Visual Abstract

The influence of sustainable reinforcing particulates on the density, hardness and corrosion resistance of AA 6063 matrix composites

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ABSTRACT. The need for the fabrication of sustainable aluminium matrix composites (AMCs) is being sought after as practical alternatives to conventional metals and their alloys. This study was undertaken to investigate the effect of sustainable materials on the mechanical, physical and corrosion resistant properties of AA 6063. The weight fraction of the hybrid reinforcements was varied at 2.5, 5.0, 7.5 and 10.0 wt.%. For each variation, the fly ash and eggshells were weighed equally. The fabrication route selected was stir casting. The analysis of the density showed that the property decreased with increasing weight fraction of the hybrid reinforcements. Evaluation of the microhardness revealed hardness values of 78.13, 81.19, 81.54, 82.14, and 86.71 HV for the base metal, 2.5, 5.0, 7.5 and 10.0 wt.% samples respectively. The corrosion resistant properties were studied in 3.5 wt.% NaCl medium. The investigation showed that the reinforced AMCs exhibited improved corrosion resistance compared to the base metal. However, the 7.5 wt.% sample exhibited the least corrosion rate of 8.649 X 10^{-5} g/h.

KEYWORDS. AMCs; Aluminium; Sustainable materials; Fly ash; Eggshells.

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INTRODUCTION

The ever-growing need for the fabrication of AMCs at lower cost while retaining the improvements in mechanical and physical properties has remained a conscious effort by researchers. AMCs are rapidly replacing monolithic metals and their alloys in several industrial applications due to improvements in their strength, stiffness, corrosion and wear resistance [1]. Current applications of AMCs include aerospace, automobile and marine equipments [2]. Research over the last few decades have identified price as a major hinderance to the fabrication and application of AMCs due to the high costs associated with the reinforcing phases [3]. Ononiwu et al [4] also highlighted that environmental sustainability is a major sentiment being shared by researchers in the fabrication of AMCs. This reason has led to the incorporation of certain materials into the fabrication of composites either as replacements for the existing synthetic reinforcements or as a combination with synthetic reinforcements. The sustainable materials being applied as reinforcing phases of AMCs are categorized based on their origins. The classifications have been identified as industrial (e.g. fly ash and red mud) [5] and agricultural wastes (e.g. rice husk, eggshells, and coconut shells) [6]. In addition to the environmental impact of the methods of disposal of these waste materials, cost and availability, further studies of these materials have highlighted the presence of oxides, nitrides and sulphides which are excellent ceramics utilized in the fabrication of AMCs.

Among these sustainable materials, fly ash and eggshells have been considered as possible reinforcements for the fabrication of aluminium matrix composites. This is because of their low density [7], hardness [8], availability [9] and cost [10]. In light of these merits, researchers including Ononiwu et al [11], Idusuyi et al., [12] and Dwivedi et al [13] have successfully utilized these sustainable materials to reinforce aluminium alloys. Fly ash and eggshells are both waste products that currently constitute environmental issues due to the lack of adequate disposal means. As these waste materials are not bio-degradable, their disposal is primarily done by dumping in landfills. This method of waste management has been shown to be detrimental to the environmental ecological system. As a result, the reuse of these waste materials has been proposed to perform the functions of environmental cost savings. Several researchers have successfully fabricated aluminium reinforced with fly ash and eggshells either as binary or ternary composites. Such researches include that conducted in [14] which investigated the effect of fly ash on the mechanical properties of AA 1050. Improvements of 11.04% and 31.90% on the tensile and compressive strength respectively was reported. Al-Zn reinforced with fly ash and SiC was fabricated by Kanth et al. [15]. The results indicated uniform dispersal of the reinforcements in the aluminium matrix. The analysis of the density showed a decline with increased weight fraction of fly ash. The hardness improved by 22.5%. The authors also reported improvements in the tensile strength of the fabricated composites compared to the base metal. Dwiwedi et al. [16] investigated the influence of eggshells on the wear behaviour of AA 6061. The results showed that the coefficient of friction (COF) of the cast composite was significantly lower compared to that of the base metal indicating improved wear resistance. The potentiodynamic polarization studies of AA 6063 reinforced with eggshells was conducted by Ononiwu et al [17]. The investigation revealed a decline in the corrosion rate (4.08×10^{-8} g/h) compared to the base metal (5.53×10^{-6} g/h). This is indicative of improved corrosion resistance brought about by the utilization of the reinforcements.

