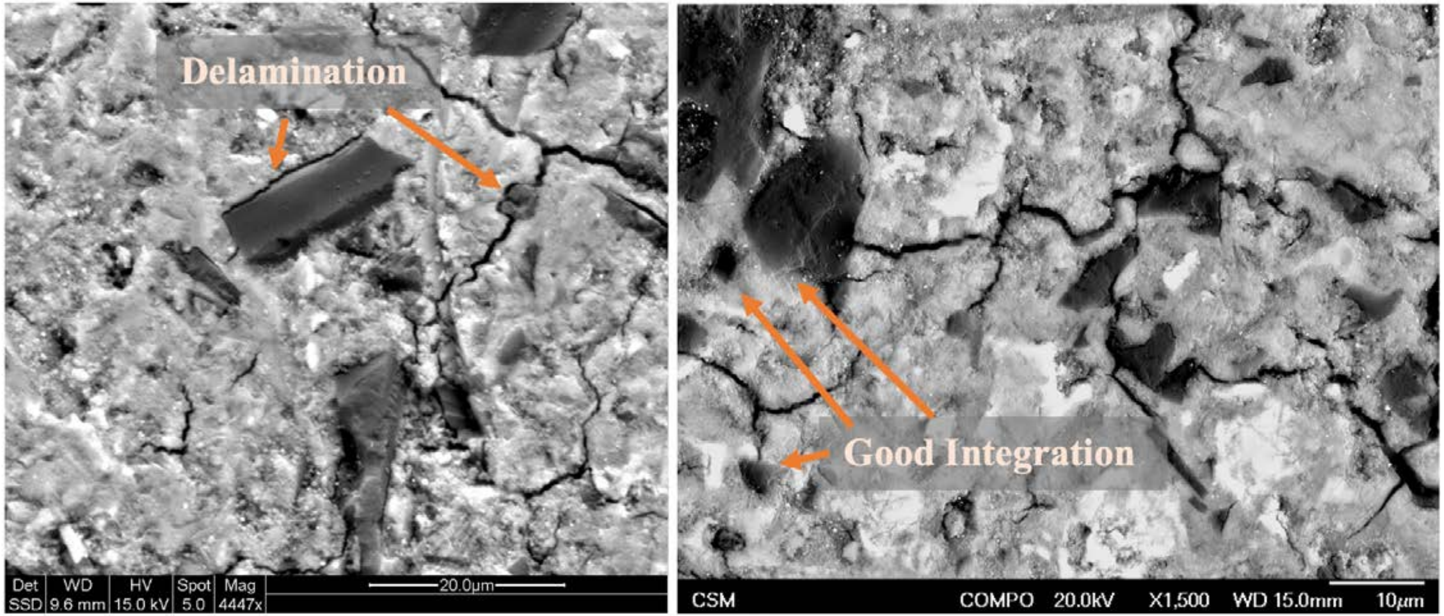
Mechanism 2: Nucleation

- Differential scanning calorimetry
  - CH decomposes 500 °C
- High surface area disperses hydration products, nucleates CSH
- Internal curing only accounts for densification, not major change in strength



