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EFFECTS OF PARTICLE SIZE ON MECHANICAL, THERMAL AND CORROSION BEHAVIOUR OF QUARRY-DUST REINFORCED ALUMINIUM 6063 COMPOSITES

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ABSTRACT

This research investigated the effects of particle size on the mechanical, thermal and corrosion behaviour of quarry dust-reinforced (QD) aluminium 6063 composites. Double stir casting process was used to produce the composites with quarry dust of different particle sizes. Mechanical characterisation, thermal and corrosion behaviours were used to assess the performance of the produced composites and compared with the unreinforced aluminium 6063 alloy. The results showed that the hardness of the aluminium composites improved generally compared to the unreinforced alloy and decreased with increasing particle size. Sample A with 30+45 µm particles had the highest ultimate tensile strength of 106 N/m2 and this was seen to decrease marginally as the particle size increased. Sample A also had the highest impact energy of 10.5 J and this reduced as the particle size increased. The hardness value of the reinforced composites was generally higher than the unreinforced sample with sample A having a hardness value of 89.7 VHN. Thermal conductivity was found to increase with increasing temperature with Sample A having the highest thermal conductivity value of 194 W/mk at 300 oC. The potentiodynamic results of the study conducted shows that sample A is less prone to corrosion attack in 3.5 weight % NaCl environment with corrosion rate of 0.060087 mmpy. The addition of quarry dust to Al6063 alloy shifted the Ecorr downwards, depicting that the quarry dust can be utilized to inhibit corrosion of Al6063 in 0.5M H2SO4 environment. However, the highest resistance of the dissociation of Al 6063 composite system was observed in composite Sample D in acidic environment having the least corrosion rate of 3.4938 mm/year with corrosion current density of 320.99 A/cm2. The results from this research shows that the use of quarry dust as a single reinforcement do not jeopardise the integrity of the material most especially in saline environment.

Keywords: Quarry dust, Particle size, Thermal analysis, Mechanical properties, Corrosion

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• INTRODUCTION

Over a couple of years, researches have been directed towards composite materials development due to good tensile strength, outstanding elastic modulus, good toughness, very good wear resistance, appreciable thermal stability, good corrosion resistance and strength of these composite materials when compared with the based metal or the reinforcing materials (Aldas and Matt, 2005; Mei *et al.*, 2006). The various areas of composite materials usage are consistently increasing and it has been projected that the demand for these materials will be on the increase in an astronomical order (Mathew and Rawlins, 1994).

Aluminium-based metal matrix composites (AMCs) are groups of metal matrix composites (MMCs) that are have proven their usefulness in automobile, aerospace, and structural industries. The reason for the reasonable attraction for metal matrix materials is their good mechanical and tribological properties. which makes them to withstand normal service conditions Senthilvelan *et al.*, 2012. Refractory Materials like SiC, Al_2O_3, and TiC are among the most widely used in the fabrication of AMCs. These refractory materials help tremendously in improving the service performance of Aluminium-based composite, especially with regard to wear and mechanical properties (Singh *et al.*, 2012). Though, most of the reinforcing materials are produced using methods like microwave sintering method (Zhan *et al.*, 2019), chemical vapour deposition (Chen et al., 2019), reactive melt infiltration (Caccia et al., 2018), and thermal plasma (Yao et al., 2014). But these techniques are not easily replicated in most developing nations. So, much dependence on importing these reinforcements at exorbitant costs and high foreign exchange is at the peril of the local market K. K. Alaneme and Olubambi, 2013. In recent times, researchers have directed their interest towards designing low-cost high-performance metal matrix composites making use of industrial waste particles (quarry dust, fly ash, and garnet) to fully or partially compliment the usage of costly synthetic reinforcement materials (silicon carbide and alumina) (Aigbodion, 2010; Macke et al., 2012; Alaneme *et al*., 2014; Ramesh *et al*., 2014).

The use of quarry dust particles (QDp) to develop Aluminium based composites as reinforcement compared to the more commonly use reinforcing materials such as alumina and silicon carbide has gained attraction from many researchers (Zuhailawati *et al.*, 2007).

Aluminium matrix composites are being reinforced using waste products derived from industrial processes (red mud, fly ash, quarry dust) Alaneme, K. K., and Olubambi, P. A. (2013). Corrosion and wear behaviour of rice husk ash—Alumina reinforced Al–Mg–Si alloy matrix hybrid composites.

