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MECHANICAL CHARACTERISATION OF CARBON-SILICA REINFORCED COMPOSITE FOR TURBINE APPLICATIONS

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Abstract: Materials selection and development for applications in advanced systems is becoming highly complex involving the need for lower cost alternatives without compromising service performance. This paper investigated selected critical mechanical properties of ceramic composites synthesized from coconut shell carbon (CSC) reinforced with silica particles (SP). Coconut shells (CCS) and silica sand (SS) were pulverized separately in a plate mill and a ball mill respectively to obtain a particle size of $250\mu m$. The CCS powders were calcined at 500^0C in an oven to obtain coconut shell ash (CSA) which was carbonized in a furnace from 500^0C-1000^0C under argon gas controlled environment. The materials were mechanically blended while the SP additions varied from 10-40 wt.% and compacted using hydraulic press. The compacted mixture was sintered at 500^0C-1200^0C, held for 2 hours and the composite characterized for mechanical properties while the microstructural integrity was analyzed using scanning electron microscope/energy dispersive x-ray spectroscopy (SEM/EDS). Results show that after sintering, coconut shell carbon developed strong cohesion with the silica particles which gave rise to effective load transfer. The mechanical properties that ensued demonstrated on the average, 52.8% comparability with conventional power plant structural materials in terms of hardness, compressive strength and impact energy.
Keywords: Ceramic matrix composite, power plant turbine, silica particles, coconut shell, mechanical properties

INTRODUCTION

One of the factors that impact the efficiency of a power plant is the thermal and mechanical characteristics of critical components of its turbine. Ceramic composites are known to exhibit high thermal characteristics; however, their brittle nature under impact load has been a major concern in application environments where stress is combined with elevated temperature (Nadejda, et al., 2010, Amirtan, et al., 2011, Lewis, et al., 2009 and Xia and Curtin, 2000). Hence, the imperative to develop ceramic composite with a unique structure capable of significantly reducing intrinsic brittleness. Both the choice of reinforcing material suitable for such structure modification and the form in which such material is to be employed, demand scientific investigation. It is reasonably conjectured that certain agro-wastes if properly processed can be utilized for this purpose.

Generation of agro-waste in most developing countries has grossly increased over the years as a result of increase both in population and agricultural activities (Sonmez and Mustafa, 2011). According to Obi et al., 2016, the most widely used method of managing these agro-wastes is open air burning. Due to the adverse effect associated with open air burning, there is a need to explore other disposal options where agro-wastes can be productively utilized with little or no harmful environmental effects. However, apart from the seemingly pioneering work of Madakson, et al., (2012) which reported that the carbon in coconut shell ash has the potential utilization as reinforcement in ceramics composites, there is a huge information gap with regard to using agro-waste in ceramic based composites. This has placed a huge limitation on the scientific basis for processing and utilising carbon particles obtained from agro-waste to produce high performance advanced materials with characteristics light weight. The aim of this work is to develop and evaluate the functional mechanical characteristics of coconut shell carbon reinforced ceramic composites for applications as power plant turbine blades and steam buckets. As an organic contaminant, the productive use of coconut shells will help to mitigate the adverse effect on the environment arising from its improper disposal.

MATERIALS AND METHOD

The major materials employed for the study consist of coconut shell (CS), silica sand (SS), sodium bentonite and distilled water. Sufficient quantities of coconuts were obtained from a coconut farm and the shafts removed to isolate the nuts. Then, the edible portion of the nuts was removed with a sharp knife while the CS left was first oven dried and then ground into powder in a ball mill (Figures 1a and 1b) and calcined into ash at 500^0C in an oven. The coconut shell ash (CSA) was then carbonized in a furnace at 500^0C-1000^0C under argon gas controlled environment. Figure 2 shows a typical X-ray Diffractogram (XRD) of carbonized coconut shells obtained under the same conditions employed in this study. The silica sand was first oven dried and then pulverized in a ball mill and sieved to $250\mu m$ particle size. Both carbon and silica powders fractions with addition of sufficient amount of distilled water were mechanically mixed with sodium bentonite according to the mix design shown in Table 1. The various mixes were compacted in a cylindrical metal mould using hydraulic press

at 30kgf. Prior to a full scale sintering in a furnace, the green compacts were oven dried between 200⁰C and 300⁰C to avoid crack during sintering. The composites were then sintered (see Figures 2a and 2b) by subjecting them to a gradual heating from 500⁰C-1200⁰C, held for 2 hours and allowed to cool in the furnace.