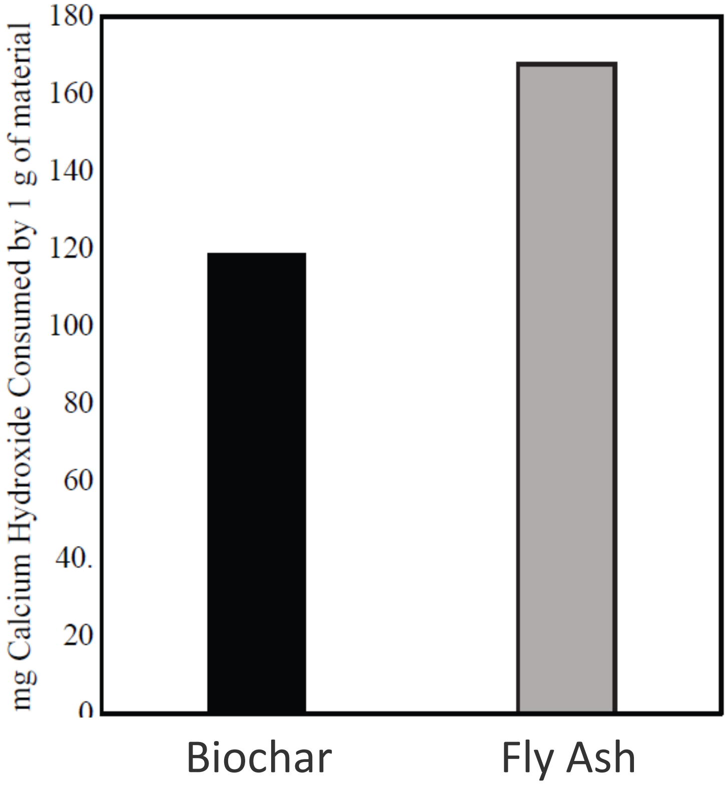
Mechanism 3: Biochar as SCM

SEM shows a complex story



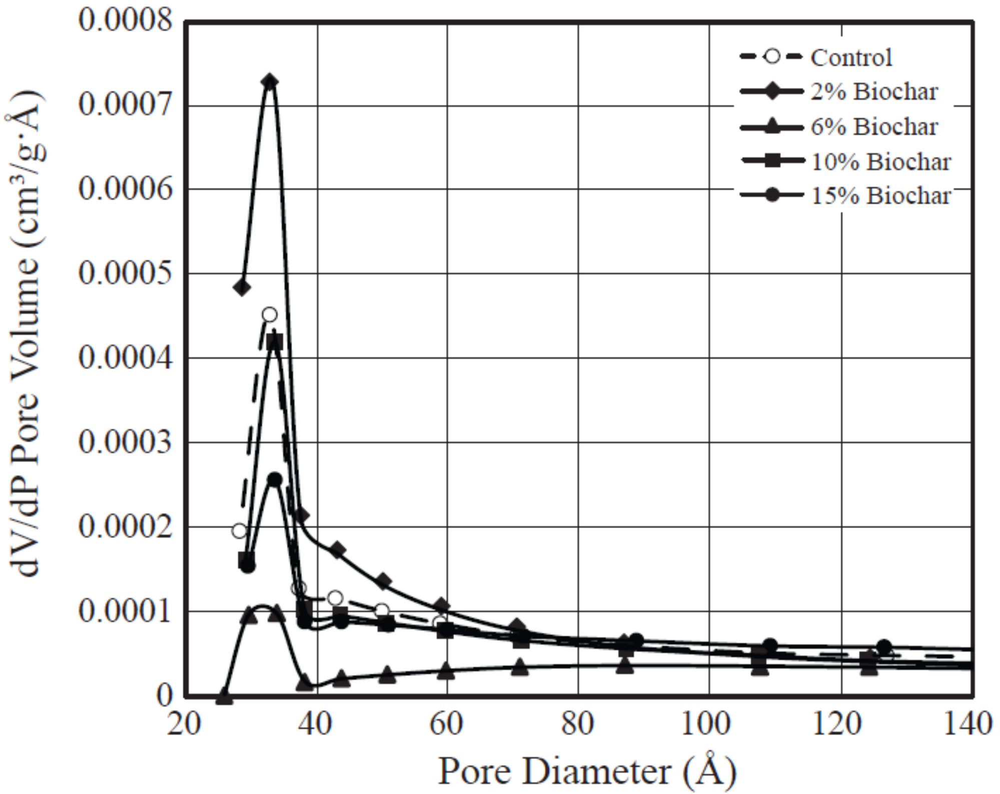
Mechanism 3: Biochar as SCM

- Pozzolonic activity catalyzes CSH formation – remaining CH
- Chappelle test- mix 3g CaO with 1g suspected pozzolan in water, stir and heat 90C, dissolve $Ca(OH)_2$ with saccharose and titrate with HCl



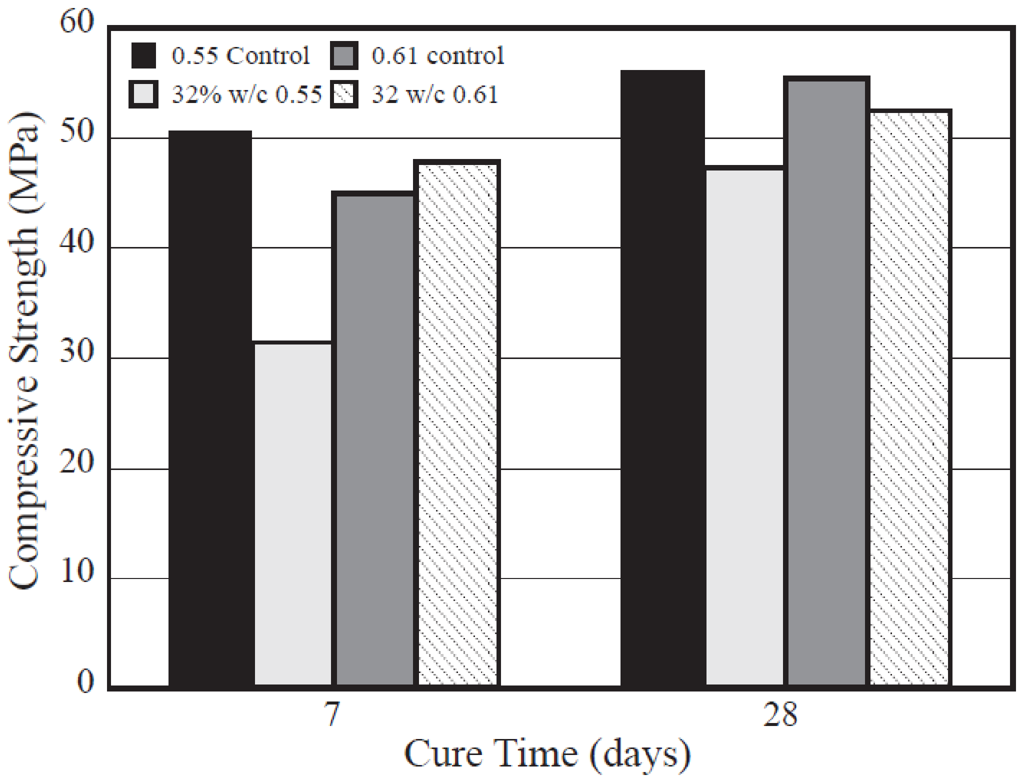
Results: Mechanism domination

- Smaller pores = improved flexural strength
- Increased pozzolanic activity exposes biochar surface acidity at higher char loadings?
- Better balance of mechanisms at lower loadings