To develop material property database of high reliability for AMCs recently developed AMCs reinforced with industrial wastes is very important. Most especially in the aspect of materials selection to know the most suitable areas of usage and limits of usage of these AMCs reinforced with industrial wastes. Based on afore-mentioned, there are attempts to get material properties data for a numerous AMCs designed with the use of industrial waste-based reinforcements (Alaneme and Adewuyi, 2013). In this regard, this present work on completion will contribute to the existing database on quarry dust particle as sole reinforcement in AMCs. very few works have been carried out on quarry dust as reinforcer for AMCs and so success in this area can lead to reduction in aluminium composite production cost and also improvement in the mechanical and thermal properties of the alloy (Issam *et al;* 2007).

2. MATERIALS AND METHODS

2.1. Materials

The materials used for this research are aluminium (6063) ingots, quarry dust (QD), set of sieves, borax to serve as wettability agent and crucibles. Aluminium (6063) ingots were commercially sourced from NIGALEX while the quarry dust was sourced from a quarry site in Akure, Ondo State, Nigeria. Borax was obtained from Department of Foundry Engineering Technology, Kogi State Polytechnic Lokoja, Nigeria. The Al6063 alloy was obtained in form of billets and its chemical composition was determined using spark spectrometric analysis.

2.2. Experimental Procedure

The following steps were taken during double stir casting for the production of the composites.

2.3.1. Stir casting

The Al 6063 alloy matrix composites reinforced with selected varying particle sizes of quarry dust were produced using double stir casting process (Alaneme *et al.*,2014). The quantitative amount of quarry dust required to produce 10 wt. % reinforcement consisting of -30+45, -45+60, -60+75 and -75 m was determined using charge calculations. The weight ratios and sample designation are presented in Table 1. The Quarry dust was preheated in an oven separately at a temperature of 250 ˚C for an hour in order to eliminate dampness in the reinforcements and improve wettability with the molten Al 6063 alloy.

Table 1: Formulation table for the composites

Sample designation	**Al 6063 alloy (wt.%)**	**QD (wt.%)**	**Particle size (m)**
X	100	0	-
A	90	10	-30+45
B	90	10	-45+60
C	90	10	-60+75
D	90	10	-75

A gas-fired crucible was used to completely melt the alloy by firing to a temperature of 720 ± 30 °C (above the melting temperature of the Al 6063 alloy billets). The molten liquid alloy was then allowed to cool just below the liquidus to a temperature of about 600 °C, to bring the melt to a semi-solid state. Manual stirring was performed at this temperature for about 2 minutes before charging in the preheated QD particles into the ladle; and the stirring continued for about 5 minutes to ensure homogeneity in the composites. The composite slurry was afterwards superheated to 800 ± 30 °C and a second stirring performed using a mechanical stirrer. The stirring was performed at a speed of 400 rpm for 10 minutes before casting into prepared sand moulds.

2.3.2. Cleaning/ fettling of the castings

All the castings were sand-blasted to remove sand adherence. A locally made blower was used to blow air unto the castings for few minutes to remove sand particles from the castings without affecting their mechanical properties. After this, the sprues were removed using a manual hand saw cutter.

2.3.3. Cut-off and machining operations

These operations were carried out at the machining workshop unit of the Spectral Laboratory Services, Tundunwada LGA, Kaduna State, Nigeria. The cast samples were machined to appropriate shape, size and dimension so as to meet up with the specification for both mechanical and thermal test. The machining was done using a lathe machine and universal polishing machine. Test samples were obtained for hardness, impact energy, tensile properties and micro-structural analysis.

2.3. Materials Testing and Characterization

The techniques/methods for the various sample characterisation were shown below:

2.3.1. Hardness test

Vickers Hardness Testing Machine was used to evaluate the hardness of the composites. Specimens cut out from each composite composition were representative of the bulk samples and polished to obtain a smooth plane surface for proper hardness indentation. A precision diamond indenter was impressed on the material at a load of 100 N for 15 s. In order to avoid segregation effect of the particles, six hardness indents were made on each specimen and readings within the margin of ±2% were taken for the computation of the average hardness values of the specimens.

2.3.2. Tensile test

Tensile tests were performed and evaluated on each composite test sample produced in Figure 1 in accordance with ASTM E8/E8M-15a (2015) standard specifications. The samples for the test were machined to round specimen configurations with 5 mm diameter and 30 mm gauge length. The tensile test was performed at room temperature (25 °C) using Monsanto Tensometer (W-type) operated at a strain rate of 10^{-3} /s. Data and graphs were generated from the machine during the test. The evaluated tensile properties from the stress-strain curve developed from the tensile test are the ultimate tensile strength (σu), the 0.2 % of the set yield strength (σy), and the strain to fracture (ε f).

