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INFLUENCE OF DESERT DATE (*BALANITES AEGYPTIACUS*) SHELL PARTICULATES ON THE PHYSICAL AND MECHANICAL CHARACTERISTICS OF A356 METAL MATRIX COMPOSITES

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ABSTRACT

The influence of desert date (Balanites Aegyptiacus) shell particulates on the physical and mechanical characteristics of aluminium matrix composites was studied. Desert date-shell particulates in varied weight percentages were added to molten A356 alloy by stir casting method for the production of the composites. The microstructure of the specimens produced was examined using optical and scanning electron microscopes. Furthermore, physical (density) and mechanical properties (tensile strength, hardness, and impact energy) were evaluated at room temperature. The composition of desert date-shell particulates was determined using an X-ray fluorescence (XRF) spectrometer. The result confirmed SiO_2, to be the major constituent of the desert date (Balanites Aegyptiacus) shell particulates while Al_2O_3, CaO, Fe_2O_3, MgO, and minor oxides were in traces. The microstructure revealed networks of eutectic Si and precipitates of Mg_2Si inter metallic compound in α-A356 matrix with desert dates shell particulates. It also revealed the particle sizes, particles distribution in the matrix and grain boundaries and good bonding of the particulates with the alloy matrix. The density of the composites decreased continuously with increase in desert date shell particles additions. The composite containing 115-µm particulates exhibited the highest tensile strength of 182.52 MPa at 9 wt. % reinforcement, which is 18 % higher than that of the unreinforced cast A356 alloy. It exhibited the highest hardness 85.59 HVF at 12 wt. % reinforcement, which is 22 % higher than that of the unreinforced cast A356 alloy. The composites demonstrated a progressive reduction in impact energy as reinforcement increased.

1. INTRODUCTION

Aluminium alloys are alloys in which aluminium (Al) is the predominant metal. The typical alloying elements are copper, magnesium, manganese, silicon, and zinc. Aluminium alloys are widely used in engineering structures and components where lightweight, or corrosion resistance is required. In particular, A356 alloy is a hypoeutectic aluminium alloy that is used in automotive, aircraft, flow and structural components [1] with appreciable mechanical properties.
Metal alloys are reinforced with other materials in order to develop metal matrix composites (MMCs) with superlative characteristics. Generally, MMCs are produced by dispersing reinforcing materials into the matrix of metals. Production is done by controlling the morphologies of the constituents to achieve optimum combination of properties. The properties of the composites depend on properties of their constituent phases, their relative amount, size, shape, bonding/interaction, and dispersed phase geometry [2]. In particular, aluminium alloys are reinforced with other materials to produce aluminium metal matrix composites (AMMCs). The reinforcing constituents can be integrated within the matrix in the form of particles/particulates, short fibers, continuous fibers or monofilaments [2]. Liquid state processing (stir casting, infiltration, squeeze casting, etc.), semi-solid processing and powder metallurgical route can be used to produce AMCs. Usually, non-metallic and ceramic particles like silicon carbide (SiC), alumina (Al_2O_3), boron carbide (B4C), graphite, carbon nanotubes (CNTs), etc. are used as reinforcements in AMCs. When loads are applied to composites, the metal matrix transfers the loads to the reinforcing materials, which carry the load as they are bonded with the matrix. Hence, good wettability between the reinforcements and matrix is important during casting [3].

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Particles reinforced AMMCs exhibit some superior characteristics over unreinforced materials such as greater strength and high specific modulus, improved stiffness, lightweight, low thermal expansion coefficient, high thermal conductivity, tailored electrical properties, increased wear resistance and improved damping capabilities [2]. These unique characteristics have made AMMCs to find application in numerous areas some of which are aerospace, thermal management areas, industrial products, automotive applications such as engine piston, brake disc etc.

