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Morphological characterization of biomass-derived biochar as cementitious material and its Partial Cement Replacement for Carbon footprint Reduction: A Review

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ABSTRACT

This article focusses on the morphological characterizations (surface area and pore diameter) of biomass derived biochar for its suitability as an internal curing agent in influencing strength and durabilityof the concrete mixture, sustainable cementitious material, agro-wastes disposal and reduction in carbon footprints, particularly in the construction industry. Surface morphology properties of the biochar are remarkably influenced by the pyrolysis process conditions (temperature and use of additive) and different types of feedstock. The fibrous structure of biochar with increased surface area and pore diameter favour higher water holding and retention capacity, causing self-curing action in the concrete composites.Based on the studies, it is inferred that the biochar would be the future potential cementitious material in the construction industry to solve many problems related to self-curing activity, high performance concrete, environment and waste management.

Key words : *Morphology of biochar, Concrete, Agricultural residues, Pyrolysis, Carbon footprint, Waste management*

Introduction

Morphological characterization of a material relates to its shape and structure for suitability of various practical applications and to explore more possible uses in the specific segments of the society. The study of surface morphology of biochar is crucial in order to enhance its applications not only as a soil conditioner but also in other areas such as in construction industry for partial replacement of cement, waste water treatment and carbon sequestration. Biochar is a fine-grained carbon rich porous product obtained from the thermo-chemical conversion of biomass at low temperatures (350-450 ^{0}C) in the absence of air through the process, called pyrolysis (Khalid *et al.*, 2018). Recently, biochar has been explored as a potential building material for the partial replacement (small fractions from 1-5 %) of cement leading to the effective disposal of waste biomass and significant reduction in the emission of CO during the production of cement which involves mining of raw materials, their processing and transportation (Akinyemi and Adesina, 2020). The number of materials such as fly ash, silica fume, ground granulated blast furnace slag, pumice powder have successfully been proved to be the partial replacement of cement in the recent past. However, the limited availability of those non-renewable resources to fulfil the growing demands of cement in the increasing civil infrastructure worldwide has diverted the attention of researchers to explore a sustainable supplementary cementitious material in the cement industry in order to reduce the use of cement and lower the carbon footprint particularly in the civil construction sector which is the third largest source of anthropogenic carbon dioxide emissions in the globe after oxidation of fossil fuels and deforestation as well as other land-use changes (Andrew, 2018). Biochar has been recognized as such an appropriate material for its suitability in cementitious composites (Mrad and Chehab, 2019). As a supplementary cementitious material, the pore diameter and surface area of the biochar need to be investigated for its suitability in concrete and mortar composites The surface morphology of biochar produced from the pyrolysis of biomass depends on the type of feedstock and the operating conditions of the pyrolytic process (Jing *et al.,* 2016). Due to the presence of inert and stable carbon, biochar also adds to reducing carbon footprint both in the agriculture and construction sector. This paper therefore focusses on the studies undertaken by the researchers on the morphological characterization of biochar for its use as a supplementary cementitious material to influence the strength and durability of the concrete/mortar and ultimately leading to reduction in the use of cement for favouring carbon sequestration and environmental sustainability.

Morphological characterization of biochar

Biochar consists of interconnected fibers, forming a microporous cellular structure that can absorb and sustain a substantial amount of water to be used for internal curing in concrete composites. Internal curing relates to the activity of supplying water to the hydrating portland cement paste from the onset of mixing to increase the degree of hydration when needed. This is achieved by introducing a well-dispersed water saturated biochar, acting as water-filled reservoir in portland cement concrete mix. The escape of volatiles and organic matters from the feedstock during biomass pyrolysis induces pores of different sizes and ranges in the biochar and gives it a honeycomb-like porous structure, making it suitable to act similar to the lightweight aggregates, usually used in the concrete mix. The morphology of biochar with respect to its pore diameter and surface area has therefore been studied by the various researchers for suitability in concrete composites and is summarized in the Table 1.

From the above review of literatures, it is revealed that the pore diameter and surface area of the biochar produced through the pyrolysis process depend on the operating temperatures. More the rise in temperature more is the increase in the surface morphology of the biochar. However, the rise of temperature is limited to achieve the better yield and quality of the biochar. The higher surface area increases the water holding and retention capacity. The larger pores also tend to have higher water retention and serve as connectors to other micro pores. The 'reservoir effect' of water inside the biochar pores may even have important implication onmitigating shrinkage cracks in concrete mix that usually occur due to limitedexternal curing and high rate of desiccation under actual site conditions. Biochar, as a novel supplementary cementitious material, favour the enhanced durability due to its dense microstructure,which contributes to longer service life and reducedmaintenance of concrete structures, compared to those with normal cement-based composites.