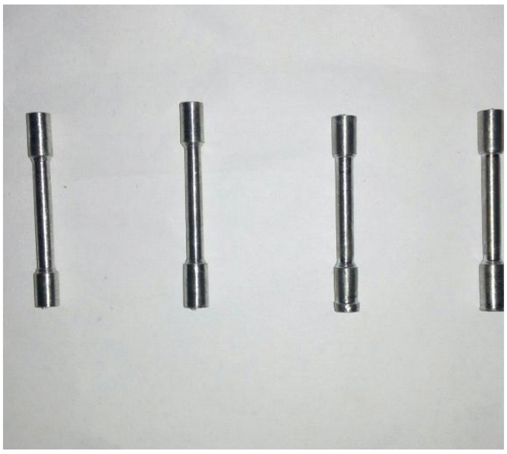


Figure 1: Tensile specimen

2.3.3. Impact energy test

The impact tests were carried out on various composite samples to determine the impact strength using Avery universal impact testing machine. The machine was operated to apply a constant impact force on the test sample. The impact strength (the amount of impact energy the samples absorbed before yielding) was then read off the calibrated scale on the Avery universal impact testing machine.

2.3.4. Thermal conductivity test

The thermal conductivity test was carried out using thermal conductivity meter at operating temperatures ranging from 0 ^{o} to 300 ^{o}C.

2.3.5 Corrosion test

Corrosion test was carried out on the produced composites using Auto - LAB Potentiostat and the samples were investigated in 3.5 wt.% NaCl and 0.5 M H_2SO_4 solution at room temperature using potentiodynamic polarization electrochemical method in accordance with ASTM G57 97 (2014). Three repeat tests were carried out for all composition of the composites to achieve reliability of the results gotten. The results of the corrosion tests were evaluated using Tafel plot extrapolations of the corrosion rate, corrosion current densities (Icorr) and corrosion potentials (Ecorr).

2.3.6. Optical microscopy

The microstructure of the composites was examined using a Zeiss Metallurgical Microscope with accessories for image analysis. After the composite's samples had been machined and cut into a suitable standard shape based on machine specification for various mechanical test, the composite samples were grounded using emery papers of different grades ranging from 220, 320, 400, 800, and 1200 grits respectively. The specimen for the test were metallographically polished using Metkon double disc polishing machine and etched in 10 ml of hydrofluoric, 15 ml of hydrochloric acid, 25 ml nitric acid and 95 ml of distilled water before microscopic examination was performed, Then, the photomicrographs of the composites were captured for analysis.

3. RESULTS AND DISCUSSION

3.1. Chemical Compositions of Aluminium 6063 Composites

The Al6063 alloy selected for this study was procured and its chemical compositions was determined using spark spectrometric analysis as shown in Table 1.

3.2. Mechanical Behaviour of the Composites

The result of the influence of the particle size of the quarry dust on the hardness, tensile properties and impact energy of the Al 6063 matrix composites which were studied are presented in Figures 1 to 4.

3.2.1. Hardness property

From Figure 1, it was observed that there was a marginal decrease in hardness with increase in the particle size of QD in the composites. Sample A (-30+45 m) had the highest hardness of 89.7 VHN among the reinforced composites. Sample B (-45+60 m) had 89.5 VHN with a 2% reduction in hardness, sample C (-60+75 m) had 89.2 VHN showing 2.3% reduction in hardness and Sample D (-75 m) m had 88.6 VHN with 5% reduction in hardness. The unreinforced composite sample X (control) had the highest hardness of 89.9 VHN. This is consistent with what has been reported by numerous other authors (Ahmad *et al.*, 2003; Khairel *et al.*, 2003 and Cerit *et al.*, 2008).

