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Biochar-mortar composite: Manufacturing, evaluation of physical properties and economic viability

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HIGHLIGHTS

- Mechanical and permeability properties of developed cement-biochar composite is studied.
- 1–2 wt% addition of biochar is optimal to improve compressive strength of cement mortar.
- Flexural strength and drying shrinkage are not affected due to addition of biochar.
- Water tightness of biochar-mortar composite is improved compared to control mix.

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ABSTRACT

Singapore generates about half a million ton of wood waste annually, which constitutes a major fraction of disposed waste. Pyrolysis of wood waste to produce biochar, that can be used as additive in cement mortar, is a viable alternative to increase recycling rate of woody residues. This article explores influence of biochar, prepared from mixed wood saw dust, on strength, elastic modulus, drying shrinkage and permeability of cement mortar. Biochar prepared by pyrolysis at 300 °C (BC 300) and 500 °C (BC 500) was added to mortar at 1–8% by weight of cement. Results show that addition of 1–2 wt% BC 300 and BC 500 improve early age (7-day) compressive strength of mortar, which is related to high water retention of 7.50 g/g and 8.78 g/g by dry BC 300 and BC500 respectively. However, addition of biochar did not significantly influence flexural strength, drying shrinkage and modulus of elasticity. Mortar with 1% addition of BC 300 and BC 500 showed up to 58% and 66% reduction in water absorption and depth of water penetration compared to control. Based on the experimental findings, it is concluded that 1–2 wt% addition of biochar may be recommended to improve strength and reduce permeability of cement mortar. This study suggests that biochar from wood waste has the potential to be deployed as carbon sequestering admixture to improve performance of cementitous mortar.

1. Introduction

Worldwide, construction industries are one of the major contributor to CO_2 emission because of the energy intensive processes involved in production of cement and concrete. According to an estimate, one tonne of CO_2 is releases to the atmosphere with production of one tonne of cement, which contributes to approximately 7% of global anthropogenic greenhouse gas emission [1]. This is likely to become a more serious concern in the future with the rising demand for materials. One of the means to reduce the net emission associated with cement based materials is by sequestration of stable carbon in the material itself without affecting the performance of the host matrix [2,3]. Performance of cement composites is determined by its strength and permeability properties. However, due to porous nature and micro-cracks cement composites allows access to foreign fluids and contaminants into the structure that results in degradation and deterioration during service stage. Therefore, a material that sequester carbon and improve performance of cement composite can be a potential solution to ensure reduction of associated emission and better serviceability of civil infrastructures.

This study explores inert carbonaceous particles, produced from woody biomass (mixed wood saw dust) as carbon sequestering additive in cement mortar. Few studies in the past have proposed carbon sequestration through carbonation of concrete [3–5]. However, this method is only limited to concrete without reinforcement because of risk of corrosion. Moreover, it is effective only in

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case of thin shell porous precast components for reasonable penetration of carbon dioxide throughout the component [6]. Using carbonaceous particles from woody biomass, also called biochar, to sequester carbon can have more widescale application compared to carbonation curing because of high stability and inert nature of the particles. Depending on the type of feedstock and preparation conditions used, biochar has the potential of reducing net greenhouse gas (GHG) emissions by about 870 kg CO_2 equivalent (CO_2-e) per tonne dry feedstock, of which 62–66% are realized from carbon capture and storage by the biomass feedstock of the biochar [7]. Nevertheless, it will increase the recycling rate of wood wastes, which are currently used as compost, fuel for cogeneration plants or incinerated for disposal in landfills. However, incineration and use of wood as fuel may be detrimental because the particulate matters in saw dust and wood chips are easily airborne that causes respiratory problem [8]. Therefore, conversion of saw dust into stable char in absence of oxygen, and its application as construction material would reduce landfilling and add value to the waste generated from wood processing industries.

