

## BIOCHAR AS A CARBON SEQUESTERING CONSTRUCTION MATERIAL IN CEMENTITIOUS MORTAR

Souradeep Gupta, Harn Wei Kua\*

Département of Building, School of Design and Environment, 4 Architecture Drive, Singapore

\*Corresponding author; [bdgkuahw@nus.edu.sg](mailto:bdgkuahw@nus.edu.sg)

### Abstract

Recent efforts to attain carbon negative construction practices in Singapore and other developed countries leads to a search for construction materials that can reduce net carbon emission associated with concrete constructions. One such material is biochar which can sequester fixed carbon in its structure. Therefore, using biochar as a mixed-in component in cementitious material can reduce the net greenhouse emission associated with concrete constructions. Our study focuses on application of biochar derived from mixed-wood saw dust as a cement replacement in mortar. Experimental findings suggest that, due to its fine particle size and micro-filler effect, up to 4% cement replacement by biochar yielded slight improvement in compressive strength while reducing sorptivity by about 70% after 28 days. Improvement in strength and permeability of mortar by incorporating biochar suggest that it can be successfully deployed as a carbon sequestering concrete construction material. Durable and strong infrastructure means reduced vulnerability to damage and thus need for subsequent repairs over its service lifespan. This will help contribute toward economic and environmental sustainability of buildings.

### Keywords:

Cement replacement; Biochar; Sorptivity; Carbon sequestration.

## 1 INTRODUCTION

Globally, the construction industry is facing environmental concerns because of the energy intensive processes being used and high amount of carbon dioxide emitted during the process itself. Worrell et al. (2001) estimated that 1 ton of cement production is associated with 1 ton of CO<sub>2</sub> emission to the atmosphere. While developed and developing countries are aiming for low-carbon constructions and low waste-generation, any material solution that fulfills these two objectives has the potential to increase sustainability of construction. One of the potential solutions to address this issue of rising emission is sequestration of carbon in cementitious materials. Biochar is one such material which can sequester high volume of stable carbon, if incorporated in cementitious mix [Gupta, 2016; Gupta, 2017]. One of the potential ways to reduce carbon footprint of cementitious constructions may be by achieved by using biochar as partial cement replacement. Depending on the type of feedstock and preparation conditions used, biochar has the potential of reducing net life cycle greenhouse gas (GHG) emissions by about 870 kg CO<sub>2</sub> equivalent (CO<sub>2</sub>-e) per tonne dry feedstock, of which 62–66% are realized from carbon capture and storage by the biomass feedstock of the biochar [Roberts et al. 2009]. The use of biochar as partial cement replacement would also promote waste recycling and therefore, can significantly reduce the

land area required for waste disposal. It follows the principle of industrial ecology where waste of one industry become 'food' for another. It means the biomass which may be wood waste, agricultural waste or food waste may be processed to make biochar that would be further used as a construction material. To expand the application of biochar beyond just soil enhancement, Canadian Biochar Initiative encouraged its use in several other industrial areas including asphalt and concrete industry.

Biochar has attracted research attention as a potential construction material in pavement and building over the past few years [Ahmad et al. 2015; Choi et al. 2012; Khushnood et al. 2016; Restuccia and Ferro 2016; Zhao et al. 2014]. Choi et al.(2012) investigated the use of commercially produced hardwood biochar as cement replacement in mortar. The findings show that 5% replacement of cement (by weight) by biochar improved the 28-day compressive strength of mortar. However, the flowability of biochar-mortar is reduced with higher replacement rate because biochar tends to absorb and hold a significant part of mixing water resulting in stiffer mix compared to reference. The physically absorbed water in biochar is later released during the hardening of mortar and can contribute to internal curing [Choi et al. 2012]. Restuccia and Ferro (2016) investigated strength and fracture energy of cement paste incorporating hazelnut shell derived biochar prepared at 800°C. The study suggests that biochar can act as micro-aggregate and improve