Studies have been conducted on the development and characterisation of AMMCs for possible application in various fields using varieties of materials. Thirumalvalavan and Senthilkumar [4] developed aluminium alloy (LM25) reinforced fused silica metal matrix composites by stir casting method and evaluated the mechanical properties of the composites. The microstructure of the composites revealed a good distribution of the silica (SiO_2) particulates in the aluminium matrix. The tensile strength, hardness, and impact energy of the composites were enhanced compared to the unreinforced alloy. Seshappa et al [2] studied analysis of mechanical characteristics of silicon carbide reinforced aluminium matrix composites developed by stir casting method. The results showed that introducing silicon carbide (SiC) reinforcements in Al matrix increased hardness and tensile strength of the composites. Microstructure revealed clustering and non-homogeneous distribution of SiC particles in the Al matrix. Porosities were observed in microstructures, which increased with increasing wt. % of SiC reinforcements in aluminum matrix composites. Suryakumai et al [3] developed hybrid aluminium metal matrix composites by reinforcing Al7075 alloy with particulates of SiC and Al_2O_3 by stir casting method. The results indicated that micro hardness and tensile strength improved by 34 % and 7 % via heat treatment. Microstructure of the hybrid composites revealed uniform distribution of reinforcements in the matrix. The development of metal matrix composites for application in various fields is ongoing because of their usefulness. Hence, the aim of this study is to examine the influence of desert date (*Balanites Aegyptiacus*) shell particulates on the physical and mechanical characteristics of AMMCs using A356 alloy.

2. METHODS

2.1. Materials, Apparatus and Equipment

The materials used are A356 alloy rod and desert date particulates. The apparatus and equipment used are ball milling machine, furnace, moulding flask, Rockwell hardness tester, impact tester, tensometer, Hounsfield tensile testing machine, lathe machine, X-ray spectrometer, digital weighing machine, optical metallurgical microscope (OPM), scanning electron microscope (SEM), grinding and polishing machine, stirrer, sieves, density bottles and grit papers.

2.2. Materials Preparation

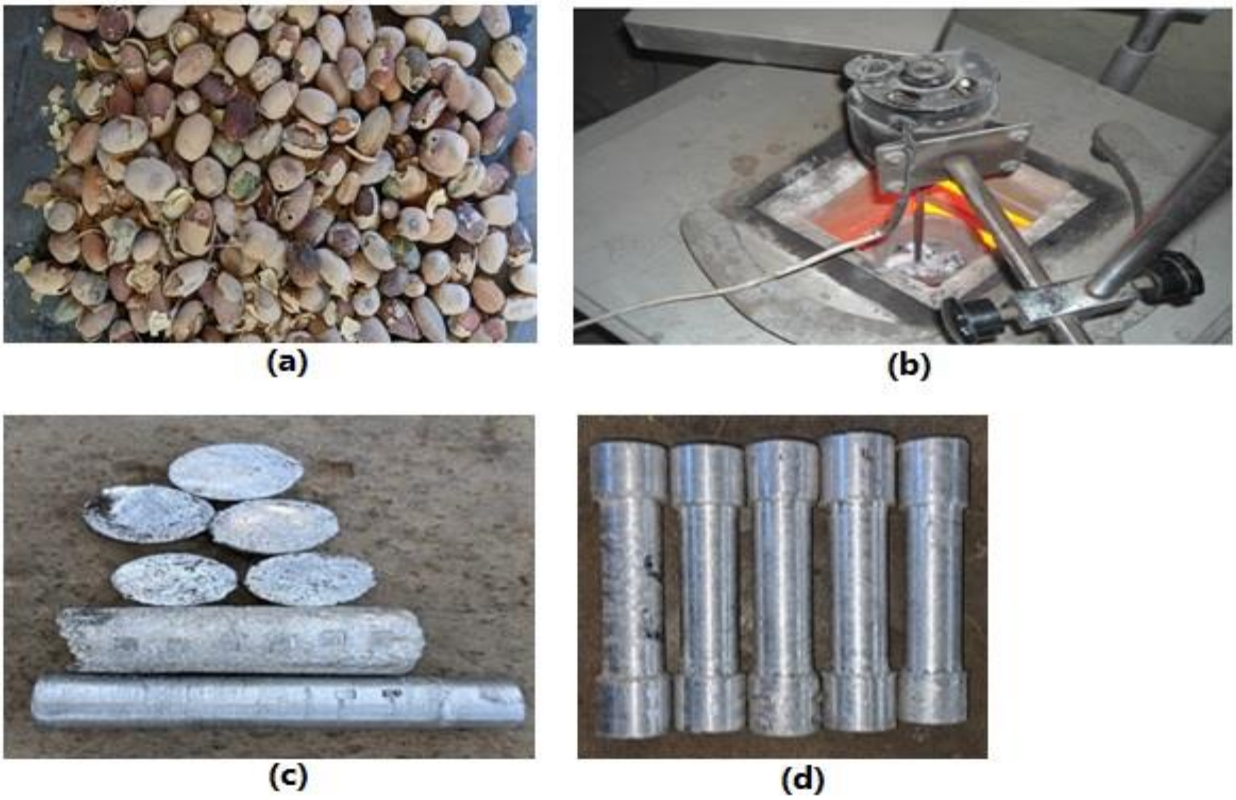


Fig 1. Photograph of materials and melting operation (a) Desert date fruits (b) materials melting and stirring (c) cast specimens for hardness and microstructural tests (d) tensile test specimens

