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Research Article

MECHANICAL AND WEAR CHARACTERISATION OF QUARRY TAILINGS REINFORCED A6063 METAL MATRIX COMPOSITES

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ABSTRACT

The viability of utilizing cheaply sourced quarry tailings (QTs) particles as reinforcing materials for the development of low cost high performance aluminium matrix composites for structural and industrial applications was explored. Aluminium alloy (A6063) was reinforced with 2 – 10 wt. % of 80 µm QTs particulates using stir casting method. Microstructural, mechanical and wear characterisations were carried out on the composites. Micro hardness and ultimate tensile strength of the composites were improved with addition of reinforced particulate in the base matrix alloy. Addition of quarry tailings reinforcements also decreased the wear rate of the composites from 245 mm/Nm^3 to 180 mm/Nm^3 for 10 N and from 260 mm/Nm^3 to 135 mm/Nm^3 for 15 N. Optical and SEM examinations revealed uniform distributions of the QT particles in the molten matrix.

Keywords: *Aluminium Matrix Composites, Quarry Tailings, Characterisation*

1. INTRODUCTION

Aluminium still remains the most utilised metal as matrix material in the development of metal matrix composites (MMCs). This is due to the desirable property combination which it exhibits thereby making it very suitable for a wide range of engineering applications. Aluminium matrix composites (AMCs) have been explored for varied technical uses due to the high specific strength and stiffness, good wear and corrosion resistance, good mechanical and thermal properties exhibited among others (Alaneme and Bodurin, 2011; Alaneme and Sanusi, 2015).

Silicon carbide, alumina, boron carbide, titanium carbide and tungsten carbide are among the mostly used conventional ceramic materials in the development of AMCs. However, high cost and limited supply of conventional ceramic reinforcing materials especially in the developing countries are among the problems associated with the development of discontinuously reinforced aluminium matrix composites (Bodurin *et al.,* 2015). Hence, studies have been carried out to find inexpensive and effective substitutes to the relatively high cost conventional ceramic particulates with the hope of still maintaining their high performance level in service applications. Aluminium was reinforced with natural resource by-products such as fly ash, silica sand, and red mud to produce AMCs for properties enhancement (Surappa *et al*., 2008; Rohatgi *et al*., 2010).

A large number of composite materials have been developed by reinforcing metallic matrix alloy with high strength, high modulus and brittle ceramic phase particles. Uniform dispersion of reinforcement materials in the metal matrix offers improvement in strength elastic modulus, corrosion and wear resistance of resultant composites (Durowaye *et al*., 2018). Due to these properties, particulate reinforced composites have found wide range of applications in the automobiles and aerospace industries compared to monolithic alloys. Particulate reinforced composites have been considered as suitable alternatives to traditional un-reinforced monolithic alloys.

The search for low cost options in AMCs production has led to a number of efforts tailored at utilizing industrial and agro waste products as reinforcing materials. This has led to the development of hybrid composites consisting of an agro-waste derivative combined with synthetic ceramic materials or an industrial waste combined with synthetic reinforcement (Bodurin *et al.,* 2015). However, the final properties of the composites depend on individual properties of reinforcement and matrix alloy. There are lots of agro waste that are being studied but the limitation to their use is the preparation which involves drying, burning, conditioning, sieving before use as reinforcements and these processes increase the production time, cost and affect the production rate.

One of the industrial by-products that is readily available is quarry tailings (QT). QT is generated from quarrying activities and is obtained as solid waste during crushing of stones to obtain aggregates. It exhibits low density and contains ceramic compounds such as silica (SiO_2) and alumina (Al_2O_3). It is available in commercial quantity at very low cost and studies on its use as reinforcement have not been extensive. QT has been researched on as partial replacement of cement in concretes but very little work has been carried out concerning its use as reinforcement for AMCs production. It has been used in the production of lightweight building materials because of its low density. It also offers the possibility of providing cost competitive reinforcement in composite production because the cost of procuring 500 grams of silicon carbide (SiC) is twice that of QT. Most of the limitations of producing particulate reinforced AMCs could be remedied with the use of quarry tailings. Hence, this study explores the use of QT particles as suitable reinforcement and substitute to conventional ceramic materials to produce aluminium based composite with high performance levels.