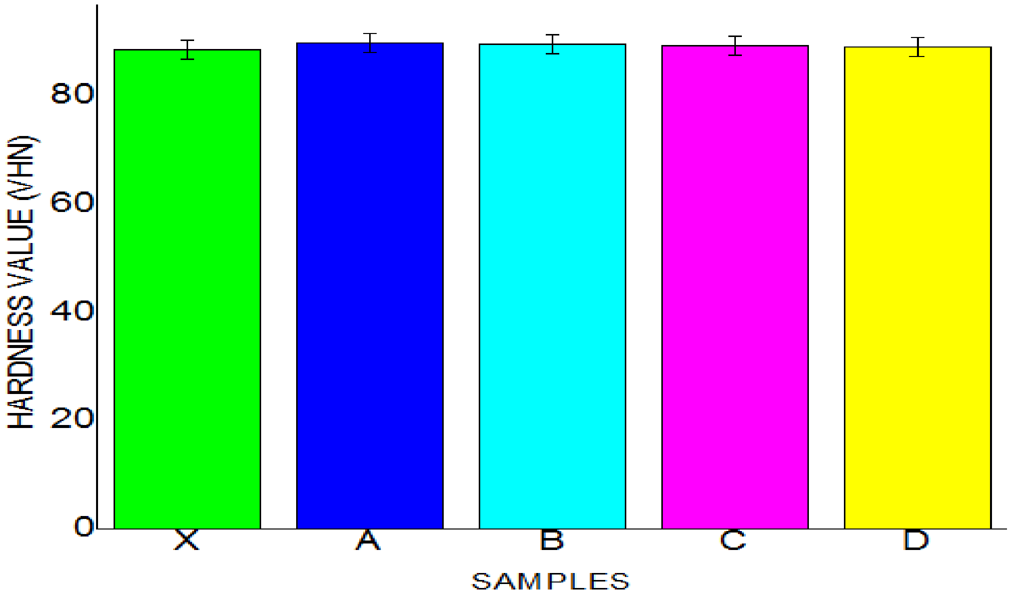


Figure 2: Variation of hardness with particle size of the QD reinforced Al 6063 composites

3.2.2. Tensile properties

The variation of ultimate tensile strength with particle size is presented in Figures 2. It was observed that the ultimate tensile strength decreased as the particle size of the composites increased. Sample A had the highest ultimate tensile strength of 106.20 N/m^2. Ideally, a fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained, since the former has a greater total grain boundary area to impede dislocation motion (Calister, 2001). This means that as the particle size increases, the strength is expected to reduce. However, wettability and porosity level differences can attenuate the ideal expectations. That could account for the higher UTS in sample A than in Samples B, C and D respectively. Reports show that the strengthening mechanism in particle reinforced AMCs is achieved due to load transfer from the matrix to the particles (direct strengthening) and creation of more dislocations which serve as constraints to plastic deformation (indirect strengthening) (Alaneme and Adewale, 2013). The indirect strengthening is achieved by thermal mismatch between the particles and the aluminium matrix arising from their differences in coefficient of thermal expansion. Analysis of the UTS result show that quarry dust as reinforcement can be used in application where tensile strength is critical for selection in service.

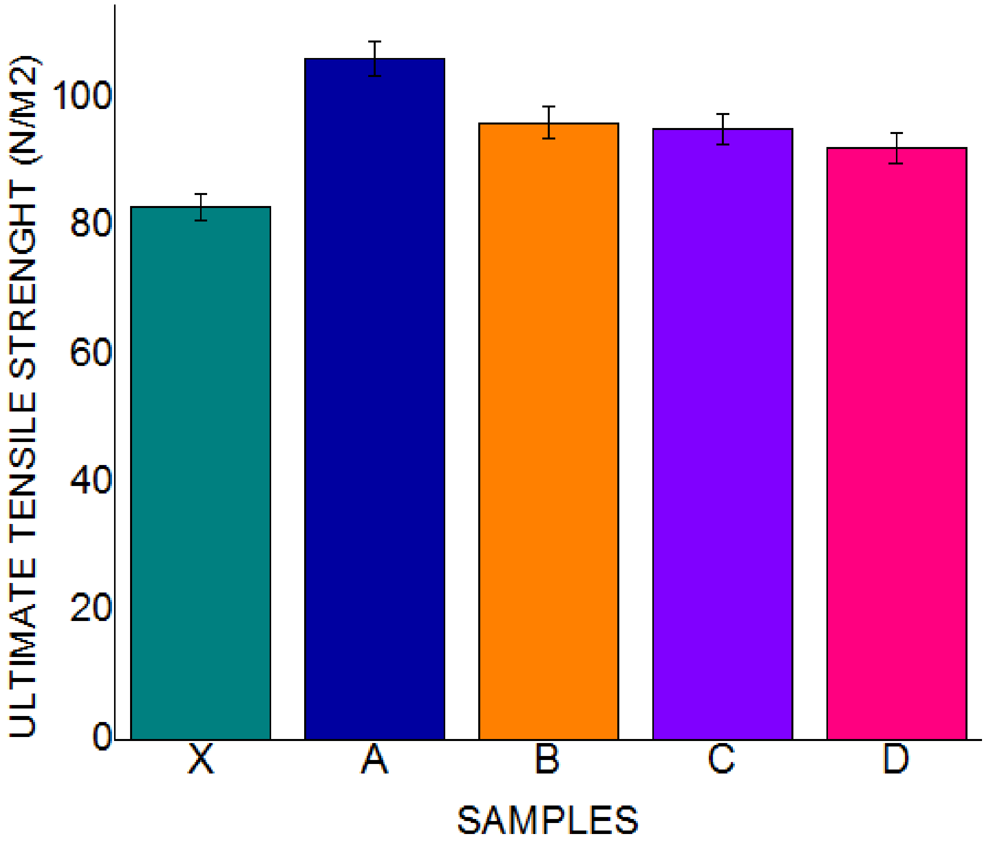


Figure 3: Variation of ultimate tensile strength with particle size of the Q-D reinforced Al6063 composites