The raw desert date (*Balanites Aegyptiacus*) fruits shown in Fig. 1a were obtained from Durum village of Bauchi State in Nigeria and A356 alloy rods were obtained from Aluminium Industries Limited, Nigeria. The rods were washed with water and dried in order to remove any surface impurity. The melting point of A356 alloy is 610 °C and its density is 2.67 g/cm^3. The desert date shells were soaked for 24 hrs, washed with distilled water, burnt, and crushed using a hand pounder. They were then dried in a furnace at 500 ºC for 20 mins to evaporate possible moisture. The dried specimen was subsequently ground using a ball-milling machine and sieved using British standardised sieves (BSS) to varied sizes (224, 150 and 115 µm). The chemical composition of A356 alloy is presented in Table 1 while that of desert date particulates determined by using a mini pal compact energy dispersive X-ray fluorescence spectrometer is presented in Table 2.

Table 1. Chemical composition of A356 alloy [1]

Element	Si	Mg	Ti	Cu	Zn	Fe	Mn	Al
Weight (%)	6.89	0.26	0.01	0.008	0.002	0.080	0.004	Balance

Table 2. Chemical composition of desert date particulates

Compound	Chemical Formula	Weight (%)	DX
Silica	SiO_2	93.095	6/7
Alumina	Al_2O_3	1.135	14/21
Quicklime	CaO	0.073	17/17
Magnesia	MgO	0.835	16/18
Ferric oxide	Fe_2O_3	0.022	7/12
Others	Minor oxides	Balance	

2.3. Production of the Composites

A356 alloy rod was cut into pieces, weighed and charged into a crucible furnace, which was heated to 720 ºC in order to melt the alloy. Thereafter, appropriate quantities (3 – 15 wt. %) of the desert date particulates (115, 150 and 224 µm) as presented in Table 3 were separately added to the molten aluminium alloy. The mixture was stirred using a stainless-steel stirrer for 10 mins to avoid clustering and to achieve good dispersion of the particles in the molten matrix as shown in Fig 1b. Thereafter, the slurry was steadily poured into a sand mould, which was embedded with a cylindrical pattern of diameter 20 mm and length 150 mm and allowed to cure for one hour. Thereafter, they were removed from the moulds. The casts were prepared and machined to suitable ASTM standard dimensions for the various tests as illustrated in Fig. 1c and Fig. 1d. Prior to the addition of the particulates to the molten alloy, the particulates were preheated to improve wettability and reduce porosity in the cast.

Table 3. Input materials formulation

Desert Date Particulates (115, 150 and 224 µm) (wt. %)	A356 Alloy (wt. %)
0	100
3	97
6	94
9	91
12	88
15	85

2.4. Microstructural Examination

The specimens for metallographic examination were cut to the appropriate sizes and mechanically ground using SiC grit papers (320 to 800 grit size) and polished. Thereafter, they were washed with distilled water and etched using 0.5 % hydrofluoric acid solution. The microstructure of the desert date particulates was examined using a scanning electron microscope (SEM) while that of the as cast alloy and composites was examined using an optical microscope.

2.5. Physical and Mechanical Properties Determination

The density of each specimen was determined by measuring the mass and volume of the specimen used. The weight of each specimen in air was recorded. Thereafter, they were separately immersed in water and the volume of the water displaced was recorded (Archimedes' Principle). The density was calculated using Eq. (1).

$$\rho = \frac{m}{v} \quad (1)$$

Where,

ρ = density (g/cm^3), m = mass (g), and v = volume (cm^3).