2. MATERIALS AND METHODS

2.1. Materials

The A6063 alloy used for this study was obtained from the Nigerian Aluminium Extrusion Company (NIGALEX) Oshodi, Lagos, while the quarry tailings used as the reinforcement was obtained from a quarry company in Akure, Ondo state, Nigeria. The picture of the pulverized and sieved quarry tailings is shown in Fig. 1. The chemical compositions of the aluminium alloy and the quarry tailings were determined using the X-ray fluorescence (Mini Pal 4 ED-XRF) machine and are presented in Tables 1 and 2 respectively.

Fig. 1. Picture of 80 μm quarry tailings particles

Table 1. Chemical composition of A6063 alloy

Element	Si	Fe	Cu	Mn	Mg	Ti	Ni	Zn	Al
Weight (%)	0.366	0.351	0.026	0.013	0.514	0.014	0.0053	0.120	98.56

Table 2. Chemical composition of quarry tailings

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO	BaO
Weight (%)	64.97	14.86	6.27	4.92	2.68	3.09	1.14	0.001

2.2. Materials Preparation and Composite Samples Production

The A6063 alloy was cut into small sizes for ease of weighing. The quarry tailings were pulverized in a ball mill and sieved to 80 μm particle size. The quantities of the A6063 alloy to be melted were calculated based on the size of the mould that was used. The measurement was done using a digital weighing balance model UW1020H. The proportion of the materials mixture is presented in Table 3. The quarry tailings particles were preheated in an oven at a temperature of 250^0 C for an hour in order to remove moisture and improve wettability with the molten A6063 metal alloy. The A6063 alloy was melted at 750^0 C in a gas fired crucible furnace. The molten metal alloy was allowed to cool to 600^0 C to reach a semi-solid state. Stirring of the melt was carried out at this temperature for about 2 minutes before pouring appropriate quantities (2, 4, 6, 8 and 10 wt. %) of the preheated quarry tailings into the molten alloy and also stirred for about 5 minutes. The composites slurry was afterwards heated to 800^0 C and stirred at 300 rpm for 10 minutes before pouring into a cylindrical metallic mould of diameter 16 mm and length 60 mm. Manual stirring was done using a long stainless steel rod to avoid clustering and to achieve good dispersion of the particles in the melt. The cast samples (Fig. 2) were allowed to cure at room temperature for 24 hours after which they were removed from the moulds.

2.3. Microstructural Characterisation

The microstructure and the chemical compositions of the phases present in the test samples were examined using an X-SUPREME 8000 by Oxford instruments, USA.

2.4. Tensile and Ductility Characterisation

The test samples were prepared using qualilathe-210–CNC lathe machine and an Instron universal testing machine was used to determine the tensile property of the samples at room temperature based on ASTM 8m-15a standard. circular tensile test piece with one step grip was used with dimension of 5 mm diameter and gauge length of 30 mm. The samples were stressed to fracture while the data generated was used to evaluate the tensile property. the elastic deformation behaviour of the specimens was evaluated by the percentage elongation suffered during tension.

2.5. Hardness Characterisation

The hardness behaviour of the composites was determined using Wolpert micro hardness tester 930 in accordance with ASTME 384 standard. A direct load of 5 kg was then applied on each of samples for about 10 secs. The micro hardness tester was placed on the sample to make indentation at three different positions in the sample and the average reading values were selected.

