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Mechanical properties and microstructure of High-Performance Concrete with bamboo leaf ash as additive

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ABSTRACT

The demand for High-Performance Concrete (HPC) is on the increase for its good workability, high strength, and better durability. HPC are obtained by incorporating supplementary Cementitious Materials (SCM) into concrete to attain a long-term strength and durability performance. Though, several SCM have been investigated in HPC, the use of Bamboo Leave Ash (BLA) in HPC as an SCM has not been considered. Thus, this research investigated the use of BLA as SCM in HPC. The bamboo leaves were calcined in an electric furnace at a temperature of 700 °C. The ash was characterized using Energy Dispersive X-ray Fluorescence (EDXRF) and were found to possess pozzolanic properties with silica content above 70%. Cement was replaced by BLA at 5%, 10%, 15%, and 20% by weight of cement. Concrete made from these combinations were tested for compressive and splitting tensile strengths at 7, 28 and 56 days of curing. It was observed that optimum strength was attained at 5% replacement at 56 days of curing. The microstructures of the concrete revealed that at 5% incorporation of BLA in concrete, there was a better interlocking of concrete grain. It was concluded that cement can be replaced with 5% BLA in High Performance Concrete.

1. Introduction

Concrete, a major material in the construction industry, has cement as the binder for other ingredients (Ramonu et al., 2019). Production of cement not only involves high consumption of energy at elevated temperature (something in the range of 1500 °C), but also includes the emission of greenhouse gases into the atmosphere (Cobîrzan et al., 2015). Besides, concerted efforts are being made to ensure that the cost of manufacturing cement is reduced to improve profitability (Gana et al., 2020), ensure affordability (Olutoge and Oladunmoye, 2017), and make the product more accessible to users (Suhendro, 2014). Attempts have also been made to reduce the raw materials consumption, to ensure environmentally friendly operations and to improve the quality of cement. To achieve this, consideration is being given for partial replacement for cement using waste materials such as bamboo stem (Ikeagwuani et al., 2019), ground glasses and coal bottom ashes (Kasaniya et al., 2021), palm kernel shell ash (Odeyemi et al., 2019), and guinea corn husk ash (Odeyemi et al., 2020b) by researchers. These waste materials, which are either industrial or agricultural by-products, are environmentally friendly. When these low cost materials are added to Portland cement, the resulting mixture is either called "blended cements" (Asha et al., 2014) or composite cements" (Olutoge and Oladunmoye, 2017). The general behaviour of these materials is compatible to that of Portland cement since when in finely ground form in combination with water they react chemically with $Ca(OH)_2$ at room temperature to form hydrated phases possessing cementing properties. The

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commonest ingredients used to blend cements clinkers are latent hydraulic components such as blast furnace slag and pozzolanic materials which include pozzolana, rice husk ash, fly ash, burnt clay, condensed silica fume, limestone and other waste materials (Villar-Cociña et al., 2011). However, the availability of some of these natural pozzolans is fast declining (American Coal Ash Association, 2019) and reducing in quantity (British Petroleum UK, 2020). Thus, their availability for use in concrete may not be possible in the nearest future (Juenger et al., 2019). Therefore, it is expedient to find alternative pozzolans to meet the increasing demand for sustainable supplements for cement in concrete (McCarthy et al., 2017).

Agricultural wastes such as oyster shell (Prusty et al., 2016), coconut husk (Madurwar et al., 2013), bamboo leaf ash (Dhinakaran and Chandana, 2016), and sugarcane bagasse ash (Parande et al., 2011) are presently being considered as possible replacement for cement in concrete production (Liuzzi et al., 2017).

Utilization of BLA as a partial replacement for cement in concrete provides an effective way for bringing down the volume of environmental wastes, thus, saving energy and reducing the effect of greenhouse gas emission on the environment (Inim et al., 2018). It has been confirmed that BLA, which is obtained by the burning of dried bamboo leaves, has the potential of a pozzolan for use as cement replacement in concrete (Onikeku et al., 2019). Bamboo resources is the second largest in the universe (Sharma et al., 2015), being grown in over more than 10 million hectares of land (Atoyebi et al., 2018). Paper industries munch through an abundance of bamboo timber and a large volume of bamboo leaves remain as stray (Mohapatra et al., 2011). These are usually disposed of mainly by burning which results in the production of ash in landfills endangering the environment (Frías et al., 2012).