compressive, strength, bending strength and fracture energy of cement paste. The improvement in fracture energy due to introduction of hazelnut shell biochar has been attributed to tortuosity of crack path. The biochar particles introduce inhomogeneity in the matrix and attract the crack paths towards them. The biochar particles have the ability to absorb energy before failure which improves fracture energy and bending strength [Restuccia and Ferro 2016]. Similar findings have been reported by Khushnood et al.(2016) that 1% addition of biochar derived from peanut shell and hazelnut shell resist crack propagation and divides crack into few narrower cracks which results in more ductile failure of cementitious composites. Ahmad et al. (2015) reported that inclusion of coconut shell derived biochar improved modulus of rupture, compressive strength, and fracture toughness of cement paste. Scanning electron microscope images showed the tortuosity of crack path in presence of biochar particles [Ahmad et al. 2015]. However, shape and size of biochar particles are important parameters in this case because interaction between biochar particle and cement paste would play an important role in absorbing fracture energy and resisting crack propagation.

Therefore, based on the carbon capture and sequestration potential of biochar and its suitability as construction material, possibility of using biochar as a construction material should be further explored. Therefore, this study explores the effect of partial replacement of cement by biochar on mechanical strength and sorptivity of mortar samples. Strength and sorptivity values obtained by partial replacement of cement by biochar is further compared with mortar containing silica fume as cement replacement.

## 2 MATERIALS AND METHODS

### 2.1 Cement, sand and silica fume used

Locally available natural sand with maximum size of 2.75 mm was used. The specific gravity and fineness modulus of sand used are 2.55 and 2.58 respectively. Ordinary Portland cement CEM I 52.5N conforming to specifications stated in ASTM C150-16 is used for all the mixes. Undensified silica fume (Elkem microsilica Grade 940) is used to replace 5% cement in mortar mix. The bulk density is between 500-700 kg/m<sup>3</sup> with surface area of about 15m<sup>2</sup>/g, while other properties are tested as per ASTM C1240-14.

### 2.2 Preparation and properties of biochar

The biochar used in the study is prepared by pyrolysis of mixed wood saw dust at 300 °C with heating rate of 10 °C/min. The prepared char is grinded before mixing into mortar. Bulk of the particle is in the particle size range of 300-600µm while about 20% of the particles are less than 75µm. Particles below 300µm were sieved and used in the preparation of the coating. Elemental composition and physical properties of biochar used is presented in Tab 1.

### 2.3 Mix proportions, mixing process and tests conducted

Tab. 2 presents the different mixes and mix proportions used in this study. Sand to cement ratio of 2.75 and water-cement ratio of 0.40 were followed for all the mixes. Biochar is not cementitious in nature and therefore the water and sand content was adjusted with respect to the weight of cement in the mix. Particle size distribution of produced biochar was studied and

only those char particles less than 50µm size were used to replace cement at different percentages by weight, as stated in Tab 2.

Tab. 1: Elemental composition and physical properties of biochar

	Composition (% by weight)
Carbon	62.25
Hydrogen	7.17
Oxygen	25.60
Calcium	0.20
Magnesium	0.26
Potassium	0.42
Silica	0.40
O/C ratio	0.47
H/C ratio	0.11
pH	11.85
Bulk density(g/cc)	1.55
Specific surface area (BET (m <sup>2</sup> /g)	0.53
Average pore diameter(nm)	0.80
Total volume in pores (x10 <sup>-3</sup> cm <sup>3</sup> /g)	
<2.02 nm	41.97
<400.30 nm	80.75

Compressive strength was carried out following the preparation and loading conditions stated in BS EN 12390-3. Flexural strength was performed using prisms of dimension 40x40x60 mm loaded at displacement rate of 0.1mm/minute. Sorptivity test was carried out as per ASTM C1585-13 to study the effect biochar as cement replacement on permeability of mortar. Samples for sorptivity test were cut from 100mm(d)x 200mm(h) cylinder samples using a highspeed concrete cutter. The samples were conditioned following the specifications in ASTM C1585 and the test was carried out at 25±1 °C. For each of these tests, at least 4 samples were tested.