The tensile strength of the as cast alloy (unreinforced) and as cast composites was determined using a universal tensile testing machine of maximum test load of 5,000 kg and gear rotational speed of 1.5 mm/min in accordance with the ASTM E8 standard. Each of the specimens was machined appropriately and was tightly locked between the upper and lower cross beams of the machine. The load was applied to set the specimen in the grips. The applied load was increased gradually until necking and subsequently fracture occurred. The same procedure was applied for all the specimens. The maximum load was determined for each of the specimen and the tensile strength was calculated using Eq. (2).

$$P_{UTS} = \frac{P_{max}}{A_0} \quad (2)$$

Where,

P_{UTS} = ultimate tensile stress

P_{max} = maximum load

A_0 = cross sectional area

Some of the cast specimens were machined to dimension 25 x 25 x 6 mm. Their surfaces were smoothened, and they were used for hardness test. Their hardness was determined in accordance with ASTM E18 standard using a Rockwell hardness-tester with F scale and 116-inch indenter made of steel ball. The indenter of minor load 10 kg (fixed) and a major load of 60 kg was applied. Three readings were taken for each specimen and their average value was recorded. The impact energy of the specimens of dimension 55 x 10 x 10 mm with a V-notch of 2 mm depth at the middle was determined in accordance with ASTM E23 standard using a Charpy impact tester. Each of the specimens was placed vertically in-between the grips of the testing machine and clamped into position The pendulum's angle, weight, impact energy and striking velocity of 140^0, 22 kg, 300 J and 5 m/s respectively were used to break the specimen.

3. RESULTS AND DISCUSSION

3.1. Density of the Composites

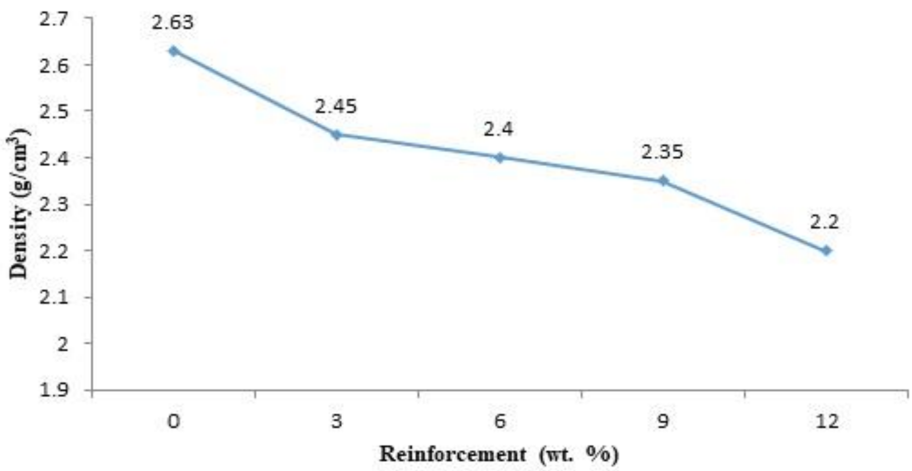
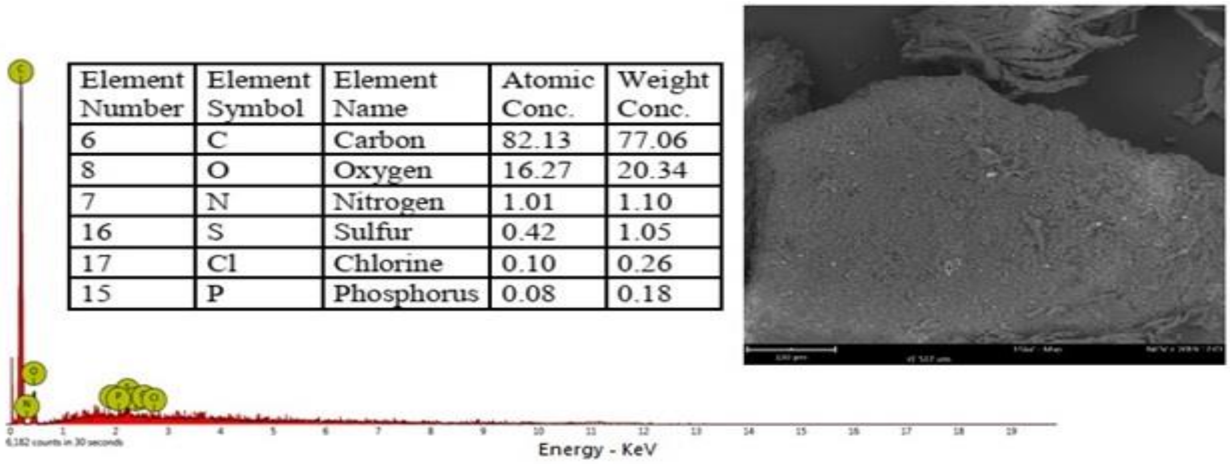


Fig 2. Density of the as cast alloy and composites with varying wt. % of desert date particulates

The density of the composites decreases with increase in the concentration of the desert date particulates in the matrix as presented in Fig. 2. This may be because the matrix is denser than the reinforcement, which agrees with the report by [5].