HPC are engineered concrete in which designed blending of properties and uniformity requirements can be achieved (Kadri et al., 2012), which is not possible using traditional raw materials and conventional mixing, placing, and curing methods (Manugunta et al., 2019). HPC provides better materials for special projects in Civil Engineering (Zhang et al., 2017). When compared with the regular concrete, HPC have better mechanical properties and durability, thus widening their demand for Civil Engineering projects (Etxeberria, 2020).

Many researches have been carried out on the use of SCM in concrete. For example, Dembovska et al. (2017) investigated the effect of pozzolanic additives on the strength development of HPC. The pozzolans used were Silica Fumes (SF) and Calcined Clay (CC). They recommended an optimum replacement of 20% of cement with Silica Fume in HPC. Ternary pozzolan systems, a combination of SF and CC, was not recommended for use in HPC.

Vitola et al. (2017) used coal combustion bottom ash (CCBA), commercial illite clay bricks (CB), barley ashes (BA), waste glass (WG), waste metakaolin (MK) and illite (IC) clay as supplements for cement in concrete. They recommended a replacement level of up to 20%. However, the materials were not considered for HPC.

Basavaraja et al. (2018) studied the strength properties of HPC containing ultra-fine fly ash and nano silica. They obtained an optimum compressive, flexural, and split tensile strengths of 82.36 N/mm^2, 6.41 N/mm^2, and 5.51 N/mm^2 respectively was achieved at 10% of ultrafine fly ash blended with 4.5% Nano-silica admixtures. The result obtained is higher than that of conventional concrete. Banjare and Jaiswal (2017) determined the performance of Metakaolin, Fly Ash and Silica Fume as SCM on high strength concrete. The combinations performed better in compression than the control mix.

Onikeku et al. (2019) evaluated the characteristics of ordinary concrete mixed with BLA and concluded that BLA improved the mechanical properties of concrete at 10%. However, they did not consider its use in HPC. Odeyemi et al. (2020a) considered the effect that Guinea Corn Husk Ash (GCHA) would have on the Mechanical Properties of HPC. They recommended 10% GCHA as the optimum replacement for cement in HPC. Xia et al. (2020) also looked into the possibility of using natural pozzolans in HPC for the Mombasa–Nairobi railway. They produced concrete samples by using 30% Fly Ash (FA), 30% Fine Tuff (FT) and 30% Fine Volcanic Slag (FVS). They concluded that FVS performed favourably well as FA. The optimal mechanical strength was obtained by combining FA with FVS.

Though, several SCM have been investigated in HPC, the use of BLA in HPC as an SCM has not been considered. The commercial use of BLA as a supplementary cementitious material will be an alternative solution to environmental problems caused by toxic gases emitted during cement production and the indiscriminate disposal Bamboo leaves. Therefore, this study investigates the impact of BLA as additive on the mechanical properties and microstructure of HPC.

Table 1
Mix proportions for cube and cylindrical samples per cubic metre of concrete.

W/C Ratio	BLA (%)	Cement for cube and cylindrical samples (kg/m^3)	Aggregates for cube and cylindrical samples	
			Fine (kg/m^3)	Coarse (kg/m^3)
0.31	0	810	640	1180
0.31	5	770	640	1180
0.31	10	720	640	1180
0.31	15	680	640	1180
0.31	20	650	640	1180

2. Materials and methods

2.1. Materials

The cement used in the production of the concrete samples used in this research was Ordinary Portland cement (OPC), 42.5 N which conforms to NIS 444–1:2003 (2003). Potable water with a pH of 6.8 was used for concrete mix and curing. The fine aggregate (natural sand) that pass through British Standard (BS) sieve 4.75 mm and coarse aggregate (crushed stone) of maximum size of 12.5 mm was used and both conform to BS EN 12620:2002+A1:2008 (BS EN 12620:2002+A1:2008, 2008). Paracel Superplasticizer which conform to ASTM C494 (ASTM C494/C494M-16, 2019) was used as a water reducing agent. One (1) percent of the superplasticizer by mass of the cement used was added to the mix to improve the strength of the concrete by reducing the water cement ratio. The bamboo leaves used were handpicked to ensure that they are free from other leaves.