Table 3. Proportion of the materials mixture

Samples	Aluminium		Quarry tailings		Total (g)
	(g)	(wt. %)	(g)	(wt. %)	
1	384.15	100	-	-	384.15
2	376.47	98	7.69	2	384.16
3	366.60	96	15.27	4	381.87
4	356.82	94	22.78	6	379.60
5	347.12	92	30.18	8	377.30
6	337.51	90	37.51	10	375.02

Fig. 2. Picture of some of the composite cast samples

2.6. Impact Characterisation

A V-notch was cut on each sample, using a Hounsfield notching machine ensuring that the notch screw is set at a depth of 2 mm so that the cutter just touches the piece. Each test piece was broken with a pendulum on the Hounsfield balanced impact machine and the energy absorbed in fracturing is measured. The test was performed on different samples of the composite and average value of each result were taken.

2.7. Wear Characterisation

The wear characterisation of the composites was evaluated using a Din abrasion tester FE05000. Cylindrical pin samples of 10 mm diameter and 20 mm height were machined from the 16 mm rod. The surface of each sample was prepared with 220 grit SiC abrasive paper. The test was carried out using applied loads of 10 N and 15 N, sliding speed of 0.32 m/s, sliding distance of 1 m and a constant time of 2 minutes. The rubbing action between the sample and the abrasive wheel driving the rotation motion of the machine resulted in the generation of loosed composites debris from the samples surface. The weight of the samples was measured before and after each test using a digital weigh balance with model number UW102H and the wear rate was determined using ‘‘Eq. (1)’’ (Agunsoye *et al*., 2018).

$$R = \frac{\Delta W}{SA} \quad (1)$$

where,

R is the wear rate, ΔW is the weight difference of the sample before and after the test in mg, S is total sliding distance (m) and A is the applied load (N).

3. RESULTS AND DISCUSSION

3.1. Composition and Microstructure

As shown in Table 1, the major constituent of A6063 alloy is aluminium with 98.56 wt. % while other elements are in traces. The result also indicated that silica (SiO_2) has the highest composition of 64.97 wt. % in quarry tailings followed by alumina (Al_2O_3) with 14.86 wt. % while BaO has the least with composition of 0.001 wt. % indicating that it is a ceramic compound. Fig. 3 is the SEM micrograph of the unreinforced A6063 cast sample revealing pores and Al matrix. Fig. 4 shows the SEM micrograph of cast sample reinforced with 2 wt. % quarry tailings. It shows the uniformly distribution of quarry tailings particulates in the aluminum matrix. Fig. 5 shows the SEM micrograph of cast sample reinforced with 10 wt. % quarry tailings. It reveals a homogeneous distribution of quarry tailings particulates in the aluminum matrix. There is the presence of $Al_2O_3{\cdot}SiO_2$ (mullite) a hard ceramic compound in Figs. 4 and 5 which enhanced the hardness of the samples.