The reviewed literature indicates the prospects of fly ash and eggshells as reinforcing phases for fabricating aluminium matrix composites. From the reviewed literature, minimal considerations have been made towards the prospects of utilizing hybrid waste reinforcements for the fabrication of AMCs. This work selected these reinforcing particles from the 2 different classes of waste materials used in the fabrication of AMCs. This work examined the effect of fly ash and eggshells on the physical, mechanical properties and corrosion resistance of AA 6063.

MATERIALS AND METHODS

For this study, stir casting was selected as the fabrication route. This liquid metallurgy method was selected due to its simplicity, ability to produce parts with complex geometries and cost [18]. The elemental composition of the aluminium alloy shown in Tab. 1 was obtained via mass spectrometry.

Composition	Mn	Ti	Fe	Cr	Cu	Zn	Cr	Mg	Al
%	0.02	0.02	0.07	0.14	0.45	0.60	0.14	1.02	97.18

Table 1: Elemental composition of AA 6063.

The quantitative analysis of reinforcements was done using X-ray diffractometry to obtain their respective constituents. These are summarized in Tab. 2 and 3 according to Ononiwu et al [19].

Constituent	Calcium	Aragonite
Percentage (%)	13.67	86.33

Table 2: Quantitative analysis of the eggshell.

Constituent	Mullite	Quartz	Hematite	Alumina	Wustite
Percentage (%)	50.63	41.05	4.23	3.25	0.65

Table 3: Quantitative analysis of the fly ash.

The designations of the fabricated samples are summarized in Tab. 4.

S/No	Designation	Eggshell wt.%	Fly ash wt.%	Total wt.%
1	A	-	-	0
2	B	1.25	1.25	2.50
3	C	2.50	2.50	5.00
4	D	3.75	3.75	7.50
5	E	5.00	5.00	10.00

Table 4: Designation of the cast samples.

A ball milling machine, rotating at 180 rpm, was used to reduce particle sizes of the fly ash and eggshell samples. For both reinforcements under consideration, the milling period was set to 7 hours to achieve an average particle size of 75 μm. The eggshells were then carbonized to increase carbon content, decrease moisture content, and improve wettability between the matrix and dispersion phase [20]. The reinforcement percentages were varied at 0, 2.5, 5.0, 7.5, and 10.0 wt.%. Carbonized eggshells and fly ash were used in equal amounts in each variation of the reinforcements. The supplied AA 6063 sheets were then cut and weighed before being charged into the graphite crucible to fabricate the composites. To begin the melting process, the furnace's temperature was raised to 760 °C. The reinforcements were preheated at 400 °C for 1 hour before being introduced into the molten aluminium to promote interfacial bonding with the matrix. The preheated reinforcements were then introduced into the molten matrix. To achieve appropriate dispersion of the reinforcements in the aluminium matrix, the molten mix was stirred in two stages. The first stage of stirring took place after the reinforcements were charged into the molten matrix, while the second stage took place before casting the AMC into the prepared sand mould. For both stirring stages, the mechanical stirring was done for 10 mins. The experimental setup and cast cylindrical bars are shown in Fig. 1.

The densities of the fabricated samples were measured using the Archimedes principle. The mass of the fabricated AMCs and the volume of displaced water in the measuring cylinder were measured. Using the expression in Eqn. 1, the density of the samples under considerations was obtained.

$$D_e = \frac{m}{\Delta v} \tag{1}$$

where D_e is the density in g/cm^3, m = mass of the sample, and Δv is the volume of water displaced. To calculate the porosity of the samples, the theoretical densities of the cast samples were obtained using the rule of mixtures shown in Eqn. 2. The theoretical density was in turn used to obtain the porosity using the expression in Eqn. 3.

$$D_t = D_m\left(w_m\right) + D_f\left(w_f\right) + D_{es}\left(w_{es}\right) \tag{2}$$

where D_t is the theoretical density of the composite sample, D_m is the density of the matrix, w_m is the weight fraction of the matrix, D_f is the density of the fly ash, w_f is the weight fraction of the fly ash, D_{es} is the density of the eggshell and w_{es} is the weight fraction of the eggshells.

With the aid of the theoretical densities of the fabricated samples, the porosity was obtained using the expression in Eqn. 3.

$$P = \left(1 - \frac{D_e}{D_t}\right) \times 100\% \qquad (3)$$

where P is the percentage porosity of the cast AMC.