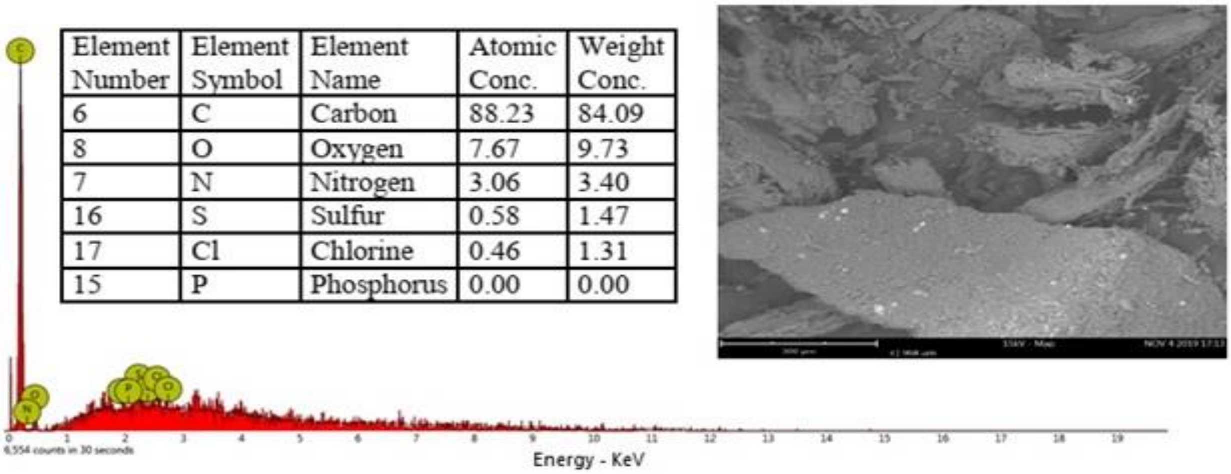
3.2. Microstructure

The microstructures show that the reinforcement (desert date) contains irregular shaped particulates as shown by the SEM images in Fig. 3 and the presence of C, O, N, S, Cl and P as revealed by the energy-dispersive spectroscopy (EDS) spectra.



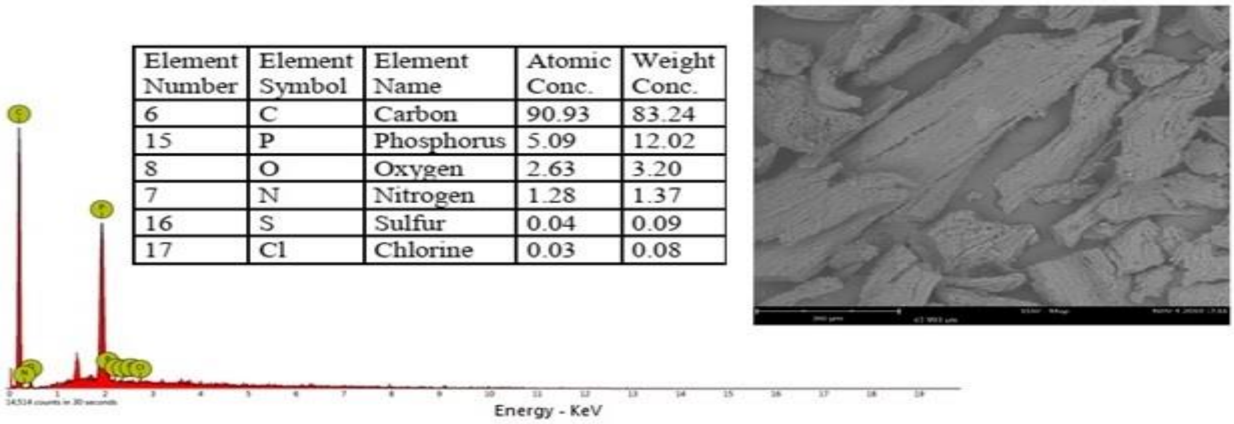
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	82.13	77.06
8	O	Oxygen	16.27	20.34
7	N	Nitrogen	1.01	1.10
16	S	Sulfur	0.42	1.05
17	Cl	Chlorine	0.10	0.26
15	P	Phosphorus	0.08	0.18

