Construction and Building Materials 181 (2018) 301–308

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Synthesis, characterization and evaluation of biochar from agricultural waste biomass for use in building materials

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HIGHLIGHTS

- Recycling is one of the most important waste management strategy.
- Rice husk and bagasse biomass present as frequent agricultural wastes in different regions.
- Biochar of siliceous agricultural waste could improve engineering properties of concrete.

ARTICLE INFO

Article history:
Received 4 November 2017
Received in revised form 7 May 2018
Accepted 30 May 2018

Keywords:
Green concrete
Biochar
Rice husk
Bagasse

ABSTRACT

Cement is a critical material for urbanization and its production is responsible for most of the CO_2 emissions in the world. The use of substances capable of substituting the material responsible for greenhouse gases can reduce global warming, which is caused by the emission of greenhouse gases into the atmosphere, especially CO_2. Among such materials is agricultural waste ash which has been found suitable to partially replace Portland cement in concrete production and can contribute to a decline of the environmental impact of cement production. The objectives of this study were to evaluate the effect of two agricultural wastes namely: rice husk and bagasse which were burnt in the absence of oxygen at 700 °C, in order to produce biochar, on the mechanical properties of concrete samples containing variable amounts of these substitutes. X-ray diffraction, BET and Scanning Electron Microscopy were applied for biochar characterization and investigation of its feasibility in concrete. A total of 0, 5 and 10% of the cement (by mass) was replaced by the agricultural waste biochar. For these mixtures, mechanical tests were conducted. The results were compared with those of concrete without biochar (control concrete), with compressive strength and splitting tensile strength. The results showed that the synthesized materials can be used as pozzolanic materials based on the XRD, SEM and BET methods. Concrete samples containing pretreated rice husk biochar (5%), unpretreated rice husk biochar (5%), pretreated bagasse biochar (5%), unpretreated bagasse biochar (5%), pretreated bagasse biochar (10%), and unpretreated bagasse biochar (10%) had a compressive strength of 36, 20.4, 54.8, 24.4, 21.1 and 23% higher than the control concrete, respectively. There was a 78% increase in tensile strength for concrete sample with 5% treated bagasse biochar compared to the concrete without any biochar. Overall, it has been concluded that rice husk and bagasse biochars are favorable substitutes and can be used in concrete without any adverse effect on the environment.

1. Introduction

The cement industry is currently faced with multiple challenges such as: depleting fossil fuel reserves, scarcity of raw materials, growing demand for construction materials, as well as growing environmental concerns such as air pollution and climate change [17]. It has been estimated that the cement industry is responsible for about 1.8 Gt of the world's total CO_2 emissions and approximately 5–7% of all anthropogenic CO_2 generated [10]. Clinker is a component of cement and is involved in the conversion of limestone ($CaCO_3$) to lime (CaO). During the production of clinker, CO_2 is produced as a byproduct [14]. When limestone and clays are crushed and heated to high temperatures, CO_2 is released [25].

Green concrete is defined as a concrete which uses waste materials such as industrial by-products including bottom ash [23], slag [6,13] and fly ash [29,30]. Agricultural wastes such as waste oil palm shell [18], palm oil fuel ash [4,27], waste coconut shell [20],

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https://doi.org/10.1016/j.conbuildmat.2018.05.271
0950-0618/

Table 1
XRF analysis of rice husk and bagasse biochar.

Sample	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	CaO %	Na_2O %	MgO %	K_2O %	MnO %	P_2O_5 %	LOI
TRHB	12.58	N	0.709	0.179	0.112	N	0.056	0.02	0.229	81.56
RHB	8.54	0.356	1.209	1.583	0.681	0.206	0.381	0.022	0.145	86.76
BB	7.841	0.428	1.191	5.998	0.495	0.74	2.239	0.03	0.435	78.97
TBB	13.123	N	0.762	1.716	0.233	0.419	2.704	0.064	0.689	80
TRHA	58.005	0.183	1.087	0.196	0.204	0.019	0.144	0.024	0.343	39.5

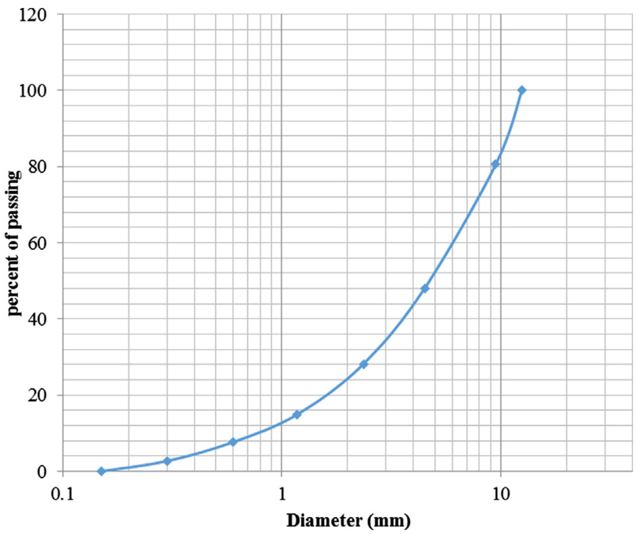

Fig. 1. Particle size curve of aggregates.