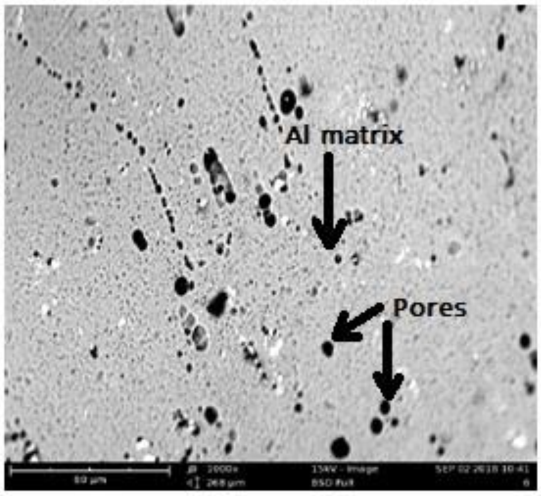

Fig. 3. SEM micrograph of unreinforced A6063 cast sample

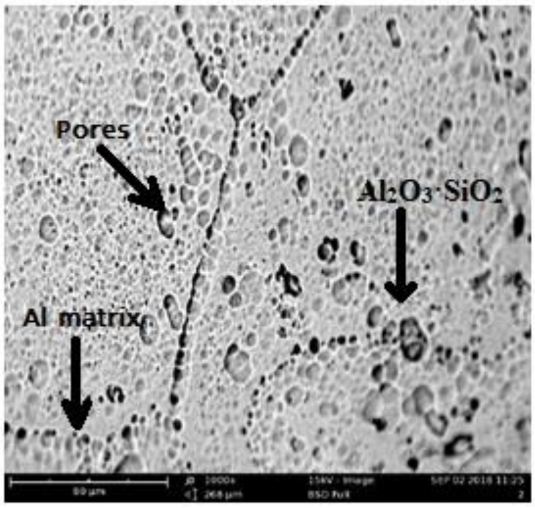

Fig. 4. SEM micrograph of cast sample reinforced with 2 wt. % quarry tailings

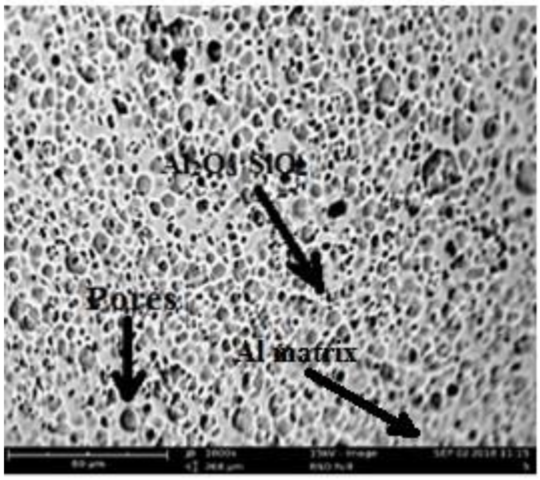

Fig. 5. SEM micrograph of cast sample reinforced with 10 wt. % quarry tailings

3.2. Tensile Strength

The tensile strength of the composites increased steadily with increase in quarry tailings addition as shown in Fig. 6.

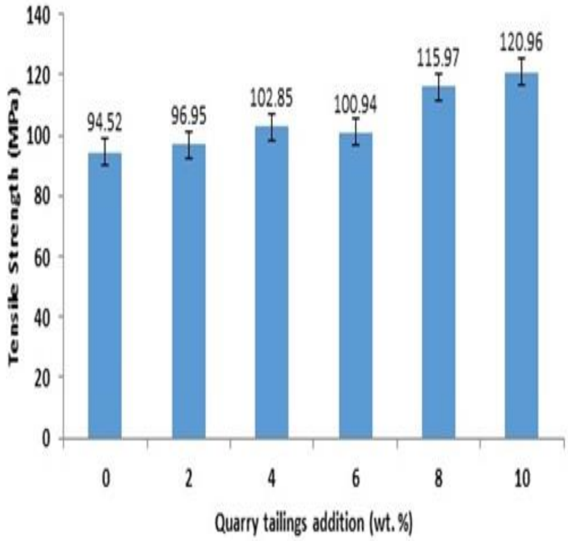

Fig. 6. Effect of quarry tailings on the tensile strength of the composites

The unreinforced A6063 cast sample exhibited the lowest tensile strength value of 94.52 MPa while sample 6 reinforced with 10 wt. % quarry tailings exhibited the highest tensile strength value of 120.96 MPa which is 28 % increase over the unreinforced. The increase in tensile strength is attributed to the applied load transfer to the strongly bonded quarry tailings reinforcements in Al matrix which increased dislocation density near matrix-reinforcement interface. Also, the grain refining strengthening effect as well as the uniform distribution of the quarry tailings particulates in the aluminum matrix enhanced the tensile strength of the composites.