## 3 RESULTS AND DISCUSSIONS

### 3.1 Effect on compressive strength

Fig. 2 presents the compressive strength of control mortar and mortar mix with different replacement percentages of cement by biochar (w/w) and silica fume. Both mixes with 2% and 4% cement replacement by biochar meet the requirement for structural use as prescribed by Building and Construction Authority, Singapore. The compressive strength of Cemrep-4% shows highest strength at 7 day, 14 day and 28-day age of mortar. While 4% cement replacement by biochar results in 23% and 18% increase in compressive strength at 7 day compared to control and silica fume replacement respectively, 28-day strength is similar to control mix. When 2% and 8% cement is replaced by biochar, the strength at 7 day is lower compared to 4% cement replacement by biochar. The increase in 7-day strength is mainly due to reduction in free water in the

mortar added during mixing. 4% of cement replaced by biochar results in higher densification of mortar by absorbing free water compared to when 2% cement is replaced by biochar. Fine biochar particles also produce micro-filler effect in mortar that improves the interfacial zone between cement paste and fine aggregates. However, 8% replacement of cement by

biochar was found to introduce voids in the mortar mix that resulted in reduction of compressive strength (Fig.3). Voids are introduced as a result of excessive absorption of water by high volume of biochar which affect compaction of fresh mix even when the mix is placed in moulds on a vibration table.

Tab. 2: Mixes and mix proportions explored in this study

Mortar mix	Mix description	Cement(g)	Sand(g)	Water(g)	Biochar(g)	Silica fume (g)
<b>Control</b>	Plain mortar (without fiber)	10000	27500	4000	0	0
<b>Cemrep-2%</b>	2% cement replaced by biochar (by wt.)	9800	26950	3920	200	0
<b>Cemrep-4%</b>	4% cement replaced by biochar (by wt.)	9600	26400	3840	400	0
<b>Cemrep-8%</b>	8% cement replaced by biochar (by wt.)	9200	25300	3680	800	0
<b>Cemrep_SF5 %</b>	5% of cement replaced by silica fume	9500	27500	4000	0	500

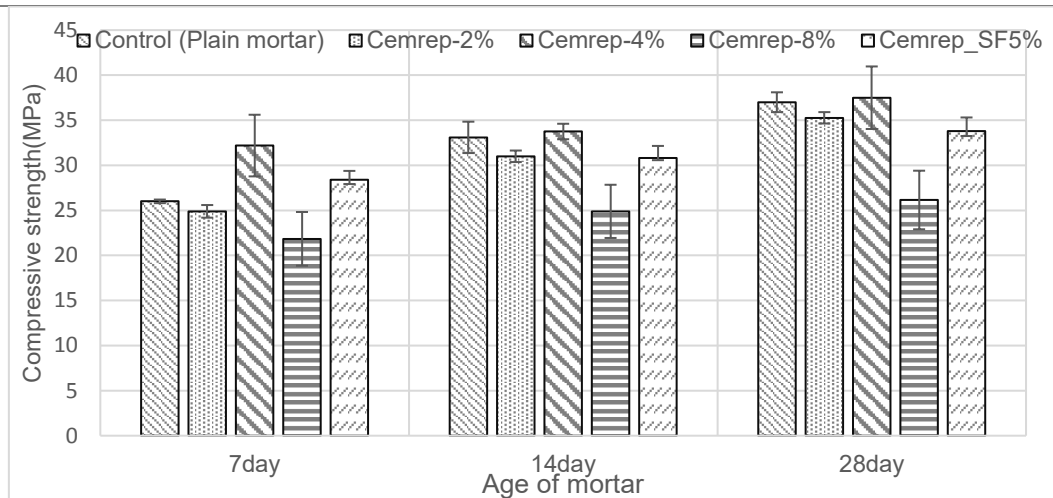


Fig. 2: Compressive strength of plain mortar, and mortar with cement replacement by biochar and silica fume