3.2.3. Impact property

Figure 4 shows the variation of impact energy of the QD-reinforced Al 6063 composites with particle size. The energy absorbed by the samples before fracture was observed to decrease with increase particle size of QD in the composites. Sample A, B, C and D had impact energy of 10.5 J, 9.0 J, 8.5 J and 7.0 J respectively which may be due to increased particle cracking (Fatile *et al.*, 2014). However, the unreinforced alloy (Sample X) had the highest impact energy recorded to be 12.0 J which may be due to the absence of thermal mismatch between the quarry dust and aluminium alloy. Prasad, D. S., *et.al.*, (2013).

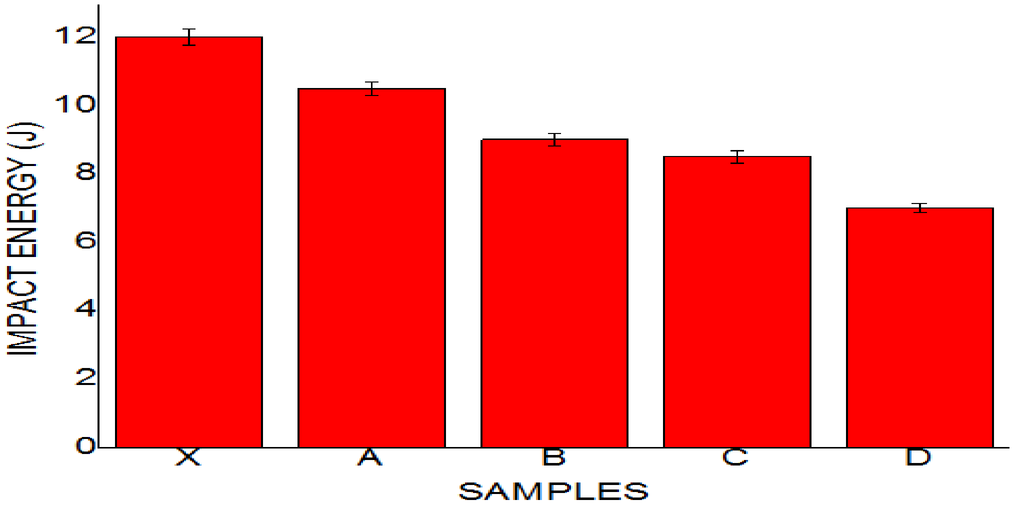
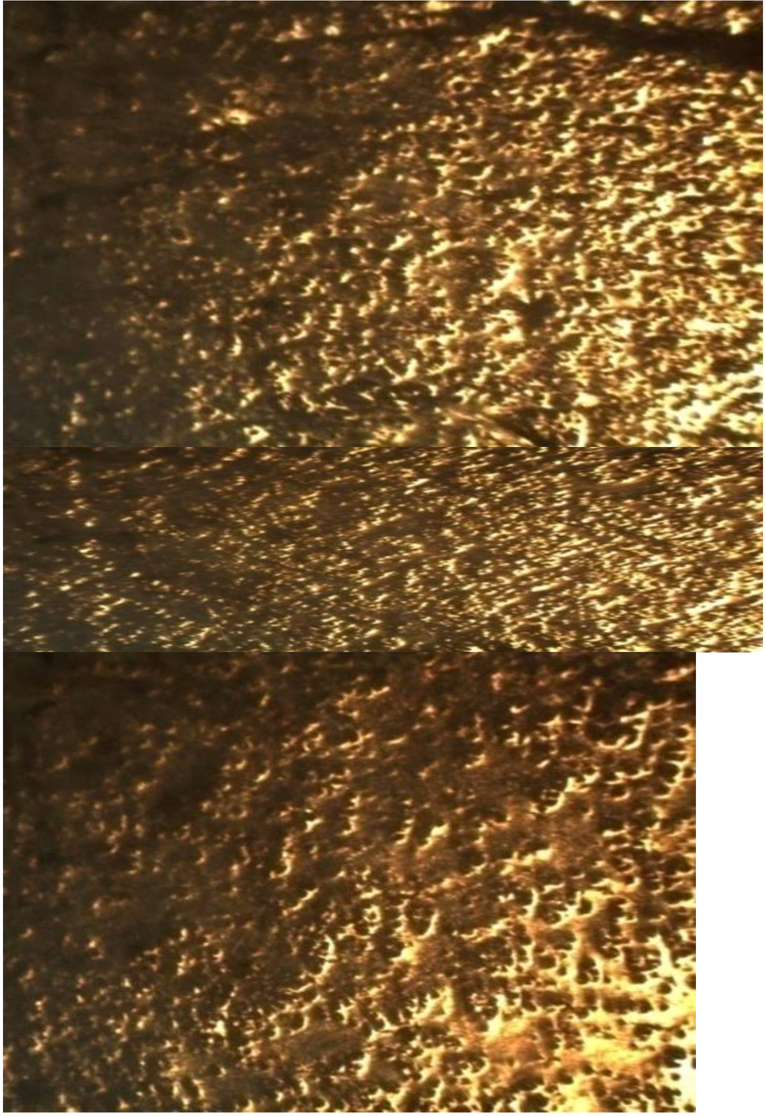