a)

b)

Figure.1: (a) Pulverizer (b) Ball mill

The sintered composite samples were characterised for microstructural integrity and mechanical properties using JEOL JSM-5900LV scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDS) facility, Instron universal testing machine, Avery impact tester and Brinell hardness testing machine respectively.
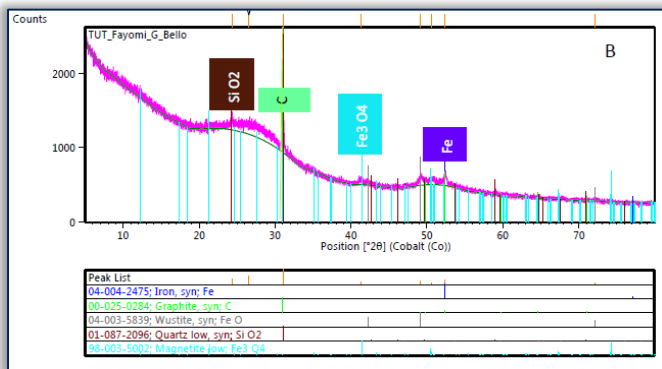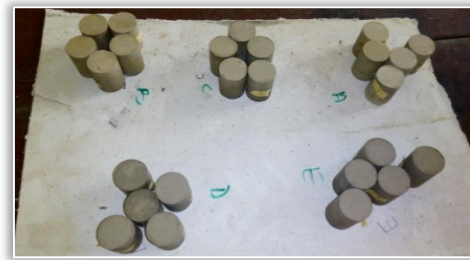

Figure 2. XRD image of coconut shells (Bello, et al., 2016)

Table 1. Samples formulation

Sample	Materials (wt. %)		
	Carbon	Silica	Bentonite
A	80	0	20
B	70	10	20
C	60	20	20
D	50	30	20
E	40	40	20

a)

b)

Figure 3. Compacted silica reinforced carbon matrix composites (a) Green compacts (b) Sintered samples

RESULTS AND DISCUSSION
⊞ Compressive strength

The maximum load bearing capacity of the composite was determined in a compressive strength test and the results are illustrated in Figure 4. It is observed that the sample without silica particles (SP) addition has the lowest compressive strength of 115.3MPa compared with other samples reinforced with varied additions of SP showing compressive strength ranging between 138.3MPa and 187.8MPa which compare well with that of conventional martensitic steels used in power plant structural components. The sample with 20 wt. % SP demonstrated the highest compressive strength of 187.8 MPa. This behaviour can be explained in term of the extent of wettability provided by the carbon matrix on the SP resulting in effective load transfer. It thus appears that the absence of SP in the control sample invariably gave rise to carbon-carbon interactions that resulted in a relatively low compressive strength. As observed in the current study however, the effectiveness of carbon as a wetting agent in a ceramic system appears to be on the average, in the ratio 8:1 for carbon/silica. This assertion is corroborated by the fact that a decrease in carbon/silica ratio to 4:1 gave rise to corresponding decrease of about 15 percent in compressive strength from 162.5 MPa to 138.3 MPa.
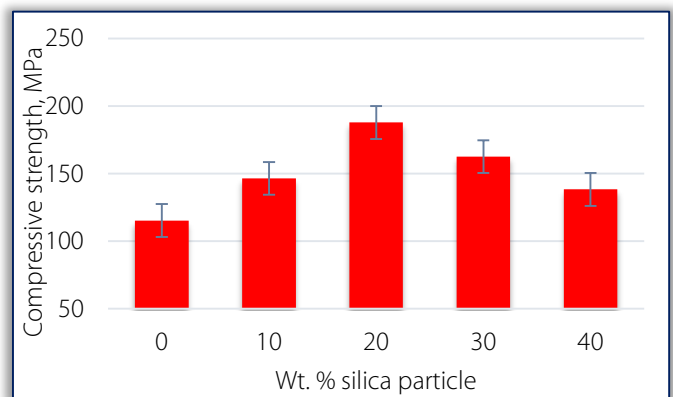

Figure 4. Variation of compressive strength with silica particle additions

⌗ Hardness

The results of hardness property analysis conducted on the carbon composite samples are as presented in Figure 5. The composites hardness values range from 106.5-178.4 Brinell hardness number (BHN) with the unreinforced sample having the lowest value while the peak is exhibited by the sample with 20 wt.% SP addition. The contribution to a relative high hardness of the reinforced samples may have stemmed from strong cohesion between the carbon matrix and the reinforcement phase that provide effective barrier to dislocation motion.