Use of biochar as cement replacement in concrete

Sustainable development in the construction industries is currently a global concern as they are at present striving to face the challenges of the issues of high pollutants emission, material cost and availability as well as energy consumption in the production of cement. Use of materials, produced from the local wastes, to partially replacecement may be a cost-effective and sustainable strategy to achieve high performance concrete mixes. One such material is the biochar derived from the pyrolysis of abundantly available agricultural residues in the agrarian based society. Biocharhas therefore gained considerable academic and commercialinterest as a supplementary and carbon sequestering admixture for cement based materials. The potential uses of biochar for cement replacement in concrete composites have therefore been studied by the various researchers and is summarized in the Table 2.

From the above review of literatures, it is revealed that the high porosity of biochar qualifies it to be considered as an internal curing agent in cementitious materials resulting into the increase of strength, improvement in durability and reduction in the permeability and autogenous shrinkage in concrete composites.

Use of biochar as a supplementary cementitious material to reduce carbon footprints

Cement is a key component in the construction sector and its production constitutes a significant amount of CO_2 emission to the atmosphere. The cement industry is currently faced with multiple challenges such as depleting fossil fuel reserves, scarcity of raw materials, growing demand for construction

Table 1. Surface morphology of biochar from the pyrolysis of agricultural residues

Biochar from agro-residues	Pyrolysis process conditions	Surface morphology of biochar	Reference
Corn stover	(i) Microwave power (W)=500(ii) (ii) Microwave power (W)=700 (iii) Microwave power (W)=900	(i) BET Surface area (m^2/g) = 37.25 and pore dia (nm) = 0.91 (ii) BET Surface area (m^2/g) = 50.71 and pore dia (nm) = 2.18 (iii) BET Surface area (m^2/g) = 55.80 and pore dia (nm) = 2.24	Fodah AEM, 2021.
Willow chips	Temperature = 170 ^{0}C. Microwave pyrolysis (MWP)	Char yield: 27.3 wt%; Gas yield: 30.5 wt%; Liquid yield: 42.2 wt%; BET surface area = 3.87 m^2/g,	Masek *et al.*, 2013
Switch grass (SG)	Temperature = 400 ^{0}C (MWP)	Biochar BETsurface area 76.3 m^2/g.	Mohamed *et al.*, 2016
Wheat straw	T = 400- 600^{0}C (MWP)	Char yield: 40-50 wt%; specific surface area of char increased from 0.89 m^2/g (400 ^{0}C) to 9.81 m^2/g (600 ^{0}C)	Zhao *et al.*, 2012
Cauliflower waste	Pyrolysis in muffle furnace, Temp. 300-600 ^{0}C, in absence of air	BET surface area (m^2/g)	Pradhan *et al.*, 2020
	Temp. 300 ^{0}C	1.6	
	Temp. 400 ^{0}C	1.8	
	Temp. 500 ^{0}C	3.7	
	Temp. 600 ^{0}C	7.9	
Banana peels	Pyrolysis in muffle furnace, Temp. 300-600 ^{0}C, in absence of air	BET surface area (m^2/g)	Pradhan *et al.*, 2020
	Temp. 300 ^{0}C	1.4	
	Temp. 400 ^{0}C	1.6	
	Temp. 500 ^{0}C	5.8	
	Temp. 600 ^{0}C	6.4	
Cabbage wastes	Pyrolysis in muffle furnace, Temp. 300-600 ^{0}C, in absence of air	BET surface area (m^2/g)	Pradhan *et al.*, 2020
	Temp. 300 ^{0}C	1.7	
	Temp. 400 ^{0}C	1.9	
	Temp. 500 ^{0}C	4.1	
	Temp. 600 ^{0}C	6.1	
Acacia magnium	Downdraft gasification at 700 °C	BET Surface area (m^2/g) = 50.0 and pore dia (nm) = 4.25	Azargohar *et al.*, 2014
Rubber wood saw dust	Pyrolysis (450-850 ^{0}C)	BET Surface area (m^2/g) = 10-200.	Ghani et al 2013