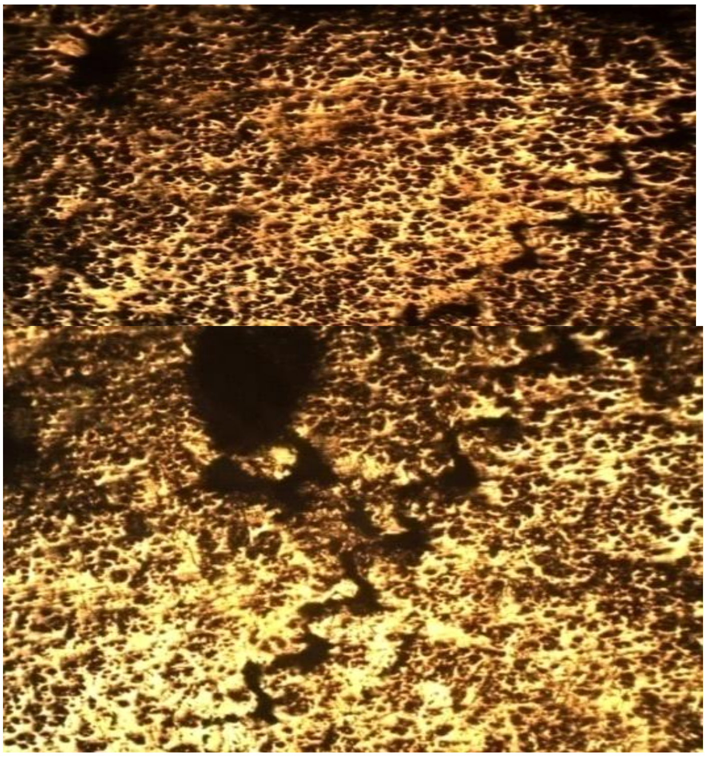
Figure 4: Variation of impact energy with particle size of the QD reinforced Al 6063 composites

3.2.4. Thermal conductivity

The thermal conductivity of the composites produced according to varying temperatures are shown in Figure 5. The thermal conductivity of the composites and the alloy increased with increasing temperature. The addition of quarry dust was seen to decrease the thermal conductivity value of the composite. The unreinforced alloy had higher thermal conductivity 150 W/m.K at 50 °C and increased to 290 at 300 °C. On addition of quarry dust, the thermal conductivity of the composites dropped with sample A having 121 W/m.K at 50 °C and 194 at 300 °C. The particle size also had its effect on the thermal conductivity; as the particle sizes increased, the thermal conductivity increases. Sample B having 120W/m.K at 50 °C and 189 W/m.K at 300 °C showed lower thermal conductivity compared to Sample A. Sample C showed 116 W/m.K at 50 °C and increased to 177 W/mK at 300 °C and sample D had 111 W/m.K at 50 °C and increased to 169 at 300 °C. In line with the observations reported by Ramesh *et al.,* (2014), the reduction in the thermal conductivity of the alloy on addition of quarry dust may be attributed to the scattering of the heat carriers such as electron from the metal alloy and phonons from the non-metal reinforcement. Okumus *et al.*, (2012) explained that the reason for the decrease of the thermal conductivity of the composites with decreasing grain size can be attributed to the interfacial properties between the Al matrix and the quarry dust particles.

Figure 5: variation of thermal conductivities of the composites with temperatures.





3.3. Microstructural Analysis of Reinforced and Unreinforced Composites

The micrographs of the reinforced and unreinforced composites are shown in Plate 1- 5. The micrographs were taken to reveal the appearance of the samples before the corrosion test was carried out on them. The micrograph of unreinforced Al6063 alloy (Plate 4.1) was observed to have uniform distribution of alloy particles. The unreinforced alloy is composed of developed integral dendrite of primary Al-rich phase (α - FCC). Plates 4.2 - 4.4 shows the reinforced Al 6063 composites, which are similar, showing a concealed dendritic grain structures arising from the presence of fairly homogeneous dispersion of the reinforcing particles of quarry dust in Al 6063 alloy. The microstructures show uniform distribution of quarry dust particles even at the same magnification, the micrographs reveal pores on some places as shown in Plate 4.5 while at lower micron size of quarry dust particles, there was increase in interfacial bonding of reinforcement with aluminium alloy matrix.

