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Synthesis and Structural analysis of Aluminium-filled Polystyrene Composites from Recycled Wastes

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In this study, the effects of powdered Aluminium (Al) as reinforcing fillers for polystyrene-based resin (PBR) matrix has been evaluated based on the analysis of mechanical and structural properties. Samples were prepared by hand lay-out technique enhanced with the usage of single roller. The PBR was reinforced by Aluminium powders (μm) at selected weight fractions of (0, 5, 10, and 15 %) and investigated by X-ray diffraction (XRD) physical and mechanical testing. The study of mechanical properties includes: elongation at break, time to failure and young modulus. The XRD studies confirmed no chemical reaction but rather the introduction of crystalline structure in the polystyrene matrix based on the amount of aluminium content and the even distribution of aluminium powder in the matrix. The tensile strength increased with increasing filler content; however elongation at break and time to break showed decrement as the weight fraction of aluminium powder is increased in the composites. The mechanical and XRD analysis demonstrated that the presence of aluminium micro particles in PBR matrix enhances structural properties of the composites.

Keywords: Composites, Polystyrene based resin (PBR), Mechanical properties, Aluminium reinforcement.

Introduction

Currently, the emerging sophisticated industrial processes and technologies require materials with unusual combinations of properties that cannot be provided by the available and conventional polymers, ceramics, and metal alloys products. These needs can be met through the design and development of composite materials whose constituents synergistically meet the terms of these emerging applications (Jui *et al*., 2008). In most industrial applications, thermoplastics are used as a matrix for very fine particulates in the production of composite materials when such particles can interact physically and/or chemically with the thermoplastics creating high performance polymeric composites (Alwan *et al,* 2016). Metallic powders are a special type of particle filler that impart special qualities in plastic composites. These fillers enhance properties such as thermal conductivity, electrical conductivity, response to magnetic fields and heat capacity.

Production of Aluminium/polymer composites has focused on attractive material development exploration due to its associated combination of properties like low density, corrosion resistance, thermal stability, and ease of fabrication. Consequently, studies have been made to investigate the mechanical, thermal, and electrical properties of aluminium powder reinforced polymer composites (David, 2007; Alwan *et al*., 2016; Hachani and Meghezzi, 2015). However, good particle dispersion and interfacial strength between aluminium powders and the host matrix has been the main issues in the fabrication of aluminium/polymer composites because of the surface properties of Aluminium and the fabrications methods employed being majorly hot pressing and extrusion at elevated temperatures and/or epoxy reinforced technology (Chung *et al.,* 2005; Alwan *et al.,* 2016; Hachani and Meghezzi, 2015). To address this issue, some studies have attempted the surface treatment of aluminium powders before mixing with the host matrix (Jallo *et al.2010* Chen *et al.2010);* their results confirm surface treatment as non-effective.

The polystyrene in its virgin state is of poor mechanical properties and of bad resistance to surfactants (Myer, 2002). As a reinforcement method to enhance the properties of the polystyrene, a lot of research works have been focused on polystyrene composites with metal oxides (Jui *et al.,* 2008), carbon nanotubes (Archana *et al.,* 2013) and glass-fibers (Quanyao *et al.,* 2010). The addition of powdered fillers has been demonstrated to be an effective way to improve the mechanical properties of the polymer matrix. However, not much investigation has been carried out on the possibility of reinforcing aluminium powder with polystyrene based resin to improve fracture and tribological properties of aluminium reinforced composites.

Moreover, in its waste state, disposal of polystyrene (PS) has been recognized as a worldwide environmental problem. Reuse of waste PS in composite products development is a greener attempt in product development. In this study, the binding effect of polystyrene based resin on the production of aluminium reinforced composites was investigated. The aim of the present work is to evaluate the effect of powdered aluminium (Al) as reinforcing fillers for Polystyrene based resin (PBR) matrix through the measurement of the mechanical and structural properties. A secondary aim is to study the effect of different loadings (0 - 15) % of the investigated fillers on the properties of PBR-Aluminium composites. The present paper discusses the results obtained from the structural study and characterization of the prepared composites for mechanical properties.

