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Novel biochar-concrete composites: Manufacturing, characterization and evaluation of the mechanical properties

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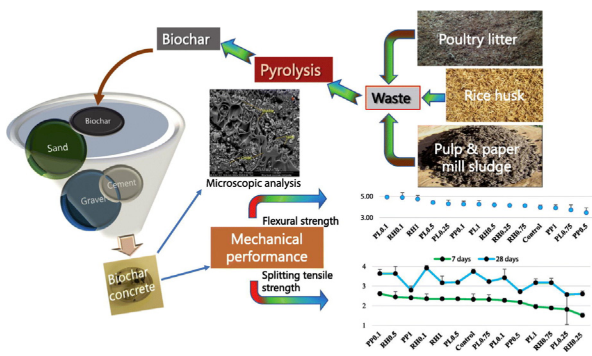
HIGHLIGHTS

- Waste derived biochar has potential to be used as cement replacement.
- Flexural strength improved approximately 20% with the addition of biochar.
- Water absorption of biochar concrete is comparable to the control at 0.1% of total volume.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, biochar, a carbonaceous solid material produced from three different waste sources (poultry litter, rice husk and pulp and paper mill sludge) was utilized to replace cement content up to 1% of total volume and the effect of individual biochar mixed with cement on the mechanical properties of concrete was investigated through different characterization techniques. A total of 168 samples were prepared for mechanical testing of biochar added concrete composites. The results showed that pulp and paper mill sludge biochar at 0.1% replacement of total volume resulted in compressive strength close to the control specimen than the rest of the biochar added composites. However, rice husk biochar at 0.1% slightly improved the splitting tensile strength with pulp and papermill sludge biochar produced comparable values. Biochar significantly improved the flexural strength of concrete in which poultry litter and rice husk biochar at 0.1% produced optimum results with 20% increment than control specimens. Based on the findings, we conclude that biochar has the potential to improve the concrete properties while replacing the cement in minor fractions in conventional concrete applications.

1. Introduction

Concrete is an essential part of any construction project, be it a multi-storey commercial building or bridges to connect people of two sides and thus it is being produced in huge amounts. According to Klee (2009), annual concrete production has crossed over 25 billion tonnes which is >3.5 t for every person in the world. Even though concrete usually has different compositions according to its required use, cement in concrete is an essential component along with sand, water and gravels (Stolaroff et al., 2005). The main components of cement are tricalcium silicate (C_3S) (50–70%), dicalcium silicate (C_2S) (15–30%), tricalcium aluminate (5–10%) and tetracalcium aluminoferrite (5–15%). Other minor components include sodium oxide, potassium

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oxide and gypsum which are <5% (Mindess and Young, 1981). It can be observed that tricalcium and dicalcium silicates are the major components of cement which are also responsible for so called hydration products, calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (C—S—H) gel (Barron, 2010).

$$2(CaO)_3(SiO_2) + 7H_2O \rightarrow (CaO)_3(SiO_2)_2 4(H_2O) + 3\ Ca(OH)_2 \quad (1)$$

Carbon dioxide (CO_2) production has been a great debate in the current scenario where it is contributing as a greenhouse gas and causing a major threat to the environment. One of many man-made sources of CO_2 production; cement industry has a significant role in producing CO_2 through production, processing and preparation phase adding approximately 7% of total world's production of CO_2 (Oh et al., 2014). The major part contributing towards the CO_2 emission is the heating of limestone during calcination process. Cement contribution in concrete is merely 20% of total volume but it is responsible for approximately 90% of the total emission of CO_2 (Yang et al., 2015) with one tonne of cement production causing0.95 t of CO_2 (Ludwig and Zhang, 2015). This makes cement the most studied material to understand the properties and possibly replacing it with other materials called as supplementary cementitious materials. The number of materials introduced successfully in concrete to partially replace the cement in recent years include fly ash and pumice powder (Kabay et al., 2015), silica fume (Zhang et al., 2016), ground granulated blast furnace slag (Divsholi et al., 2014), waste glass (Aliabdo et al., 2016). For example, Aliabdo et al. (2016) found that glass powder exhibited pozzolanic properties and 15% replacement of cement with glass powder enhanced the compressive strength and 10% showed optimum replacement for splitting tensile strength for targeted 33 MPa concrete. Babu and Neeraja (2017) studied the effects of hen eggs shell inclusion in concrete and mortar with fly ash as partial replacement of cement and recommended that the dosage of hen shell at 0.25% and fly ash at 55% not only improved strength performance but was also found to be cost effective. Elsewhere, Vegas et al. (2006) reported that paper mill sludge after calcination at 700 °C for 2 h produced optimal pozzolanic properties. This calcined product showed slightly higher compressive strength at the age of 28 days with 10% replacement of cement content in cement paste showing the potential to utilize the waste sludge in partial cement replacement.