Although, on its own, silica is reported (Hassan and Aigbodion, (2010), Alaneme et al., 2013) to be one of the hardest materials however, the low hardness exhibited by the sample with 0 wt.% SP additions can be attributed to the monolithic and relatively soft carbon matrix. Again, the composite hardness reduces on further SP addition probably due to porosity suggesting that 20 wt. % SP is the optimum required for enhanced hardness characteristic of the carbon composite. However, the composites hardness value being in the range 131.8-178.4 BHN is 54.4% of the standard hardness put at 270-300 BHN for most power plant turbine blades (Ziegler et al., 2013, Bouwlte et al., 2015).
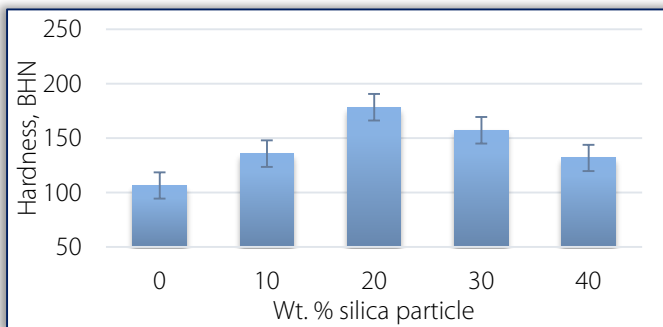

Figure 5. Variation of hardness with silica particle additions

⌗ Impact energy

Figure 6 illustrates the amount of energy required to fracture the composites at varied SP additions which is observed to increase progressively from 17.8 Js, peaked at 28.7 Js and then dropped monotonously to 19.6 Js. The unreinforced sample demonstrated the lowest impact energy which is 17.8 Js while the sample with low carbon/silica particle ratio of 4:1 also has relatively low impact energy, 19.6 Js. Given these observations, it appears that variations in the level of cohesion between the carbon particles and SP additions influence significantly the impact energy of the composites as an indication of the tough-to-brittle transition behaviour of the composites (Xia and Curtin (2000), Witold and Haley (2010). This is because, within ratios 8:1 and 5:1 of carbon/silica particle-matching within the system, the composites are conferred with the requisite ability to undergo substantial level of plastic deformation giving rise to impact energy values comparable with standard values of 20 Js (minimum) for steam turbine blades (Dowson et al., 2008).
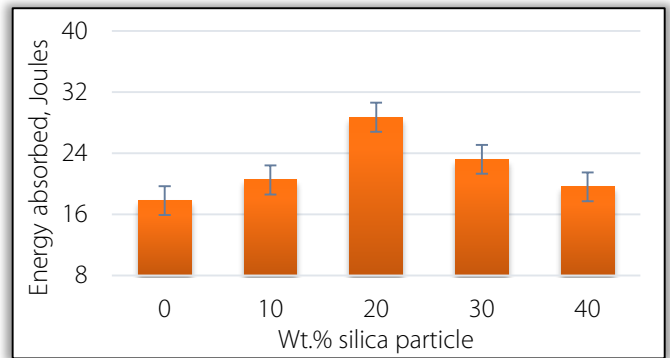