Materials and Methods

Materials

The major materials used were obtained from solid waste streams. The polystyrene were sorted and cleaned from University of Ilorin solid waste while the aluminium wastes were obtained from a local fabricator's workshop and were dried in oven for 24 hours at 50° C to remove free water present in it. The dried sample was graded through No. 100 sieve to obtain the powder of 150μm in size.

Synthesis of Aluminium Filled Polystyrene Composites

Aluminium Filled Polystyrene Composites (AFPC) were prepared by incorporating Aluminium Powder (150μm) of varied content (0, 5, 10, 15 wt %) in Polystyrene based resin (PBR). PBR was obtained as described in Abdulkareem and Adeniyi, 2017. This involved dissolving 59 gram of Polystyrene in 100 mL of petroleum solvent followed by addition of the aluminium filler. The PBR–Aluminium powder mix was thoroughly masticated at room temperature. The final mixture of each formulation was formed by hand layup method enhanced by a single roller before film casting. The cast films were left for 7 days for complete solvent evaporation. The prepared composite films were utilized for characterization. To attain accuracy in performance and results, samples were prepared in triplicates and the average values were reported after characterization.

Structural and Mechanical analyses

X-rays diffraction analysis

The phase identification of polystyrene and aluminium, the crystalline state investigation of the PS/aluminium composites, were both studied using X-ray diffraction technique. The XRD diffraction patterns were obtained using Bruker D2 diffractometer within 2θ varies from 10 to 90° with a scanning speed of 2° min^{-1}. The studied samples were all films. The usage of cobalt anode at ambient temperature was employed.

Mechanical analysis

Tensile testing

Universal testing machine (UTM: M500-50 AT) with tensile test fixture and different types of self-aligning grips were used for holding test specimen in machine. It is fitted with load cell and extensometer to record the test load and elongation accurately. Tensile tests were conducted according to ASTM D638-10. A computerized universal testing machine model was used to conduct a test at a constant cross head speed of the order 4mm/min. Tensile loads were applied till the failure of the sample and load-elongation curves was obtained for all the composite materials produced. All tests were carried out at room temperature (25± 2)˚C. Three specimens were used for all the tests and final results represent the average.

Measurement of Density

The experimental densities of the aluminium powder, solvated polystyrene and composites were gotten using the laboratory-made density setup. Theoretical densities () of the solvated polystyrene/aluminium composites were calculated by the rule of mixture using equation 1 with the assumption of no voids present in the samples and no loss of material during the sample preparation using the density of the solvated polystyrene and aluminium are 0.855 g/cm^3. and 2.7 g/cm^3 respectively.

$$\rho_{td} = \frac{1}{\left(\frac{w_f}{\rho_f}+\frac{w_m}{\rho_m}\right)} \qquad (1)$$

Where w_f and w_m are weight fraction of the aluminium filler and PBR matrix respectively while ρ_f and ρ_m are densities of the aluminium filler and PBR matrix.

The void content (v_{void}) in a composite was estimated by comparing the theoretical density with its actual density.

$$\rho_{td} = \frac{1}{\left(\frac{w_f}{\rho_f}+\frac{w_m}{\rho_m}\right)} \qquad (2)$$

where, ρ_{td} – theoretical density of the composite material; ρ_{ed} – Experimental density of the composite materials