(a)



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	88.23	84.09
8	O	Oxygen	7.67	9.73
7	N	Nitrogen	3.06	3.40
16	S	Sulfur	0.58	1.47
17	Cl	Chlorine	0.46	1.31
15	P	Phosphorus	0.00	0.00

(b)



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	90.93	83.24
15	P	Phosphorus	5.09	12.02
8	O	Oxygen	2.63	3.20
7	N	Nitrogen	1.28	1.37
16	S	Sulfur	0.04	0.09
17	Cl	Chlorine	0.03	0.08

(c)

Fig 3. SEM images and EDS spectra of desert date particulates (a) 115-μm (b) 150-μm (c) 224-μm

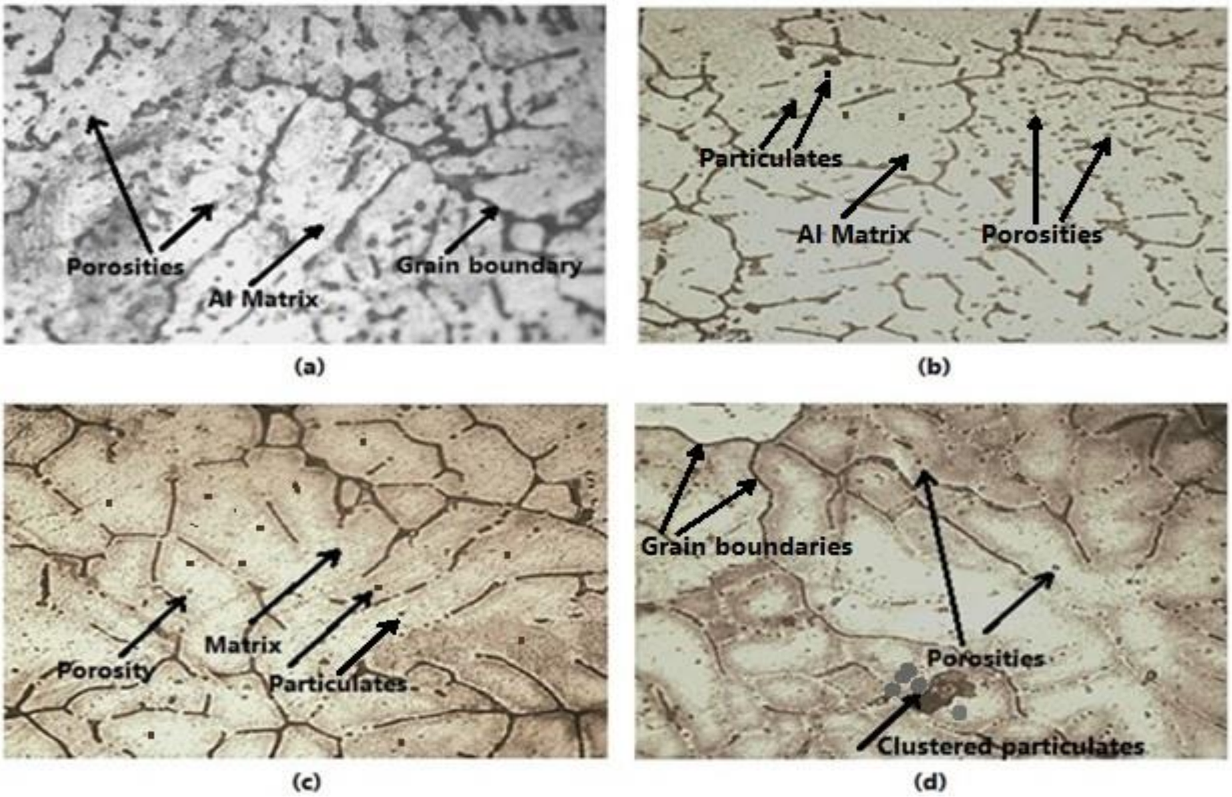


Fig 4. Optical micrographs of as casts (a) A356 alloy (b) 3 wt. % 115-μm desert date reinforced aluminium matrix composite (c) 12 wt. % 115-μm desert date reinforced aluminium matrix composite (d) 15 wt. % 115-μm desert date reinforced aluminium matrix composite (100X magnification)