materials, as well as rising environmental concerns such as air pollution and climate change. It has been estimated that cement industry contributes around 8 % to the worldwide CO_2 emission (Akinyemi and Adesina, 2020). The major part contributing towards the CO_2 emission is the heating of limestone during calcination process. The contribution of cement in the concrete is merely 20% of total volume but it is responsible for approximately 90% of the total emission of CO_2. It has been reported that there is the release of about 0.95 tonne of CO_2 in the production of one tonne of cement (Riera *et al.,* 2020). This makes cement the most studied material to understand its properties and possibly replacing it with other suitable materials as supplementary cementitious ones. For this reason, there is the growing interest in finding sustainable solutions to reduce its carbon footprint by exploring suitable substitutes, may be of smaller replacement in the concrete mix. Biochar is, proved to be the such material as a potential candidate for partial replacement of cement in the concrete composites. The utilization of biochar from the agricultural wastes does not contribute negative impact on the environment, creates opportunity for their effective and safe disposal and would reduce loads in the production of cement.

The current production of cement in the globe during 2020 is about 4.1 billion tonnes. With the replacement of 1 % biochar for cement in the concrete mix, there would be reduction in the production of 41 million tons of cement per year in the world. Considering carbon content in biochar to range from 80-95 % depending on the conditions of the pyrolysis followed, the amount carbon sequestration would range from 33 Mt-39 Mt, which is equivalent to 120 – 140 Mt $CO_{2(equivalent)}$ (3.66 times, the ratio of atomic weight of CO_2 to C).

Table 2. Use of agricultural residues based biochar as cementitious materials

Biochar from agro-residues	Biochar percentage replacement with respect to weight of cement	Effects on concrete/ mortar mix	Reference
Rice husk	20 % rice husk ash.	10-15% higher compressive strength at 28-day age compared to normal/ control concrete, due to pozzolanic effect and reduction of local water-cement ratio owing to water retention in porous rice husk ash particles	Dixit *et al.,* (2019)
Hard wood	5 %	10-12% higher compressive strength at 28-day age compared to normal/ control mortar.	Choi *et al.* (2012)
Rice straw	5 %	7 % reduction in fresh density of mortar due to lower specific gravity of biochar	Gupta *et al.* (2018)
Wood and food waste biochar	3 %	13 % and 10 % reduction in the flow (workability) of mortar mix for wood and food waste biochar respectively due to higher water absorption of biochar.	Gupta *et al.* (2018)
Wheat straw	0.5-1.5 %	4.1 to 17.3 % higher compressive strength compared to normal concrete	Ahmad *et al.* 2020.
Woody biomass	0.5-2.0 %	Improved compressive strength by 16 % and 9% compared to control concrete mix. Inclusion of 2% biochar reduced permeability by 40 %.	Gupta *et al.* (2020)
Bagasse and rice husk	5 %	23 % and 78 % increase in compressive and tensile strength respectively compared to control concrete mix.	Zeidabadi *et al.* 2018

Conclusion

Based on the findings of the literatures reviewed on the morphological characterization of biomass-derived biochar for its suitability as a building material and contributing to the partial replacement of cement in reducing carbon footprints for the cement industry, the following conclusions are drawn.

(i) Increased surface area and pore diameter of biochar derived from the pyrolysis process favour internal curing in concrete composites, thus increasing strength, improving durability and reducing permeability to become a promising candidate for high performance concrete

(ii) Rise in the process temperatures and addition of catalytic materials up to the conditions favourable for the higher yield and quality of biochar during the pyrolysis process, increases its surface area and pore diameter resulting into higher water holding and retention capacity for self-curing action in concrete mix.

(iii) The partial replacement of biochar for cement, even in a small percentage (1-5 %) would not only reduce the emission of CO_2 in the cement production industry but also promotes the safe disposal and effective utilization of agro-residues, waste recycling and environment sustainability

(iv) It has been estimated that even 1 % replacement of biochar for cement in the concrete mix, would reduce the production of about 41 million tons of cement per year in the world and mitigate the emission of around 120–140 Mt $CO_{2(equivalent)}$ to the environment.

(v) Biochar has the potential to be successfully deployed as carbon sequestering admixture in concrete technology and also improving strength and durability of concrete composites.

Hence, morphological studies of the biomass derived biochar needs to be investigated thoroughly for its suitability as internal curing agent in the concrete mix andthus a potential candidate of cementitious material to reduce carbon footprints, to improve strength and durability of concrete and ultimately favouring the effective disposal of biomass wastes as well as environmental sustainability.

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