3. Methods

The dried leaves were ignited in an open drum to reduce the volume, without any application of external energy like the use of firewood or charcoal. Air burning was stopped as soon as all the leaves were charred and became black in colour. It was then taken to an electric furnace and heated at a temperature of 700 °C for 2 h at which it became greyish in colour. After cooling, the ash was sieved before partially using it to replace cement for HPC preparation. This method conforms with the method used by Cociña et al. (2018) and Umoh and Odesola (2017) in previous research.

The oxide composition of the BLA was determined using X-ray fluorescence spectrometer Shimadzu EDXRF-702HS operated at 40 kV and 18 mA. The current of the equipment was adjusted to a maximum value of 1 mA using a 10 mm collimator. A counting period of 100 s was adopted for all the measurements taken. The intensity of element Kα counts per second (cps/μA) was obtained from the sample X-ray spectrum using the Shimadzu EDX software package. Pellets, 19 mm in diameter, were prepared from 0.5 g powder mixed with three (3) drops of organic binder (i.e. Polyvinyl chloride dissolved in Toluene) added to the sample, carefully mixed, and pressed in a hydraulic press. The pellets were loaded into the sample chamber of the spectrometer. Maximum voltage of 40 kV and a maximum current of 1 mA were applied to

Table 2
Elemental composition of BLA at 700 °C calcination temperature.

Parameters	Chemical Formula	% Composition
Silicon Oxide	SiO_2	72.81
Aluminium Oxide	Al_2O_3	3.49
Ferric Oxide	Fe_2O_3	2.00
Titanium Oxide	TiO_2	0.23
Calcium Oxide	CaO	2.50
Phosphorus Oxide	P_2O_5	8.57
Magnesium Oxide	MgO	0.17
Sulfur Trioxide	SO_3	0.15
Potassium Oxide	K_2O	2.09
Barium Oxide	BaO	0.03
Chromium Oxide	Cr_2O_3	0.01
Manganese Oxide	MnO	0.20
Loss of Ignition	LOI	5.71

produce the X-rays that excite the sample for 10 min.

The designed mix adopted for the HPC was obtained using the Council for the Regulation of Engineering in Nigeria (COREN) Standard Design Method (Council for The Regulation of Engineering In Nigeria, 2017) for a characteristic compressive strength of 50 N/mm^2 and designed target mean compressive strength of 56.56 N/mm^2. The designed mix for the concrete and cylindrical specimens used in this research are presented in Table 1. The BLA was added at 5, 10, 15, and 20% by weight of the cement. This range of replacements was in conformity to previous studies conducted by Ndububa et al. (2015), and Odeyemi et al. (2020a).

Forty-five (45) concrete cubes of 150 mm by 150 mm by 150 mm and cylinders of 150 mm diameter by 300 mm depth were produced (9 each as control experiment and 36 each for the varying percentages of BLA). The specimens were fully immersed in water for a period of 7, 28 and 56 days for curing since concrete containing pozzolanic materials are known to gain strength slowly at the early days of curing (Voit et al., 2020). At the end of these curing ages, the compressive and split tensile strengths of the concrete cubes and cylindrical samples were determined in conformity to BS EN 12390-3 (2009) (BS EN 12390–3:2009, 2009) and BS EN 12390-6 (2000) (BS EN 12390–6:2000, 2000) respectively.

For the compressive strength test the weighed cubes were placed carefully in a Haida Universal Testing Machine (UTM) of 2000 kN capacity. Loading was applied and increased until the failure of the cubes. The compressive strength was then obtained directly from the equipment.