The optical micrographs of the as cast specimens are shown in Fig. 4(a) to 4(d) with some degrees of porosity in them. This is because when desert date particulates were added to the melt during casting, it introduced air into the melt, which were entrapped between the particles. Hence, increasing weight percentage of desert date particulates increased entrapped air, which resulted in increased porosity. All the micrographs in Fig. 4(a) to 4(d) show the presence of silicon flakes in the matrix of Al-Si dendrite, which is characteristic of unmodified eutectic solidification of an Al-Si system. The dark lines in Fig. 4(a) to 4(d) represent the grain boundaries. In Fig. 4(a), the microstructure reveals networks of eutectic Si and precipitates of Mg_2Si inter metallic compound in α-A356 matrix. In Fig. 4(a) to 4(d), the presence of desert date particulates and networks of eutectic Si and precipitates of Mg_2Si inter metallic compound in α-A356 matrix are revealed. The amount of desert date particulates is seen from the increasing darkness of the grain boundaries. When the concentration of desert date particulates is more than 12 wt. %, there is clustering/agglomeration of the particulates in the matrix as shown in Fig. 4(d), but the particulates are well distributed in the matrix as shown in Figs. 4(b) and 4(c).

3.3. Tensile Strength of the Composites

Fig 5. Tensile strength of the as cast alloy and composites with varying wt. % of desert date particulates

The composites demonstrated increase in tensile strength as the concentration of desert date particulates increased in the matrix up to 9 wt. % as presented in Fig. 5. Influence of the size of the desert date particulates on the tensile strength of the composites can be seen as the composite containing 115-µm particulates exhibited the highest tensile strength of 182.52 MPa at 9 wt. % reinforcement. This is 18 % higher than the tensile strength (154.47 MPa) of the unreinforced cast A356 alloy. Small size particles enhance densification, which in turn enhance the mechanical properties better than coarse particles of the same concentration [6]. Increase in tensile strength of the AMMCs can be because of the applied tensile load transfer to the strongly bonded particulates in A356 matrix, increased dislocation density near matrix-reinforcement (particulates) interface, and grain refining strengthening effect, which agrees with the report by [2]. The matrix phase (A356 alloy) strength was enhanced by the addition of particulates based on the principle of solid solution strengthening mechanism. This is in line with the mechanisms by which dislocations cause change in mechanical properties, which are strengthening by grain size reduction, solid solution alloying and strain hardening [7, 8].
Generally, good dispersion of the particulates in the matrix, reduced porosity and strong bond between the reinforcing particles and molten alloy matrix enhanced the tensile strength of the composites. This agrees with the report by [1, 9]. The decrease in the tensile strength beyond 9 wt. % reinforcement may be due to reduction in space between the particles, which enhanced stress raiser/riser that interrupted the distribution of stress in the composite. This agrees with the report by [10]. The decrease in tensile strength could also be due to clustering/agglomeration of desert date particulates (as evident in Fig. 4d) and cooling rate of the castings [11]. The decrease in tensile strength also agrees with the report by [1].

3.4. Hardness of the Composites

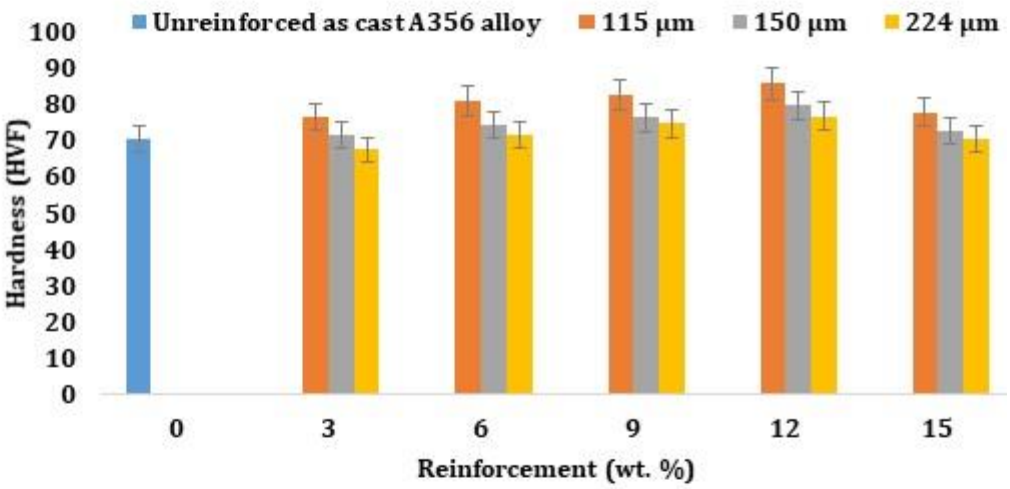


Fig 6. Hardness of the as cast alloy and composites with varying wt. % of desert date particulates