Different waste materials are being added to concrete to improve its properties and also to reduce the impact of greenhouse gases. Spiesz et al. (2016) suggested the use of waste glass with fly ash and ground granulated blast furnace slag to reduce the effect of Alkali-silica reaction (ASR) and also recommended the use of washed glass to remove other impurities associated with glass for better strength and durability properties. Torres et al. (2017) incorporated fine and coarse foundry waste in concrete and found that fine foundry waste at 30% replacement produced optimum strength (compressive, splitting tensile and flexural) properties rather than a mixture of coarse and fine foundry waste. Ling and Nor (2006) have reported the use of waste tyres in concrete paving blocks and found that paving blocks containing rubber found to improve the skid resistance, however, reducing the compressive strength. Similarly, Modarres et al. (2016) used the coal waste ash and coal waste powder in concrete pavements at different percentages of cement replacements from 5 to 20% and 5% of replacement of coal waste powder and ash improved the compressive strength and toughness of pavements.

There has been a growing trend in the utilization of agricultural waste in concrete as well for several reasons. Primarily, one of which is to minimize the burning of waste on fields to eradicate the handling costs. Secondary reason explains the importance in strength improvement where many waste sources like bamboo can produce overall good properties with the sustainable availability of the material (van der Lugt et al., 2006). Agarwal et al. (2014) reported that bamboo has the potential to produce the concrete of adjacent strength to steel reinforced concrete after proper processing of the bamboo. However, the raw inclusion of biomass leads to challenges significantly affecting the durability properties (Kriker et al., 2008). Date palm fiber was found to be effective for thermal insulation but reduced the compressive strength and increased the water absorption as the content increases (Benmansour et al., 2014).

Organic waste is being produced in vast quantity throughout the world in the form of municipal waste, industry waste, and agricultural waste etc. This type of wastes cannot be recycled like its counterpart glass and plastic. That is why a number of alternatives have been developed besides landfilling to decompose this type of waste to reduce the size efficiently and produce useful by products which can be utilized for different purposes. One of the recently recognized techniques is pyrolysis to convert organic waste into biochar. Biochar is a porous carbonaceous solid material produced through thermochemical conversion of biomass in the absence of oxygen at a temperature ranging from 450 to 550 °C (Lehmann and Joseph, 2010; Shackley et al., 2011). Biochar has found its ways into various applications, though predominantly used for soil improvement in agricultural lands as soil amendment (Zhu et al., 2017). A number of studies have been conducted to include this by-product in other applications and researchers around the world have obtained positive results e.g., as a bio modifier in asphalt cement (Zhao et al., 2014), horticultural applications (Vaughn et al., 2017) and waste water treatment application (Lee et al., 2016). For instance, study by Zhao et al. (2014) showed that biochar can be an effective asphalt binder as compared to commercially available carbon binders containing high surface area. Biochar improved the rutting resistance under high surface temperature and showed no modification in fatigue cracking resistance of the asphalt, which however, decreased with the addition of commercially available active carbon.

To date, however, there has not been a single study conducted to investigate the biochar's use in concrete making and its potential for carbon storage. Therefore, the overarching aim of this work is to study the effect of three different types of biochar as an additive in concrete on its strength properties and determine the optimal usage in conventional concrete applications.

2. Materials and methods

Ordinary Portland cement (OPC) was obtained from Golden Bay Cement, Auckland; while washmix sand, gravels, tap water and three types of biochar: poultry litter (PL) biochar, rice husk (RH) biochar and pulp and paper mill sludge (PP) biochar were other materials that were employed in this study. Gravels were of standard 10 mm size selected to minimize the uncertainty in strength caused by size and shape of gravels. PL biochar was produced at 450 °C using slow pyrolysis (residence time of 20 min), while PP sludge biochar was produced at 500 °C using high temperature gasifier, while RH biochar was produced by Oliver Enterprises Philippines at 500 °C using a slow pyrolysis process (residence time of 20 min). Chemical composition of OPC and biochar was determined by X-ray fluorescence (XRF) spectrometry and inductively coupled plasma mass spectrometry (ICP-MS) analysis respectively. Other characterization techniques used for biochar is described below.

2.1. X-ray fluorescence (XRF) spectrometry

The chemical composition of cement and concrete samples is determined by X-ray Fluorescence (XRF) spectrometry. The manufacturer of Portland cement was Golden bay cement. PANalytical Axios 1kW X-Ray Fluorescence spectrometer was employed for this test. The equipment works on the principle of wavelength dispersive X-ray fluorescence spectrometry with high resolution. The chemical composition of cement is given in Table 1.