3.3. Ductility

There was a steady decrease in elongation of the composites as the weight percentage of the quarry tailings increased as shown in Fig. 7. The unreinforced A6063 cast sample exhibited the highest elongation value of 16.442 % while sample 6 reinforced with 10 wt. quarry tailings exhibited the lowest elongation value of 6.057 %. The gradual reduction in ductility (elongation) of the composites was due to the resistance offered to the flow ability of aluminium matrix by the quarry tailings particulates as the weight of the quarry tailings particles increased. Similar results were obtained by Ramesh *et al*. (2013).

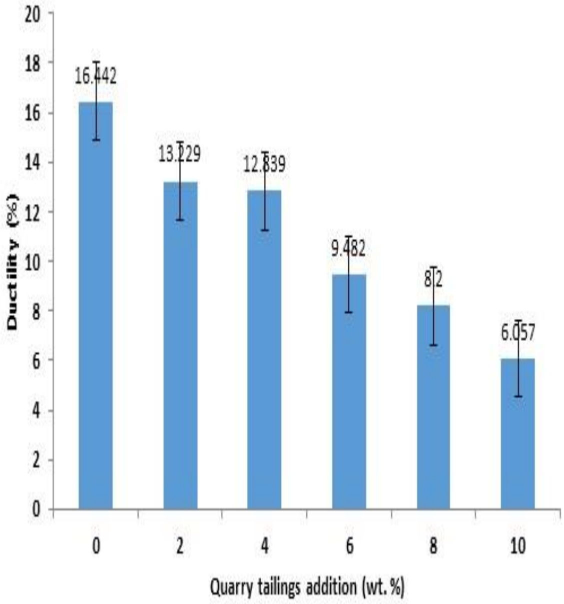

Fig. 7. Effect of quarry tailings additions on the ductility of the composites

3.4. Hardness

There was a steady increase in the hardness of the composites as the weight percentage of the quarry tailings increased as shown in Fig. 8. The unreinforced A6063 cast sample exhibited the lowest hardness value of 34.16 HV while sample 6 reinforced with 10 wt. % quarry tailings exhibited the highest hardness value of 49.95 HV. The presence of $Al_2O_3{\cdot}SiO_2$ (mullite) a hard ceramic compound from the quarry tailings offered resistance to surface plastic deformation during indentation. This rendered its inherent property of hardness to the soft matrix which significantly increased the hardness value. Again, the uniform dispersion of the quarry tailings particles and strong interfacial bonding between the reinforcement and the matrix alloy also enhanced the hardness of the composites. Similar observation was also reported by (Kalaiselvan *et al*., 2011).

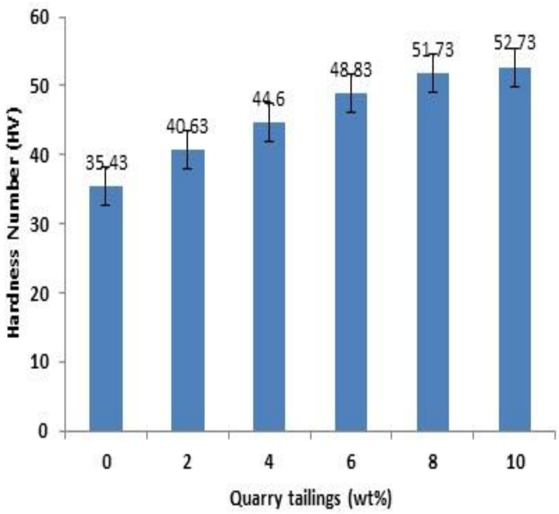

Fig. 8. Effect of quarry tailings additions on the hardness of the composites

3.5. Impact Energy

Fig. 9 shows a steady decrease in the amount of energy absorbed by the composites prior to fracture. The unreinforced sample exhibited the highest energy of 39.44 J while sample 6 reinforced with 10 wt. % quarry tailings exhibited the lowest impact energy value of 27.61 J. The gradual decrease in the amount of impact energy of the composites is due to the increased presence of hard and brittle quarry tailings particles in the soft Al-matrix alloy.