Discussion of Results

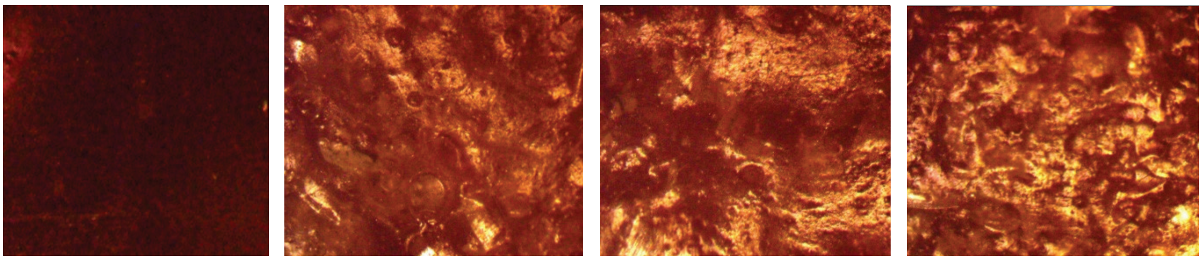
The images of the PBR film and the composites with 5, 10, and 15 wt % of aluminium powder are shown in Figure 1 (a–d). It is observed that the incorporation of filler played a remarkable role on the structure of the resultant composites. The optical micrographs of respective composites are presented in Figure 2. With the incorporation of lowest filler content (5 wt %), homogenous dispersion of filler is observed in the composites which explained good filler–resin interaction. At 10 wt % the extent of particle-to-particle connectivity increased due to improved filler-resin

Fig. 1

Photographs of the PBR film (a) and the composite with 5, (b) 10, (c) and 15 wt % (d) of Aluminium powder

Fig. 2

Micrographs of the PBR film (a) and the composite with 5, (b) 10, (c) and 15 wt % (d) of Aluminium powder



interactions, which improved throughout the matrix when the filler content is further increased to 15 wt %. The shiny areas in the images in *b*, *c*, *d* indicated the presence and extent of the aluminium powder when contrasted to *a*.

Density

The interaction of the aluminium powder with the PBR was observed intricately to be influenced by factors like voidage and weight fractions which as a result influenced the density of the resulting composite. The variation in the density of PBR/aluminium composites is shown in Table 1. This table shows that increase in weight fraction of aluminium powder also increase the densities of PBR/aluminium composites formed with corresponding decrease in voidage fraction.

It was also observed that there are some differences between the experimental and the theoretical densities of fabricated composites. This variation in density is due to the presence of voids and pores in fabricated composites. Evidently, greater void percentages are associated with composites of lower percentage

Table 1

The variation in the density of PBR/aluminium composites

S/N	Filler Content (wt %)	Density (g/cm^3) (Polystyrene/Aluminium)		Voidage Fraction (%)
		Theoretical	Experimental	
1	2	3	4	5
1	5	0.89	0.86	3.37
2	10	0.92	0.90	2.17
3	15	0.95	0.94	1.05

fillers. The density of the composite sample is sensitive to the volume fraction of voids; as the mass fraction of aluminium fillers with its corresponding volume increased in the mix, it further reduced the free spaces among the PBR molecules and further contributed to an increase in the density of the composites as reported in Anuar & Ismail 2007; Sihama *et al.,* 2015.

XRD

For determining the effect of aluminium powder in the host Polystyrene matrix, XRD spectra of the composites with 5 wt %, 10 wt % and 15 wt % of Aluminium loading were recorded (Figures 3 to 5). The x-ray diffraction spectrum shows peaks for Polystyrene and aluminium confirming the matrix and reinforcement material. The XRD pattern of neat polystyrene with a broad peak at 16°–28° and one relatively less intense peak at 10° – 16°, is common to all the patterns in Figures 3 to 5, which confirms the amorphous contributions of polystyrene to the composites structure. Similar patterns were observed in David, 2007; Hachani and Meghezzi, 2015 and Alwan *et al.,* 2016.

Another pattern in Figure 3 to 5 gives an idea about the presence of some Aluminium powder reflections. These peaks, in the same diffraction pattern, confirm the formation of properly dispersed Aluminium powder in the composite and development of crystallinity in the Polystyrene matrix. At 5 wt % (Figure 3) aluminium powder loading in aluminium reinforced polystyrene composite, three peaks at 44.4°, 52.5° and 77.0° were observed which is common to loadings at 10 and 15 wt % aluminium (Figures 4 and 5). All of these are attributed to the crystalline nature of aluminium which was similarly observed in the past contributions (Sihama *et al.,* 2015; Özge *et al.,* 2015). However, at 10 and 15 wt % aluminium powder loading, one (42°) and two (21.5° and 81.5°) additional peaks were observed respectively, which explained the fact that the composites becomes more crystalline as the percentage of aluminium powder increases.