Table 2: *E*lectrochemical data of Q-D reinforced with Al 6063 composites in 3.5 wt.% NaCl solution

Sample	Icorr (A/cm^2)	Ecorr (mV)	Corrosion rate (mmpy)
X	19.197	-1.152	0.208950
A	9.23	-745.013	0.010047
B	8.1	-914.272	0.088175
C	7.45	-824.101	0.081100
D	5.52	-860.385	0.060087

Table 3: Electrochemical data of Q-D reinforced with Al 6063 composites in 0.5M H_2SO_4 solution

Samples	Icorr (A/cm^2)	Ecorr (mV)	Corrosion rate (mmpy)
X	517.696	-511.558	5.6349
A	410.176	-694.962	4.4646
B	653.677	-670.083	7.1149
C	471.91	-690.329	5.1365
D	320.991	-667.557	3.4938

3.4. Corrosion Behaviour of the Composites

Potentiodynamic polarization curves of the produced composites in 3.5 wt. % NaCl solution is presented in Figure 6a. It was observed that the composites exhibited similar polarization and passivity characteristics. However, there is a notable difference in the corrosion behaviour as can be deduced from the tafel plot extrapolations of the corrosion current densities (I_{corr}) and corrosion potentials (E_{corr}) between the varied particle size. It was observed (Figure 6b) that the corrosion current densities were increasing as the particle sizes of QD increases. This indicates that the composites are more resistant to corrosion in 3.5 wt.% NaCl solution as compared with the unreinforced aluminium alloy. It was observed from Table 2 that the corrosion rates were improved upon due to the addition of QD, suggesting that the passive films formed on the surface of both the unreinforced alloy and the composites are stable and immune to attack when immersed in 3.5 wt.% NaCl environment. That is a clear indication that the composites will be suitable for use in saline environments. Cerrit *et. at.,* (2006).

The potentiodynamic study in 3.5 wt.% NaCl solution shows that a corrosion rate of 0.060087 mm/year was obtained from a sample reinforced with -75 µm QD as shown in Figure 4.6a. In Figure 6b, the potentiodynamic behaviour of the developed composites were studied in 0.5 M H_2SO_4. The results showed that the addition of QD to the Al 6063 alloy shifted the corrosion potential downwards, depicting that quarry dust can also be utilized to inhibit Al 6063 in 0.5 M sulphuric acid environment. However, the highest resistance to the dissociation of the Al 6063 composite system was observed in composite D having the least corrosion rate. This composite had the least corrosion current of 320.991 A/m^2 with corrosion rate of 3.4938 mm/year, as shown in Table 3 and this general poor behaviour of unreinforced and reinforced composites in acidic media had been reported by several authors.

Logarithms of Current Density (A/cm^2)

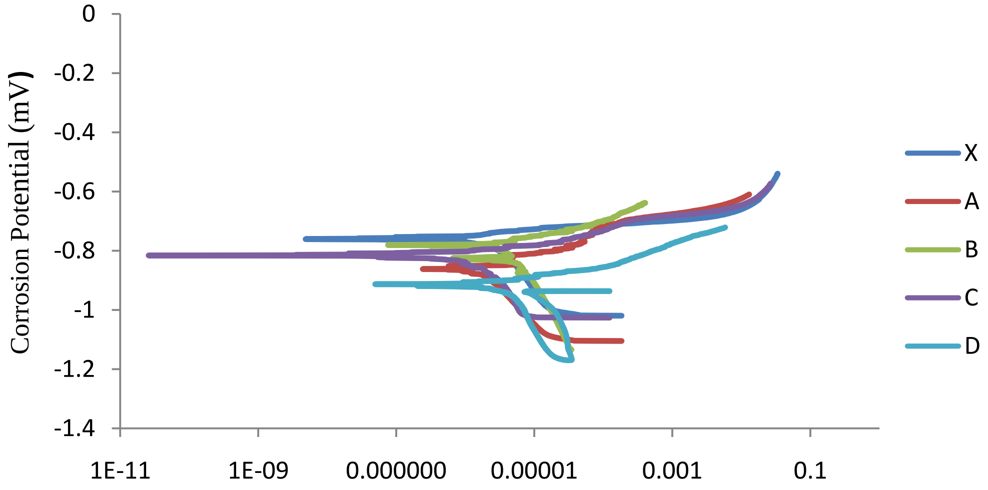


Figure 6a: potentiodynamic polarization curve of QD -reinforced with Al 6063 Composites in 3.5 wt.% NaCl solution