Results: Carbon neutral mix

- 32% replacement of cement with biochar
- Big challenge to mix- broke the KitchenAid



LCA for concrete

	lb	kg X/kg concrete	kg CO2/kg concrete	kg CO2 / yard	% net CO2 emissions reduction compared to base case OPC	cost/yard, $200/ton char	cost/yard, $350/ton char	cost/yard, $500/ton char
Base case								
Ordinary portland cement	500.0	0.1	0.1333			31.0	31.0	31.0
LC3	0.0	0.0	0.0000			0.0	0.0	0.0
Slag	0.0	0.0	0.0000			0.0	0.0	0.0
Biochar	0.0	0.0	0.0000			0.0	0.0	0.0
sand	1500.0	0.4	0.0022			16.9	16.9	16.9
course aggregate	1500.0	0.4	0.0025			16.9	16.9	16.9
water (0.5 w/c)	250.0	0.1				0.0	0.0	0.0
superplasticizer	2.1	0.0	0.0004			0.6	0.6	0.6
total	3752.1	1.0	0.1383	519.1	**0.0%**	65.4	65.4	65.4

LCA for concrete

	lb	kg X/kg concrete	kg CO2/kg concrete	kg CO2 / yard	% net CO2 emissions reduction compared to base case OPC	cost/yard, $200/ton char	cost/yard, $350/ton char	cost/yard, $500/ton char
2% biochar, OPC								
OPC	490.0	0.130736	0.1307			30.4	30.4	30.4
LC3	0.0	0	0.0000			0.0	0.0	0.0
Slag	0.0	0	0.0000			0.0	0.0	0.0
biochar	10.0	0.002668	-0.0058			1.0	1.8	2.5
sand	1500.0	0.400213	0.0022			16.9	16.9	16.9
course aggregate	1500.0	0.400213	0.0025			16.9	16.9	16.9
water (0.5 w/c)	245.0	0.065368				0.0	0.0	0.0
superplasticizer	3.0	0.0008	0.0006			0.9	0.9	0.9
total	3748.0	1	0.1302	487.9	**-5.9%**	66.1	66.8	67.6

LCA for concrete

	lb	*kg X/kg concrete*	*kg CO2/kg concrete*	*kg CO2 / yard*	*% net CO2 emissions reduction compared to base case OPC*	*cost/yard, $200/ton char*	*cost/yard, $350/ton char*	*cost/yard, $500/ton char*
15% biochar, OPC								
OPC	425.0	0.114201	0.1142			26.4	26.4	26.4
LC3	0.0	0	0.0000			0.0	0.0	0.0
Slag	0.0	0	0.0000			0.0	0.0	0.0
biochar	75.0	0.020153	-0.0439			7.6	13.2	18.8
sand	1500.0	0.403063	0.0022			16.9	16.9	16.9
course aggregate	1500.0	0.403063	0.0025			16.9	16.9	16.9
water (0.5 w/c)	212.5	0.057101				0.0	0.0	0.0
superplasticizer	9.0	0.002418	0.0017			2.7	2.7	2.7
total	3721.5	1	0.0767	285.5	**-44.5%**	70.4	76.1	81.7

LCA for concrete

	lb	*kg X/kg concrete*	*kg CO2/kg concrete*	*kg CO2 / yard*	*% net CO2 emissions reduction compared to base case OPC*	*cost/yard, $200/ton char*	*cost/yard, $350/ton char*	*cost/yard, $500/ton char*
32% biochar, OPC								
OPC	337.5	0.090746	0.0907			$ 20.93	$ 20.93	$ 20.93
LC3	0	0	0.0000			$ -	$ -	$ -
Slag	0	0	0.0000			$ -	$ -	$ -
biochar	162.5	0.043693	-0.0953			$ 16.44	$ 28.62	$ 40.81
sand	1500	0.403317	0.0022			$ 16.88	$ 16.88	$ 16.88
course aggregate	1500	0.403317	0.0025			$ 16.88	$ 16.88	$ 16.88
water (0.61 w/c)	205.875	0.055355				$ 0.04	$ 0.04	$ 0.04
superplasticizer	13.28243374	0.003571	0.0026			$ 3.98	$ 3.98	$ 3.98
total	3719.157434	1	0.0028	10.3784	**-98.0%**	$ 75.14	$ 87.32	$ 99.51

Thank you

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www.nrel.gov
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