Mix with cement replacement by silica fume show similar strength development as control and Cemrep-4% at 28 day although the 7-day strength is higher than control. Silica fume is known to improve mechanical strength due to its fine particle size and high pozzolanic reactivity. However, the strength development of mix with cement replaced by silica fume can be limited by poor dispersion of silica fume in the mortar mix. Although undensified, silica fume may contain particles up to several millimeters in size which are difficult to disperse as individual spheres without any special treatment [Diamond and Sahu 2006]. Therefore, the agglomerated particles of silica fume remaining in the mix after mixing may often exceed the particle size of cement grains thereby limiting any beneficial micro-filler effect which aid in strength development. However, the densification effect of biochar particle is not only dependent on the micro-

filler effect but the balance of free water in the mix and the water required for hydration of cement. The water absorbed by biochar particles can be later released for internal curing which promote secondary hydration [Choi et al. 2012]. Therefore, based on compressive strength results it may be concluded that 2-4% cement replacement by biochar may produce similar or improved effect on strength development as pozzolanic admixtures.

### 3.2 Effect of cement replacement on sorptivity

Fig. 4 shows that sorptivity of mixes with sorptivity is significantly reduced compared to plain mortar when 2% and 4% (by weight) of cement is replaced by biochar. In fact, the sorptivity of Cemrep-2% and Cemrep-4% mixes are similar to the sorptivity of mix with 5% cement replaced by silica fume.



Fig.3: Voids introduced in mortar mix with 8% cement replaced by biochar

It is well known that silica fume can block capillary channels in cement matrix because of its fine particle size and hydration products generated by pozzolanic reaction. Similar effect is produced by introduction of biochar particles as cement replacement which can be attributed to the role of fine biochar grains as inert micro-filler in cement mortar. Reduction in capillary porosity is caused by reduction of evaporable water in cement mix because of absorption of biochar particles. Furthermore, the continuity of pore network is blocked by biochar particles which resisted the transport of moisture by capillary absorption.

However, it can be observed from Fig. 4 that Cemrep-8% show similar sorptivity as that of plain mortar although compressive strength of this mix was significantly lower than control.

While development of strength depends on the amount of hydration products generated, transport properties depend on reduction of porosity which can be attained by higher hydration degree or blocking of pore network. Therefore, when 8% of cement was replaced by biochar affected hydration degree and introduced air voids, some fine biochar particles may have closed some of the open pore network thereby producing similar sorptivity as control.

Fig.5 presents the coefficient of sorptivity that measures the rate of sorptivity in case of the different mixes studied. Cemrep-2% and Cemrep-4% register lowest rate of initial sorptivity followed by mix with silica fume. Rate of sorptivity is significantly higher in case of Cemrep-8% although it is lower than control by about 30%. However, it can be observed that secondary rate of sorptivity of Cemrep-2% and Cemrep-4% is similar to that of plain mortar and higher than that of Cemrep\_SF5%. The initial sorptivity generally represent filling of capillary pores while the secondary sorptivity represent slower filling of air voids (Yang et al. 2009). Although the biochar grains may act as obstacles which 'break' the continuity of pore network, some air voids may have been formed because of excessive absorption of water by biochar particles and localized poor bonding with cement matrix.