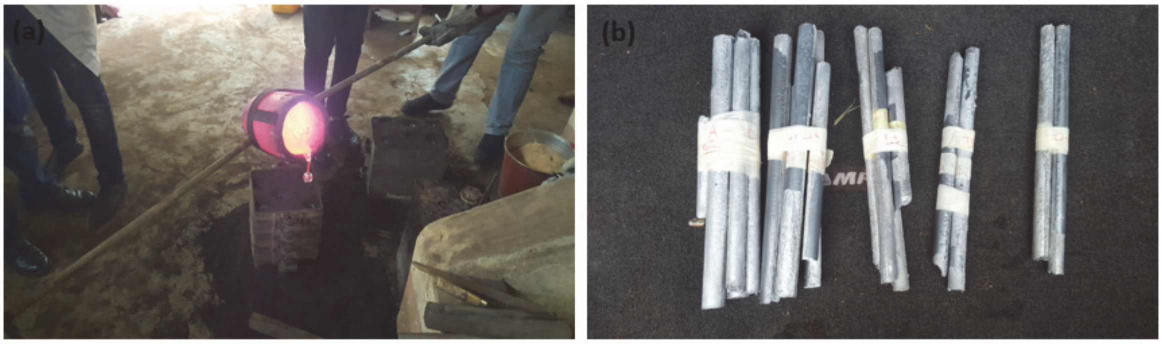

Figure 1: (a) Casting of the samples (b) Cylindrical rods

The microstructure of the fabricated AMC samples was studied using the TESCAN model type VEGA LMH scanning electron microscope. The samples were cut to reveal their cross-sections, cleaned, ground and polished prior to the commencement of the metallography studies. Etching of the prepared samples was done in Keller's reagent for 30 second to reveal their grain structure.

The surface of the samples was cleaned and polished prior to the microhardness measurement to guarantee accurate readings. During the microhardness measurement of the samples, 5 indentations 1mm apart were created. A test force of 300 gF (200 N) was applied to each indentation for a dwell duration of 15 seconds.

The influence of the reinforcements on the corrosion resistance properties of the samples under examination was investigated using potentiodynamic polarization tests. For the experiment, 10 mm X 10 mm cylindrical specimens were used. All samples were cold mounted and ground with 320, 500, 1200, and 4000 SiC emery sheets. The ground samples were cleaned with distilled water, degreased in acetone, and dried in the open air. These efforts were taken to ensure that the electrochemical processes were carried out accurately and with minimal interference. The electrochemical analyser from HCH Instruments was utilized for the potentiodynamic polarization tests, which included a silver/silver chloride reference electrode and a graphite counter electrode. The study's polarization range was -0.5 to 0.5 V, and the scan rate of 0.01 V/s.

RESULTS AND DISCUSSION

Microstructure Tables

The optical micrograph of the base metal (refer to Fig. 2a), indicates the presence of interconnected coarse grains comprised of an array of intermetallics including $Al_{12}Mg_7$, $AlFe_2Mn$, Mg_2Si [21]. Evaluation of the SEM micrographs of the fabricated hybrid AMCs revealed uniformly dispersed reinforcements in the AA 6063 matrix. This was the consequence of the utilization of the 2-step stirring technique described earlier. The level of dispersion of the fly ash and eggshells particles could also be attributed to the proper wettability and interfacial bonding between the matrix and hybrid reinforcements.

Also evident from the SEM micrographs was the presence of micro voids. This situation often characterized with stir casting is caused by the presence of trapped gases formed during the solidification of the cast AMCs [19,20]. Further evaluation of the micrographs shows the presence of agglomerations of the eggshell particles with increasing weight fraction oof the reinforcements. This is a result of the increased viscosity brought about by the increasing weight fraction of the reinforcements.