Figure 6. Variation of impact energy with silica particle additions

⌗ Microstructure

The SEM/EDS micrographs of the 20 wt.% SP reinforced carbon composite sample, being the composite that demonstrated the best mechanical characteristics is shown in Figure 7a.
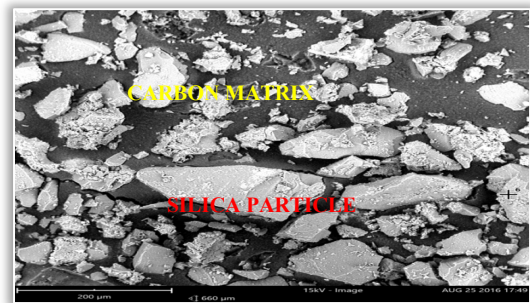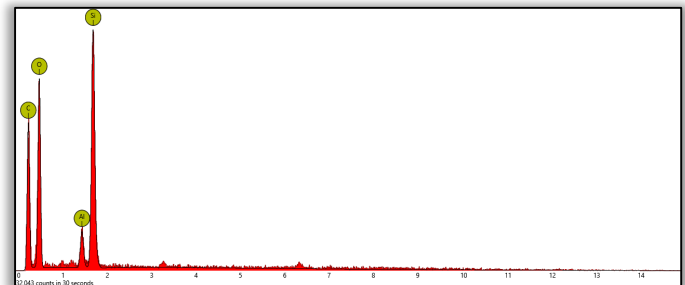

Figure 7a. SEM micrograph of 20 wt. % SP reinforced carbon composite

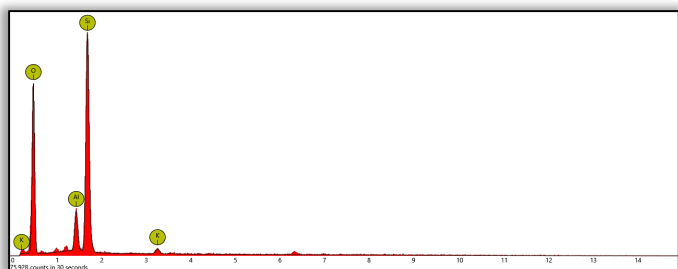| Elements	Oxygen (O)	Silicon (Si)	Aluminium (Al)	Carbon (C)
Concentrations	11.3	20.8	4.1	63.8

Figure 7b. EDS of 20 wt. % SP reinforced carbon composite

It is observed that the silica particles reinforcement phase disperse homogeneously within the carbon matrix. This actually provided the particles sufficient contact area with the carbon matrix which is relatively soft (graphite formed at the fairly low carbonization temperature of 1200^0C). However, because of the traditional strong and directional bonding between carbon atoms and silica particles, limited plasticity is conferred on the composite confirming the report by Ritchie, (2011), hence the relatively low impact toughness exhibited by the composites. Varied elemental concentrations retained within the composites phases after sintering are presented as obtained by EDS analysis in the accompany Tables under Figures 7b and 8b at 20wt.% and

40wt.% respectively. The structure developed at 40wt.%SP addition (Figure 8a) revealed two features namely: inhomogeneous particles dispersion and an extensive particle coarsening resulting in a relatively large particle size. This type of microstructural feature is known to impair desirable mechanical properties such as toughness (impact energy), modulus and shear strength because it promotes weak cohesion between the particles and the matrix. Thus, the low mechanical properties exhibited by the composite at 40wt.% SP addition is attributable to its poor microstructural integrity.

Figure 8a. SEM micrograph of 40 wt. % SP reinforced carbon composite

Elements	Potassium (K)	Silicon (Si)	Oxygen (O)	Carbon (C)	Aluminium (Al)
Concentrations	1.6	42.3	13.5	38.7	4.9

Figure 8b. EDS of 40 wt. % SP reinforced carbon composite

CONCLUSION

The mechanical characteristics of silica particles reinforced carbon matrix composite have been investigated. From the results and their analyses the following conclusions can be drawn:

— The composites best mechanical properties namely; hardness, compressive strength and impact energy are obtained at 20 wt.% silica particles (SP) addition.

— Hardness of 178.4 BHN exhibited by the composite at 20 wt.% SP addition is adjudged sufficient to prevent any surface dysfunction in service.

— Under compressive loading, the composites ultimate strength performance of 187.8 MPa influenced significantly by matrix-reinforcement ratio are within the values recommended for ceramic composites.

— At an average of 7:1 of matrix/reinforcement ratio, the composite is conferred with the requisite ability to undergo substantial level of plastic deformation culminating in 28.7 Joules impact energy.

— The carbon matrix also serve as an effective wetting agent which significantly reduces the inherent brittleness of the ceramic composites,

In view of the above mechanical performance indices, the ceramic composite produced has a huge potential for application as power plant turbine blade and steam plant bucket.

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