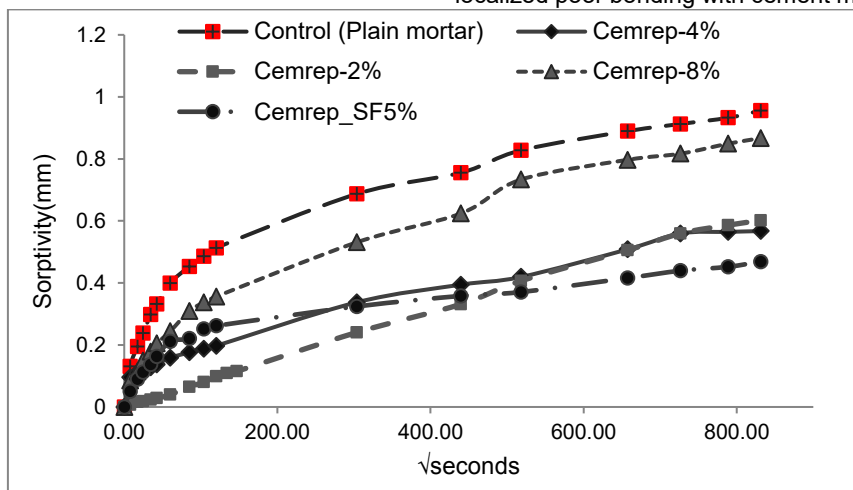


Fig.4: Sorptivity of plain mortar, and mortar with cement replacement by biochar and silica fume

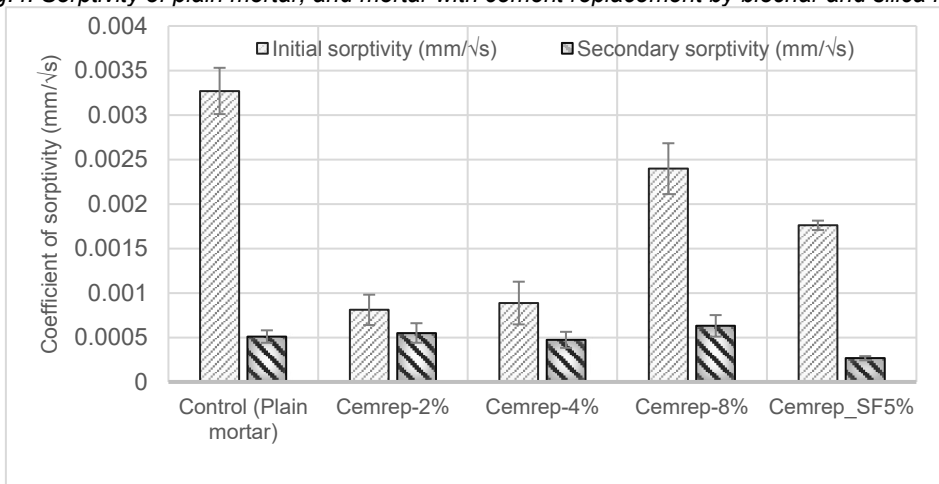


Fig.5: Coefficient of Sorptivity of plain mortar, and mortar with cement replacement by biochar and silica fume

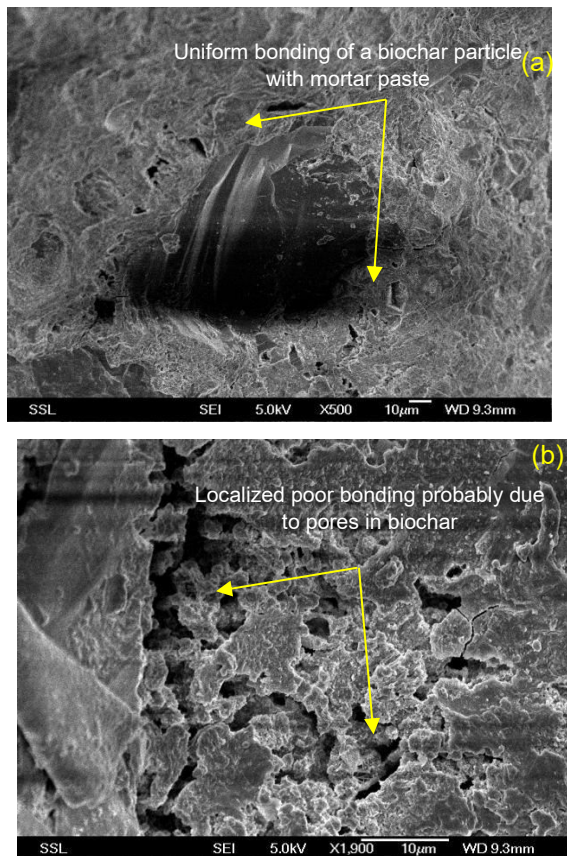


Fig. 6(a): Uniform strong bonding of mortar paste with biochar particle (28 day) (b): Localized poor bonding of mortar paste with a biochar particle around its pore locations