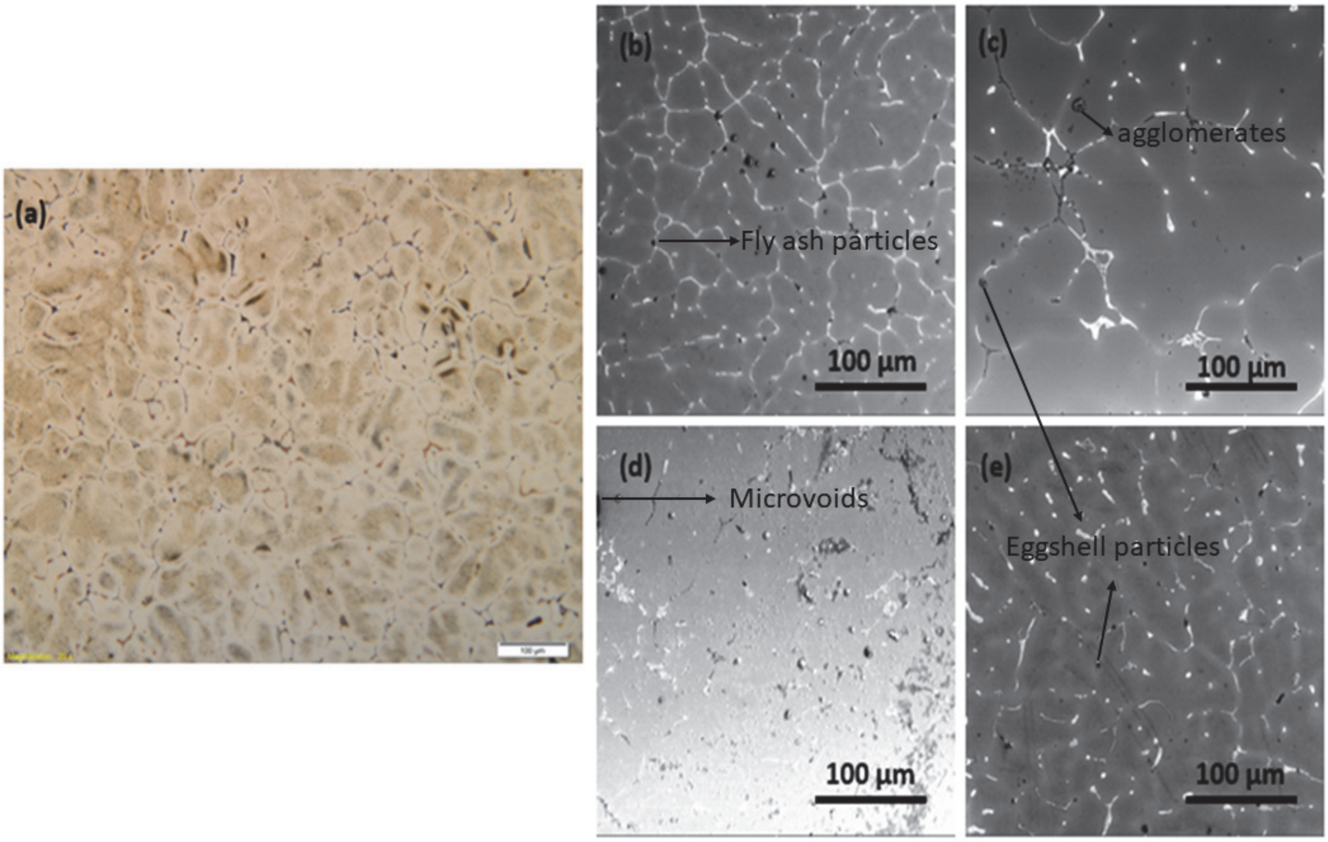

Figure 2: (a) Optical micrograph of AA 6063 (b) SEM micrographs of sample B (c) SEM micrographs of sample C (d) SEM micrographs of sample D (e) SEM micrographs of sample E

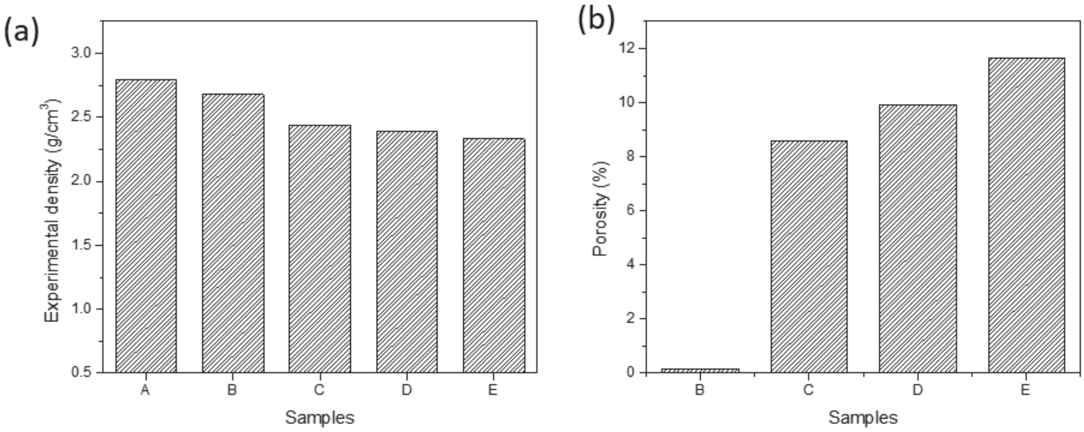

Figure 3: (a) Experimental density of the cast samples (b) Percentage porosity of the cast AMCs