2. State of the art review on use of biochar in cement composites

There has been a growing interest on use of carbonized microparticles in cementitous composites [2,9–11]. Gupta and Kua [2] discussed the key factors including preparation condition, physical and chemical properties of biochar that makes it suitable as carbon sequestering additive in cement mortar. Gupta et al. [9] reported improvement in physical properties of fiber reinforced cement mortar when polypropylene fibers (PP) are coated with biochar micro-particles. It was attributed to improved bonding between PP fiber and cement matrix due to densification by biochar micro-particles. Ahmad et al. [10] prepared carbonized particles from bamboo by pyrolysis, which was then added at 0.05–0.20 wt% of cement in cement paste. The results suggest that 0.08 wt% addition of carbonized bamboo particles resulted in increase of strength and toughness by 66% and 103% respectively compared to reference. Increase in toughness was attributed to crack deflection mechanism imparted by biochar micro-particles in cement paste. Restuccia and Ferro [12,13] also reported increase in modulus of rupture and fracture energy by about 30% and 60% respectively by addition of 0.8–1 wt% biochar, derived from hazelnut shell. Cement paste with biochar absorbs more energy before failure due to deviation of crack trajectories by biochar particles, resulting in more ductile failure compared to plain cement paste. Ahmad et al. [14] reported similar findings- addition of carbonized particles from coconut shell modified crack growth and mechanism, ductility and toughness of cement composites. Choi et al. [15] explored use of biochar as partial cement replacement by 5–20 wt% in mortar. 5 wt% replacement of cement by biochar resulted in slight increase in compressive strength without any substantial effect on flow rate. However, higher replacement rate results in very stiff mix due to high water retention capacity of char particles. The study reported that water retentive feature of biochar contributes to internal curing during hardening of mortar. Akhtar and Sarmah [11] studied strength and water absorption of concrete with biochar, derived from poultry litter, rice husk and paper mill sludge, added at 0.1% replacement of total cement volume. The authors found that addition of poultry litter and rice husk significantly improved flexural strength (by up to 20%) compared to control. Rice husk and paper mill sludge biochar also improved split-tensile and early age (7-day strength) compressive strength of concrete, although water absorption was similar to that of control.

The experimental findings show that carbonized char particles from biomass have the potential to improve mechanical properties of cementitous composites. The focus of this study is to explore the effect of biochar produced by pyrolysis of mixed wood saw dust at different pyrolysis temperature on physical properties of cement mortar. Influence of biochar addition on mechanical properties, permeability and drying shrinkage were explored in this study.

3. Materials and methods

3.1. Cement and sand used

Ordinary Portland cement 52.5 N Type 1 conforming to ASTM C150 [16] was used. The physical properties and chemical composition of the cement is presented in Table 1. Locally available river sand was used in the preparation of mortar. Fineness modulus and specific gravity of the sand are 2.54 and 2.65 respectively. Maximum size of sand used is 4 mm, and the gradation conforms to ASTM C33 [17]. Polycarboxylate based superplasticizer, conforming to ASTM C494 [18] was used to achieve sufficient workability during mixing.

3.2. Production and properties of biochar

3.2.1. Production of biochar

Biochar was produced from locally collected mixed wood saw dust, which is a by-product in the wood milling and furniture factories. It was ensured that the saw dust is completely dried before subjecting it to pyrolysis. Pyrolysis of saw dust was carried out at two different temperature: 300 °C and 500 °C, by heating in a muffle furnace from room temperature (30 °C). The furnace is equipped with a small vent to allow escape of organic vapors produced during pyrolysis. This arrangement prevents the vapors and volatile compounds from being deposited on the surface of produced biochar. The heating rate was maintained at 10 °C/min until the pyrolysis temperature was reached and then the temperature was maintained for 60 min. Once the pyrolysis was complete, the produced char was allowed to cool down and then stored in an airtight container. The yield of biochar at 300 °C and 500 °C are about 40% and 25% respectively.

Before mixing into mortar, the biochar was manually grinded down to finer particle size. The particle size distribution (PSD) of biochar produced at 300 °C (BC300) and 500 °C (BC500) respectively after grinding was determined by polarized intensity differential scattering (PIDS) using laser diffraction particle size analyzer (Fig. 1). PSD of cement used in this study was also determined using the same method, shown in Fig. 1. The elemental composition of the produced chars determined by energy dispersive X-ray spectroscopy (EDX) is presented in Table 2.

It can be observed from particle size distribution (PSD) that 40% and 37% of carbonized char particles are finer than 10 μm. D_{50} for

Table 1
Properties and chemical composition of cement used in the study.

Properties	Ordinary Portland cement used
Physical properties	
Density(kg/m^3)	3180
Blaine fineness (m^2/kg)	385
Mean particle size (μm)	13.50
Loss in ignition (%)	0.90
Chemical composition (%)	
MgO	1.8
CaO	63.5
SO_3	2.1
Al_2O_3	5.4
SiO_2	20.8
Na_2O	0.59
Chloride	0.005