Moreover, biochar particles produced at 300°C contain significant portion of hydrophilic groups on its surface. The hydrophilicity of char particles which are present at the face of mortar specimen that is subject to sorptivity may 'trap' additional water resulting in increase of secondary sorptivity (Fig.7).

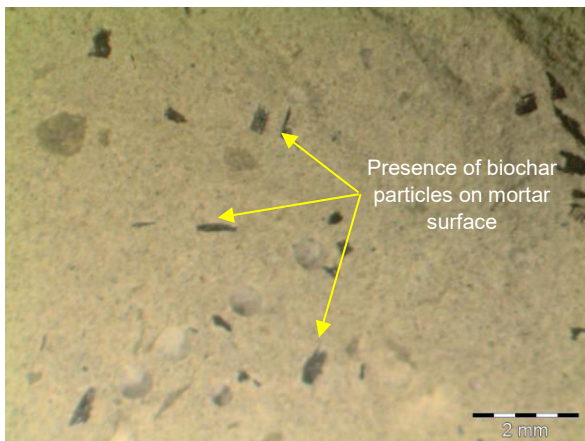


Fig. 7: Presence of biochar particles on mortar surface may contribute to additional absorption of water

On the contrary, silica fume improves the impermeability of mortar by two means- microfiller effect and formation of hydration products by pozzolanic reaction that consumes calcium hydroxide to produce more binder gel. Therefore, the densification due to additional of silica fume takes place through generation of more calcium silicate

hydrate that largely reduce voids and densifies the transition zone between aggregate and cement paste.

Fig. 6(a) shows a uniformly bonded biochar particle with mortar paste. Uniform bonding means reduced void formation around the interface of biochar particles and mortar paste. However, SEM images at some locations in the mortar show non-uniform bonding of mortar paste with biochar particles, especially at the locations of pores on the surface of biochar formed during pyrolysis (Fig.6(b)). Around the zones of biochar pores, the net area of contact of mortar paste with the particle is decreased which probably results in poor bonding and formation of localized voids in the hardened mortar paste with biochar as partial cement replacement.

What is the net impact on carbon sequestration due to biochar replacing 2-4% of cement (by weight)? Kua and Wong [2012] found that a medium-sized industrial building in Singapore can contain about 6,168 tonnes of concrete, of which 16% can be attributed to cement. Replacing only 2% of this quantity of cement requires about 19.7 tonnes of biochar. Assuming a conversion efficiency (from biomass to biochar) of 30%, a total of 65.67 tonnes of feedstock is required to produce this amount of biochar. According to estimation by Roberts et al. (2009), this will result in a life cycle abatement of about 57.13 tonnes of CO<sub>2</sub> per building (of comparable size).

#### 4 SUMMARY

This study explored the possibility of partially replacing cement with biochar particle which is a greener alternative. It can be concluded from this study that biochar can replace 2-4% of cement (by weight) while improving the compressive strength of mortar. The selection of replacement percentage is important because while lower replacement may not significantly produce the micro-filler effect, higher replacement percentage have been found to affect strength and permeability of mortar. Introduction of biochar resulted in higher impermeability compared to control mix. From sorptivity test, it may be concluded that 2-4% replacement by biochar resulted in similar permeability as can be achieved by pozzolanic substitute for cement.

Further research may be conducted to improve the bonding of biochar particles with mortar paste and their uniform dispersion in mortar mix. The morphology and particle size of biochar particles would be important factors that can be further explored and optimized to improve the strength and permeability of mortar mix with biochar as a partial cement substitute.

#### 5 ACKNOWLEDGEMENT

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