Density and Porosity

The Archimedes principle was utilized in this study to evaluate the density of the resulting composites. As depicted in Fig. 3a, the analysis of the experimental density revealed a decline with increasing weight fraction of both reinforcements. This suggests that using the hybrid materials to reinforce the aluminium alloy is capable of producing lightweight AMCs. The analysis of the porosity depicted in Fig. 3b indicated that the porosity increased with increasing weight fraction of the hybrid reinforcements. This was already outlined in the description of the microstructure was a result of the increased viscosity, agglomeration and formation of pores formed during the solidification of the AMCs during cooling.

Hardness

The microhardness of the cast samples was studied to examine their behaviour under the application of localized load. Fig. 4 indicates that the microhardness improved with increasing weight fraction of both reinforcements.

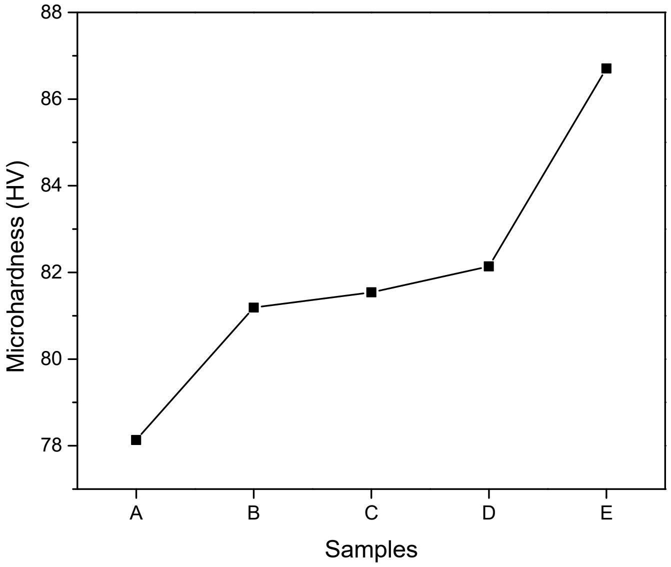

Figure 4: Microhardness of the cast samples.

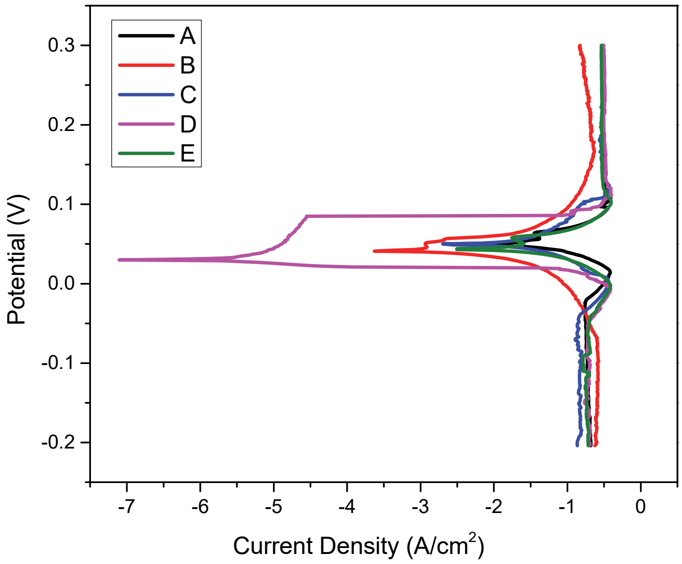

Figure 5: Tafel plots for the cast samples.