For the splitting tensile strength test, each cylindrical specimen was placed centrally between the upper and lower plates of the UTM. Load was applied to the specimen by turning on the machine. The tensile strength was also gotten directly from the equipment.

The samples of the HPC were tested for their microstructures using an ASPEX 3020 Scanning Electron Microscope with Energy Dispersive Spectrometer (SEM/EDS) at 16.0 kV accelerating voltage at the Material and Metallurgical Engineering Department, Kwara State University, Malete, Kwara State. The samples were coated with gold using Balzer's sputtering device before they were observed under the microscope.

4. Results and discussion

The chemical composition of the BLA is presented in Table 2. At 700 °C calcination temperature, the percentage composition of silicon oxide is greater than 72%. Hence, the calcination temperature is suitable. Equally, the addition of the percentage composition of SiO_2, Al_2O_3 and Fe_2O_3 are greater than 70% as specified by ASTM C-618 (2001) and BS EN 197-1 (BS EN 197–1:2011, 2011). Also, the percentage composition of SO_3 of 0.15% and Loss of Ignition (LOI) of 5.71% are less than the maximum of 4% and 10% stipulated for pozzolanic additives in ASTM C-618, 2001. These confirm that BLA is suitable as a pozzolan in concrete. These results are also in conformity with the findings of Olutoge and Oladunmoye (2017), Adewuyi and Umoh (2016), and Dhinakaran and Chandana (2016).

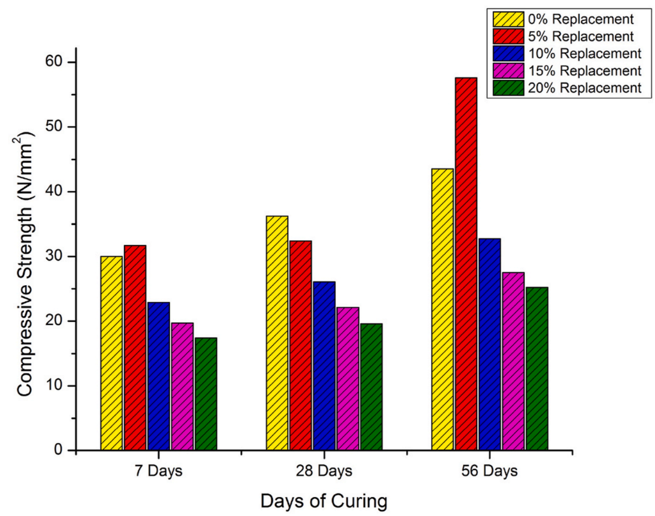


Fig. 1. Comparison of compressive strength of HPC at varied curing age.

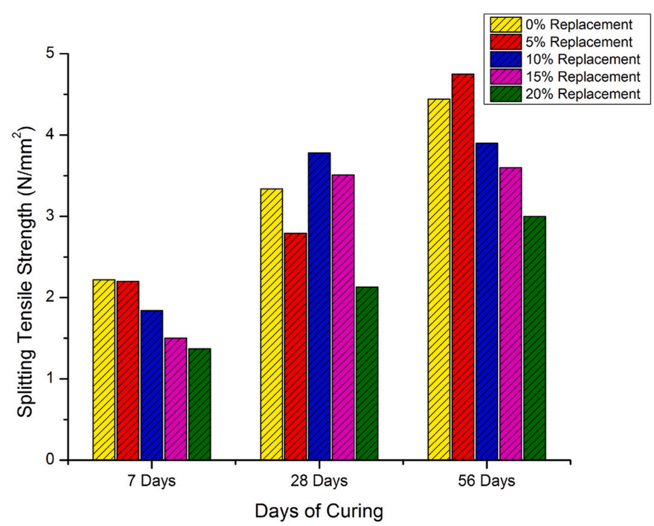
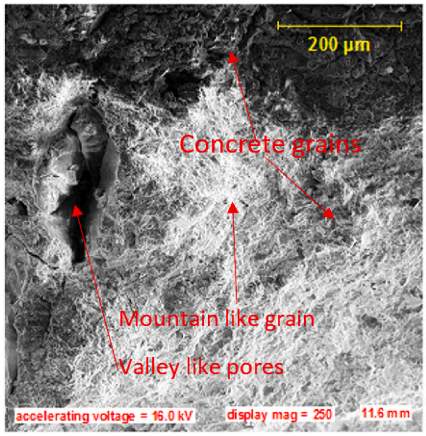