coconut fibers [16] and waste rice husk [5,21] are also used in green concrete. Numerous studies have emphasized the possibility of using agricultural waste materials such as rice husk ash in concrete as partial cement and aggregate replacement [24]. Several studies have reported the optimum percentage of RHA as 10% at the water to binder: 0.42 [5]; at the water to binder: 0.3, 0.35, 0.4 [26], 15% at the water to binder: 0.35 [9] and 20% at the water to binder: 0.32 [22]. The percentage difference is probably due to the water to binder ratios, cement amounts, conditions under which rice husk ash was produced, as well as the amount of silica in rice husk ash and its type (crystalline or amorphous).

Agricultural wastes are usually burnt outdoor and under uncontrolled conditions. This results to environmental problems such as soil, water and air pollution [11]. Despite the fact that these materials have a positive effect on compressive strength, their environmental impacts have been ignored. Therefore, it is necessary to overcome this problem and prevent air pollution from waste burning. Agricultural waste biochar can be used as a cementitious material without any damaging effect on the environment instead of agricultural waste ash. It can be estimated that from 1.0 ton of dead wood matter, approximately 0.3 ton of biochar can be produced [28]. The use of biochar in concrete allows agriculture and forestry wastes to sequester carbon instead of releasing the CO_2 and methane associated with its disposal. In this way, it prevents the climate change effects of concrete production, since it mitigates the effects of agricultural byproducts. According to Tommaso and Bordonzotti [28], it is estimated that if only 1% of bio-char (by mass of concrete) is incorporated in concrete, it can be calculated that roughly 0.5 Gt of CO_2 would be sequestered yearly by the concrete sink corresponding to about 20% of the total yearly emissions of CO_2 generated by the cement industry [28]. The use of such materials instead of cement is necessary because of the critical level of CO_2 in the atmosphere. Thus, the objectives of this research are: 1) to test if biochar can be used as a pozzolan, 2) to investigate the feasibility of biochar in concrete without diminishing the concrete strength, 3) to determine the appropriate percent of replacement cement with different agricultural waste biochars, 4) to compare the concrete strength between concrete mixes while substituting cement with bagasse and rice husk biochar by different ratios and control concrete.

Table 2
K, Ca and Mg concentrations in leachate from different matters of pretreatment.

Sample	Potassium solution (mg/L)	Calcium solution (mg/L)	Magnesium solution (mg/L)
RHA23	270	80	68.04
RHW23	214	8	38.9
RHA80	259	48	106.9
RHW80	199	8	48.6
BA23	118	384	179.8
BW23	84	192	72.9
BA80	96	336	427.7
BW80	97	128	150.7

2. Materials and methods

2.1. Raw materials

2.1.1. Agricultural wastes

This study utilized two agricultural wastes (rice husk and sugarcane bagasse). Rice husks and sugarcane bagasse, constitute one of the two highest-volume agricultural process residues. The hard protective coverings of rice are called husks. Despite its biological role of protection, rice husks can be used as building material, fertilizer, insulation material, or fuel. Rice husk ash, a product of the burning of rice hulls, could be used to make amorphous reactive silica which is variously applied in materials science. After juice extraction from the crushed stalks of sorghum or sugarcane, the fibrous remnant material is known as bagasse. It serves as biofuel and is used to produce pulp and building materials. Table 1 presents the chemical compositions of rice husk and bagasse biochars.

2.1.2. Portland cement and aggregates

The Portland cement used was the ASTM C150, Type II. Alluvial materials with good roundness, consisting of sand (0.15 mm < D < 4.5 mm) and gravel (4.5 mm < D < 12.5 mm), were used as aggregate. Fig. 1 shows the particle size curve of aggregates.

2.2. Pretreatment

Various factors affect the utilization of agricultural wastes as a pozzolanic material. The content of amorphous silica in agricultural residue ash, is vital to the reactivity of these wastes in concrete materials. If the amorphous silica content of agricultural residue ash is reduced, it will result in a decrease of its reactivity in cementitious systems [1]. Several studies showed that pretreatment can increase the amorphous silica content, as a result of the removal of metal impurities from the biomass [1,8,12].

The efficiency of removing cations such as K^+, Ca^{2+}, and Mg^{2+}, as well as altering the chemical and physical structure of agricultural wastes, can be greatly improved by pretreatment with dilute acid or water.

The effect of pretreatment, on the pozzolan reactivity of the synthesized biochar, was evaluated by separately immersing 20 g of each biomass in 400 mL of the solutions (0.1 N HCl or distilled water) in a 500 mL glass flask. At a constant temperature, the samples were stored separately, undisturbed for a 24-h immersion period in each solution. Samples which were prepared at temperatures of 23 and 80 °C with distilled water were named as W23 and W80, pretreatment at 23 and 80 °C with 0.1 N HCl was related to A23 and A80, respectively. The