The results showed that the microhardness was 78.13, 81.19, 81.54, 82.14, and 86.71 HV for samples A, B, C, D and E respectively. The improvements could be attributed to a number of factors. The presence of the hard reinforcing particles present on the grain boundaries of the aluminium matrix is responsible for resisting deformation of the cast samples during the application of localized loads. Also based on the morphology of the cast samples, the presence of the reinforcing phases (fly ash and eggshells) was responsible for resisting movement during the application of load which in turn improved the hardness with increasing weight fractions of the dispersed phases. The improved hardness of the AMCs could also be attributed to grain refinement brought about by the incorporation of the reinforcements in the aluminium matrix. This results was also reported by Ononiwu et al [17] and Chandla et al. [24]. The authors further stated that the improved hardness values of the AMCs compared to the base alloy could be directly attributed to the of the strengthening of the alloy by the reinforcements which transfers the applied load from the ductile and softer aluminium matrix to the more brittle and stiffer reinforcing particles.

Potentiodynamic polarization

The potentiodynamic polarization study was used to study the characteristics of the cast samples under the influence of electrochemical mechanisms.

The Tafel plots in Fig. 5 indicates passive and active corrosion modes in the 3.5 wt.% NaCl electrolyte. From the Tafel plots, the corrosion rates were extrapolated to figuratively show the potential of the considered samples to resist corrosion activities in the corrosion medium. The corrosion rates depicted in Fig. 6 shows that the addition of the reinforcements was necessary to improve the corrosion rate of the aluminium alloy. The corrosion rate was improved due to the formation of a sufficient passive oxide layer. The passive oxide layer is responsible for the resistance to corrosion activities, although the continuous exposure of the samples to the corrosion medium eventually leads to the deterioration and eventual rupture of the passive layer which is responsible for the initiation of localized pitting activities on the surface of the samples. According to Akinwamide et al [25], the formation of the pitting corrosion mechanism is a result of aggressive attack of the chloride ions present in the NaCl medium. From the Tafel plots, the presence of metastable pitting was visible in all the cast samples as fluctuations on regions of the Tafel curves. The metastable pitting is described as unstable pits that occur prior to the initiation of stable pits after the initial incubation period of the chloride ions [26]. Although the corrosion resistance of the AMCs samples improved compared to the base metal, several factor including the weight fraction of the reinforcements, level of dispersal, presence of segregation and agglomeration, adequate wettability and the level of interfacial bonding between the reinforcements and the matrix were responsible for the variation of corrosion rate for the fabricated composites. To this effect, sample D had the least corrosion rate of 8.65 X 10^{-5} g/h indicating that the samples exhibited the best resistance to corrosion in the NaCl corrosion medium.

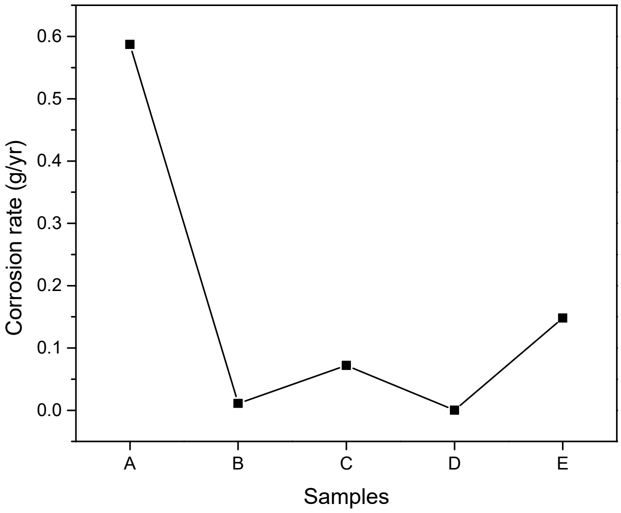

Figure 6: Corrosion rates of the cast samples.

CONCLUSION

This investigation was conducted to evaluate the effect of fly ash and egg shells on selected mechanical, physical and corrosion resistant properties of AA 6063. Results revealed that the addition of the hybrid reinforcing particles to the aluminium alloy led to the fabrication of light weight AMCs. This work also reported an increase in porosity with increasing weight fraction of both reinforcements. The studies indicates that the porosity is a function of the weight fraction of the reinforcements, micro voids, level of dispersion of the reinforcements and the presence of agglomerates in the cast samples. The microstructure was characterized by uniformly dispersed particles along the grain boundaries of the base metal. Microhardness testing showed that the property improved up to 10.3% with increasing weight fraction of the reinforcements. The corrosion investigation reported the presence of the reinforcements improved the corrosion resistance; however, the corrosion rate was lowest for the 7.5wt.% sample. Overall, it can be conclusively stated that the use of hybrid sustainable reinforcing particles can be used to conveniently fabricate AMCs with improved properties.

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