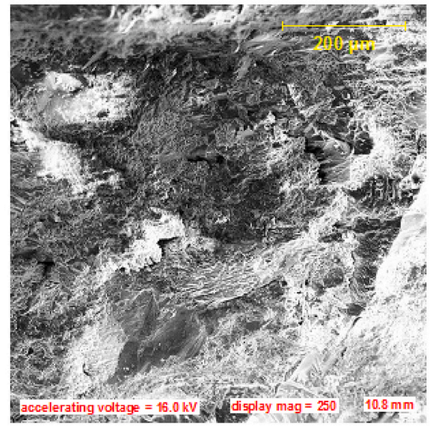
Fig. 2. Comparison of splitting tensile strength of HPC at varied curing age.

Fig. 1 and Fig. 2 shows the results of the mechanical properties i.e. compressive strength and splitting tensile strength for the concrete samples. Both properties increase with the curing age. While the strengths decrease with addition of the additive except at 5% replacement where there was improvement in the strengths of the HPC compared with the regular concrete which was used as the control sample control. The highest compressive strength of 57.59 N/mm^2 was obtained at 5% BLA replacement on 56 days curing age. This strength is above the designed target mean strength of 56.56 N/mm^2. However, this strength is 0.29% lower than the 57.76 N/mm^2 optimum strength obtained by Odeyemi et al. (2020a) when Guinea Corn Husk Ash (GCHA) was used as additive for HPC. Beyond the 5% replacement of BLA, the compressive strength began to decline. The optimum strength obtained at a replacement level of 5% GCHA agrees with the findings for GCHA for utilization in concrete production reported by Ndububa et al. (2015) and Odeyemi et al. (2020a).

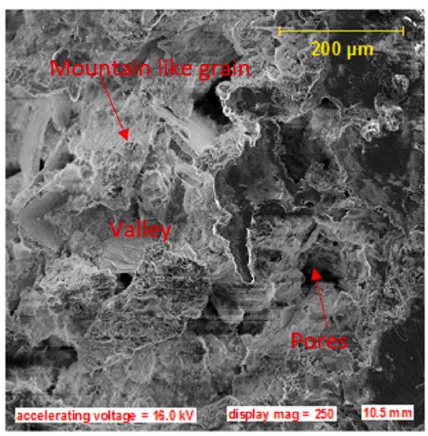
The result for the splitting tensile strength is consistent in terms of the replacement level that gave the highest strength for the HPC on the 56th day of curing. A value of 4.75 N/mm^2 was obtained. This strength is 17% lower than the 5.75 N/mm^2 obtained by Odeyemi et al. (2020a) when Guinea Corn Husk Ash was used as additive for HPC. Also, BLA