The hardness of the composites increased with increased addition of desert date particulates as illustrated in Fig. 6. As shown in Table 2, the desert date particulates contains SiO_2, Al_2O_3, CaO, MgO, and Fe_2O_3, which are hard ceramic materials that exhibit very good resistance to abrasion and/or indentation. In addition, hardness of composite materials is directly proportional to the quantity of integrated hard particles [12]. The presence of hard and well-bonded desert date particulates in Al matrix, which impeded or restricted the movement of dislocations, increased hardness of the aluminium metal matrix composites (AMMCs). This agrees with the report by [2]. The direct increase in hardness with increase in silica (SiO_2) rich reinforcement agrees with the report by [13] on reinforcement of aluminium-based composites with fly ash, which also at a certain percentage began to decline.
Influence of the size of the desert date particulates on the hardness of the composite can be seen as the composites containing 115 µm particulates exhibited the highest hardness 85.59 HVF at 12 wt. % reinforcement. This is 22 % higher than the hardness (70.15 HVF) of the unreinforced cast A356 alloy. Small size particles enhance densification, which in turn enhance the mechanical properties better than coarse particles of the same concentration [6]. Dada and Ajibola [14] also reported progressive increase in hardness with increased wt. % of agro reinforcement. The increase in hardness could be because of the good dispersion of the particulates in the matrix, reduced porosity and strong bond between the reinforcing particles and molten alloy matrix. This agrees which agrees with the report by [1, 9].
The increase in hardness with decrease in particle size can be due to the greater wettability and strong interfacial bonding achieved through surface area increase of the particles leading to good interaction with the molten alloy matrix. Beyond 12 wt. % reinforcement, the hardness decreased which could be due to the presence of much more reinforcing particles than can be held by the reinforcement which will inevitably result in casting imperfections like blow holes and porosities. The behaviour of the composites also agrees with the report by [15] on increase in hardness with reinforcement and drastic decrease at higher reinforcement.

3.5. Impact Energy of the Composites

Fig 7. Impact energy of the as cast alloy and composites with varying wt. % of desert date particulates

The composites demonstrated a progressive decrease/reduction in impact energy as reinforcement increased as shown in Fig. 7. The 115-µm particulates reinforced composites exhibited the highest impact energy of 492.48 kJ/m^2 at 3 wt. % reinforcement. The decrease in impact energy may be due to the presence of hard constituents of desert dates. High content of the hard and brittle reinforcing materials contributed to the brittle nature of the composites. This agrees with the report by [16]. As the reinforcement increased in the matrix, particles were no longer isolated in the ductile α-Al matrix. Hence, cracks were not arrested by the ductile matrix and gaps propagated easily between the silica-based particulates leading to reduced ability to absorb impact energy. The decrease in impact energy could be because of the fact that higher percentage of hard reinforcement may increase preference of grain segregation on impact for ductile matrices, which will consequently lead to snappy crack formation and ultimate rupture. This pattern of decrease in impact energy conforms to the report by [15] on increase in impact energy and drastic decrease at higher percentages of reinforcement.

4. CONCLUSIONS

In this experimental study, aluminium metal matrix composites (AMMCs) of varying desert date (*Balanites Aegyptiacus*) particulates (0, 3, 6, 9, 12 and 15 wt. %) were developed by stir casting method and were characterised. The result confirmed SiO_2, to be the major constituent of the particulates while Al_2O_3, CaO, Fe_2O_3, MgO, and minor oxides were in traces. The microstructure revealed Mg_2Si and eutectic Si in α-Al matrix with the particulates. It also revealed the size and distribution of the particulates in the alloy matrix with grain boundaries and good bonding of the particulates with the matrix. The density of the composites decreased continuously with increase in particulates addition. The composite containing 115-µm particulates exhibited the highest tensile strength of 182.52 MPa at 9 wt. % reinforcement, which is 18 % higher than that of the unreinforced cast A356 alloy. It exhibited the highest hardness 85.59 HVF at 12 wt. % reinforcement, which is 22 % higher than that of the unreinforced cast A356 alloy. The composites demonstrated a progressive reduction in impact energy as reinforcement increased.

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