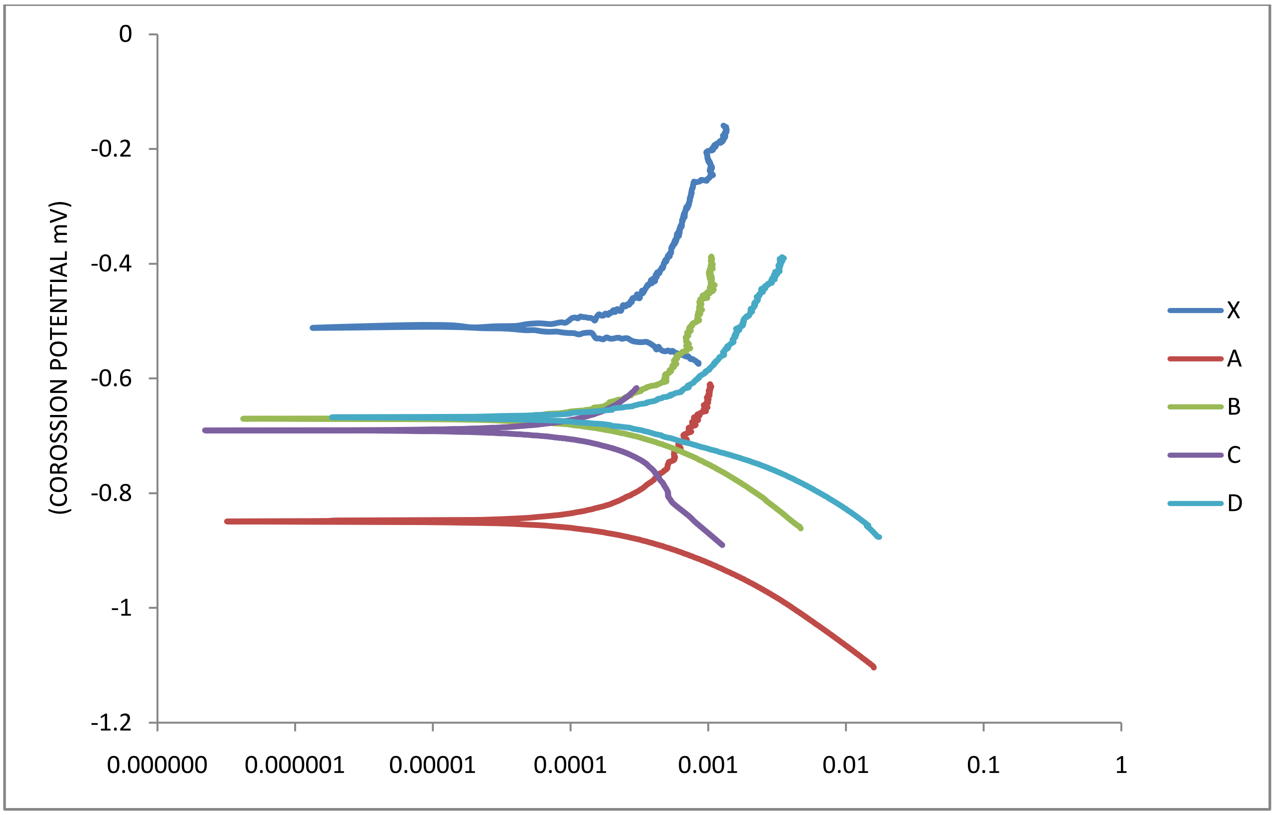


Figure 6b: potentiodynamic polarization curve of QD-reinforced with Al 6063 composites in 0.5 M H_2SO_4 solution

4. **Conclusion**

The following conclusions are drawn within the limit of this research:

- The hardness of the aluminium composites improves generally over the unreinforced alloy and decreases with increasing particle size.
- The tensile strength of the composites showed similar trend with hardness justifying correlation between hardness and tensile strength. The tensile strength also decreased with increasing particle size.

- The elongation of the composites increases as the particle size increases.
- The impact energy of the composites decreases as the particle size increases owing to particle cracking of the produced composites.
- The thermal conductivity for both unreinforced alloy and the composites increased with increasing temperature.
- The corrosion behaviour for all the particle size examined in NaCl environment showed that sample D displayed superior corrosion resistance when compared with unreinforced alloy in 3.5 wt.% NaCl while they all perform poorly in 0.5M H_2SO_4 environment except sample D with the least corrosion rate of 3.4938 mmpy.

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work

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