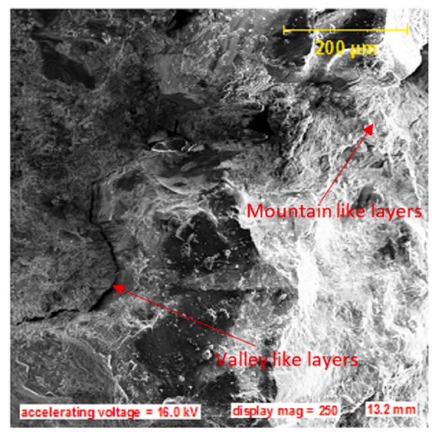
(a) 0 % Replacement of Cement with BLA



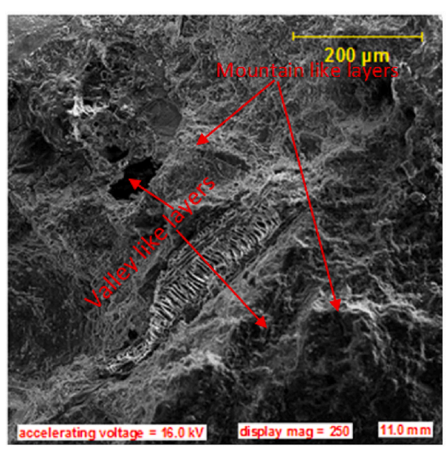
(b) 5 % Replacement of Cement with BLA



(c) 10 % Replacement of Cement with BLA



(d) 15 % Replacement of Cement with BLA



(e) 20 % Replacement of Cement with BLA

Fig. 3. Microstructure of BLA-HPC

produced a lower strength in terms of optimum replacement of cement in HPC when compared with fly ash plus silica fume, silicafume and flyash, silicafume blended flyash, and micro silica (silica fume) blended fly ash used by Subbulakshmi et al. (2014), Ismeik (2009), Kannan (2017) and Magudeaswaran and Eswaramoorthi (2013), respectively.

This percentage replacement of 5% for BLA in HPC is lower than the 10% replacement level suggested for regular concrete by Onikeku et al. (2019).

Fig. 3(a–e) presents the microstructural properties of HPC containing 0–20% BLA. Each microstructure contains many concrete grains lying over another to give valley-mountain like appearance. Micrographs obtained in Fig. 3(a–e) show a good homogenous mixing between 0 and 20%. However, differences are discernible from all structures. In the concrete possessing 0% of BLA, every pan of the concrete mix deeply flows into the one below or around giving rise to closed packed interlocking grains. Therefore, the pores are few within the entire concrete structure. However, better interlocking of concrete grains is observed in the micrograph of the concrete containing 5% of the BLA. This is evidenced from the observed nearly perfect structure having very narrow pores unlike the big trenchlike pores found in the concrete without BLA. Comparing the microstructure of the concrete containing 5% BLA with those of others having higher percentage of the additive, it is ranked with closed concrete grain packing as others have pronounced pores of large sizes resulted from poor concrete flow into one another during casting. Moreover, evidence of cracking is seen in 15% BLA concrete. This may be attributed to poor hydration, which means more water is needed during curing to reduce concrete brittleness that may lead to fracture. Since defects in materials like BLA modified concrete in this study act as stress raisers, concretes having BLA from 10 to 20% replacement are expected to fail at lower stresses than expected. This is responsible for highest compressive and splitting strengths of the 5% BLA concrete. Its better mechanical performance than the control concrete is not attributed only to BLA addition but also integrity of its structure. BLA being hydrophilic, that is water loving, it is expected to enhance hydration of the concrete and reduce concrete curing period to attain maximum hardness/strength with consequent reduction in CO_2 release to the atmosphere. Poor concrete flow into each other during casting leading to pores within the modified concrete does not give room for evaluating hydration potentials of the bamboo leaf ash since the pores have degraded the mechanical properties of the BLA modified concrete. Therefore, progressive tapping or vibration of the mould is recommended to compact the concrete and aid possible flow into one another.

5. Conclusions

The following conclusions are drawn from the study:

1. The addition of the percentage composition of SiO_2, Al_2O_3 and Fe_2O_3 is greater than 70% as specified by ASTM C-618, 2001. Therefore, BLA can be used as a pozzolan in High Performance Concrete.
2. The optimum replacement of OPC with BLA is 5%. This replacement level gave a higher compressive and splitting tensile strengths for HPC when compared with the control sample. A better interlocking of concrete grains was also observed in the micrograph of the concrete with 5% BLA replacement when compared with other percentages.
3. Increasing the curing age of BLA blended HPC beyond 28 days increases the mechanical properties of the concrete. This finding is in conformity with the recommended curing days for concrete containing pozzolanic materials given by Adesanya and Raheem (2009), Vakili et al. (2013), and Voit et al. (2020).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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