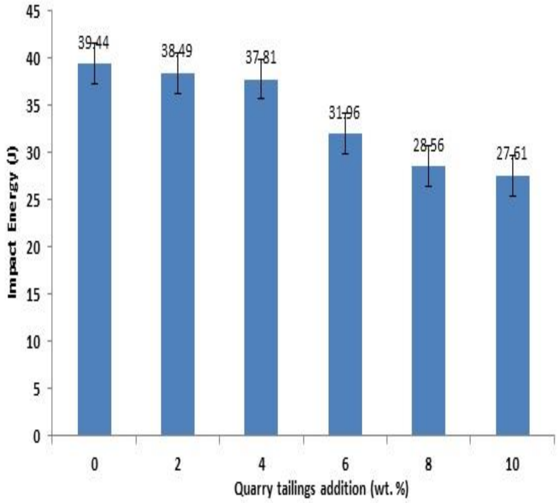

Fig. 9. Effect of quarry tailings additions on the impact energy of the composites

3.6. Wear Characteristics

As illustrated in Fig. 10, the unreinforced sample exhibited the highest wear rate of 245 mm/Nm^3 and 260 mm/Nm^3 at 10 N and 15 N respectively while sample 6 reinforced with 10 wt. % quarry tailings exhibited the lowest wear rate of 180 mm/Nm^3 and 225 mm/Nm^3 at 10 N and 15 N respectively.

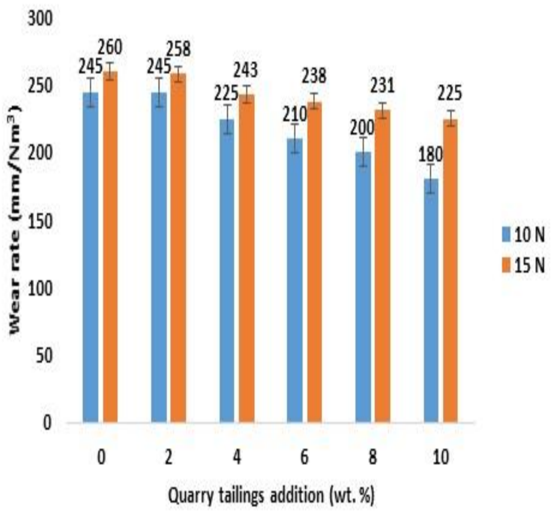

Fig. 10. Effect of quarry tailings on wear rate of the composites

The wear rate of the composites decreased with increasing quarry tailings addition which indicated the effect of concentration of quarry tailings reinforcement in reducing wear. This observation was similar to the one reported by Aigbodion and Akadike, (2010). Increased wear rate at higher load of 15 N was due to increased plastic deformation of the composites in the friction surface as a result of increase in the shear force between asperities and the ploughing force of asperities. Similar observation was also reported by Djafri *et al*. (2014) and Yawas *et al*. (2016).

The wear resistance of the composites is attributed to the presence of hard materials like alumina, silica and CaO in the quarry tailings. These acted as hard solid particles which improved the wear resistance. The strong interfacial bonding between the quarry tailings particles and the matrix alloy also enhanced wear resistance ability of the composites.

4. CONCLUSION

Quarry tailings reinforced A6063 composites have been successfully developed by the stir casting method. The 10 wt. % quarry tailings reinforced aluminium matrix composites exhibited desirable mechanical properties in terms of tensile strength (120.96 MPa) and hardness (49.95 HV). This composite also exhibited the low wear rate of 180 mm/Nm^3 and 225 mm/Nm^3 at 10 N and 15 N respectively. There was significant improvement in tensile strength and hardness of the composites with the addition of quarry tailings particulates. The uniform dispersion of the quarry tailings particles in the aluminium matrix coupled with the strong interfacial bonding between the quarry tailings particles and the matrix alloy enhanced the mechanical properties and wear resistance ability of the composites. This study has shown that quarry tailings has the potential of serving as reinforcement substitute for the expensive conventional ceramic materials in the development of AMCs.

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