Furthermore, the comparison among X-ray diffraction patterns of aluminium reinforced polystyrene composites of all aluminium loading between 5 % and 15 % (Figures 3 to 5) confirms the development of crystallinity in the Polystyrene matrix. All the three composites peaks matches with peaks of aluminium, indicating the good dispersion of Aluminium powder in the matrix crystalline composite. Also noticed is the reduction of polystyrene amorphous character and no alteration in crystal structure of aluminium. It is also seen that no reaction takes place between aluminium powder and Polystyrene during fabrication of composites but rather a development of synergic structural reinforcement in the polystyrene matrix is achieved and their combination brings more rigidity to the studied samples. This position is further confirmed by the mechanical results.

Fig. 3

XRD spectra of the composites with 5 wt % of Aluminium loading

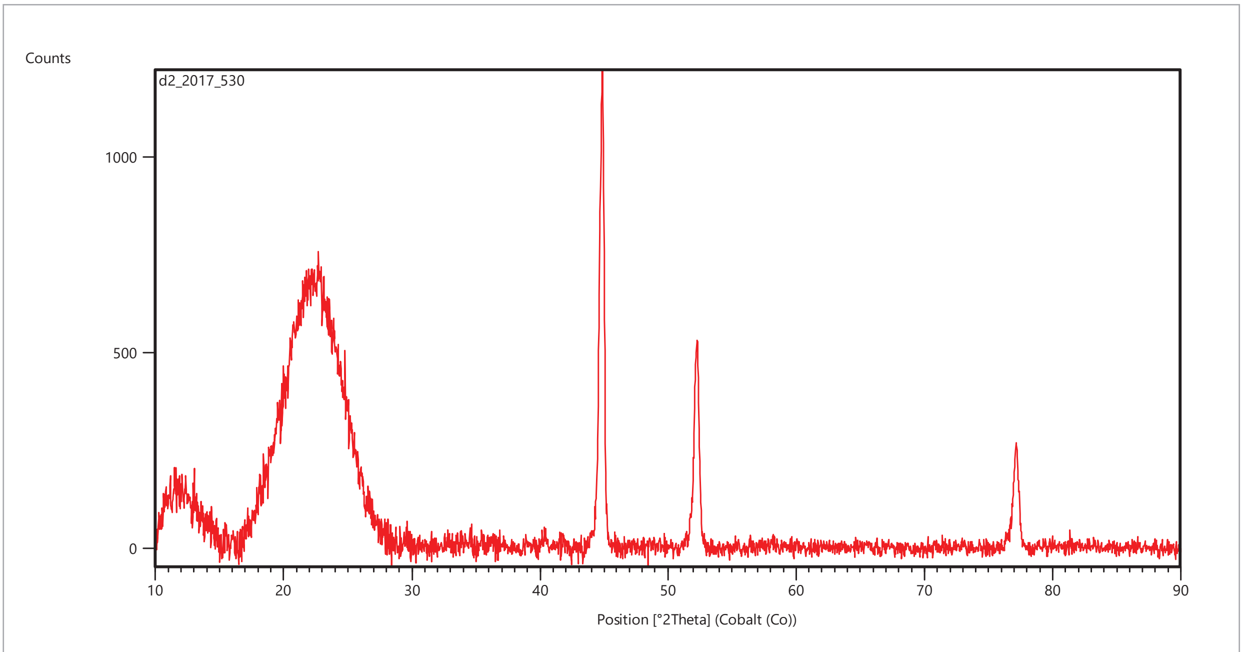


Fig. 4

XRD spectra of the composites with 10 wt % of Aluminium loading

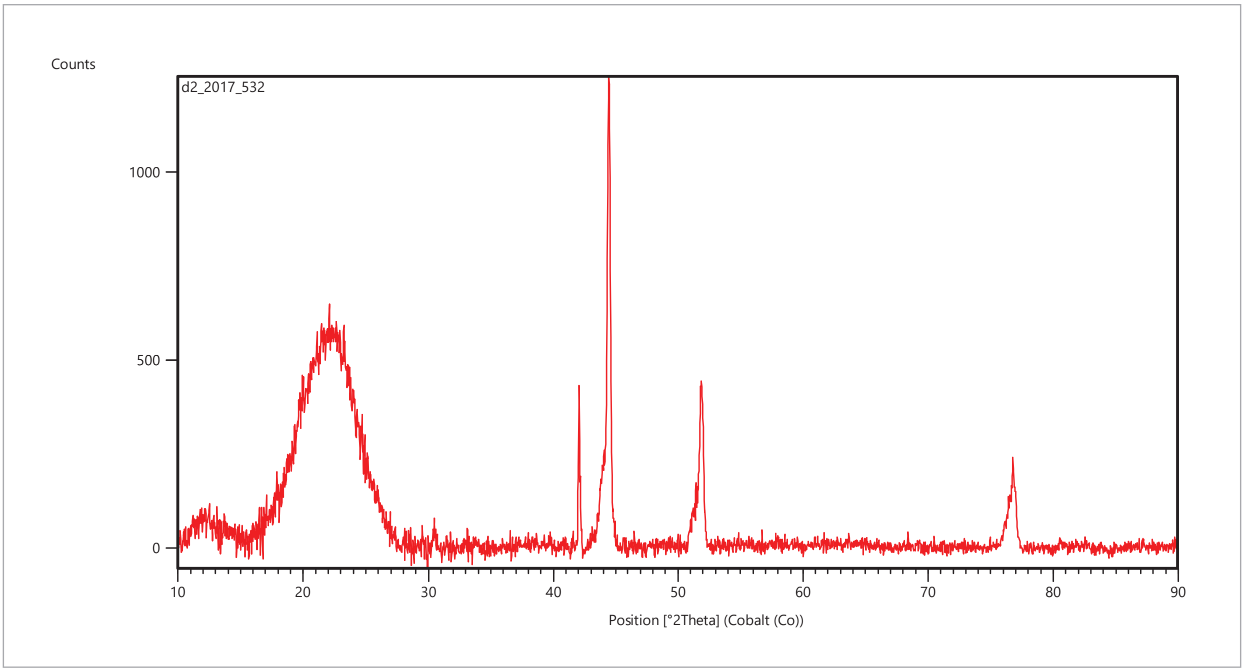


Fig. 5

XRD spectra of the composites with 15 wt % of Aluminium loading

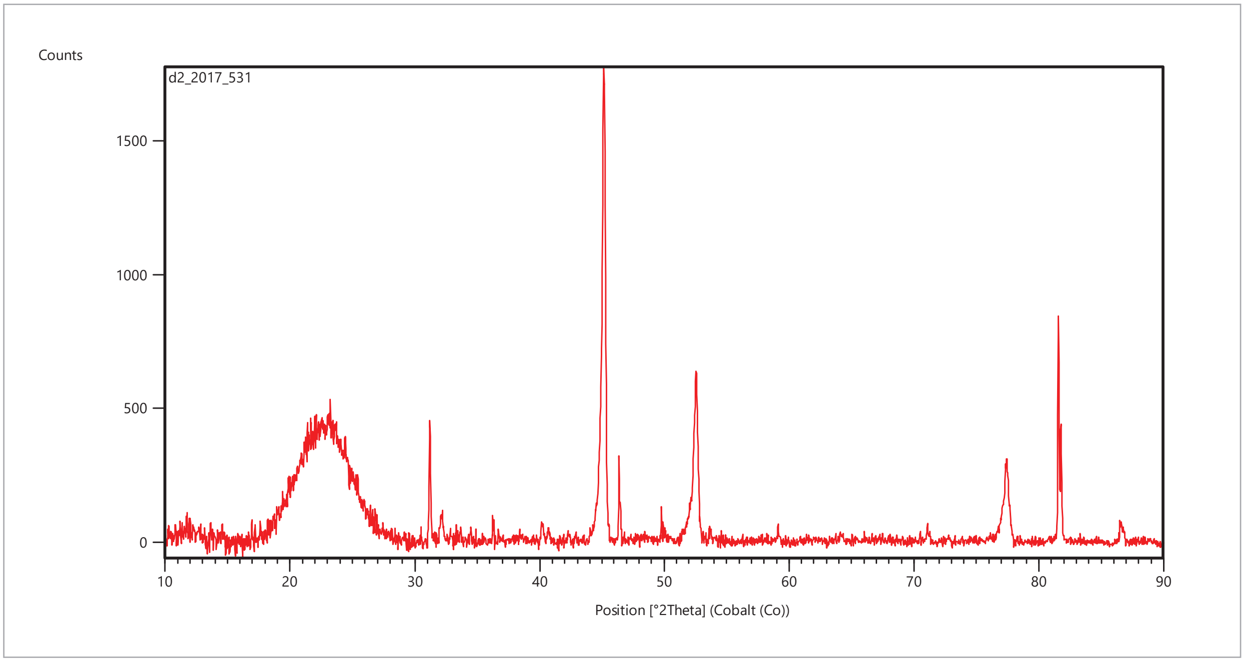
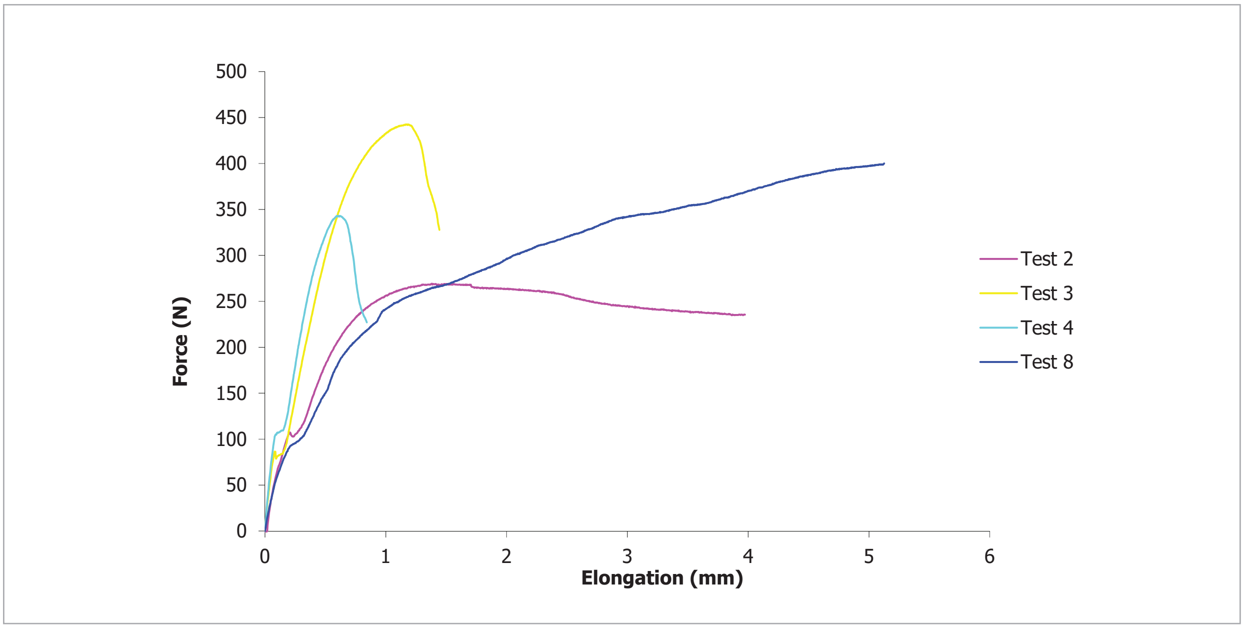


Fig. 6

Load-strain profile of the composite at 0 % (Test 8), 5 % (Test 2), 10 % (Test 3) , 15 % (Test 4) Aluminium filler



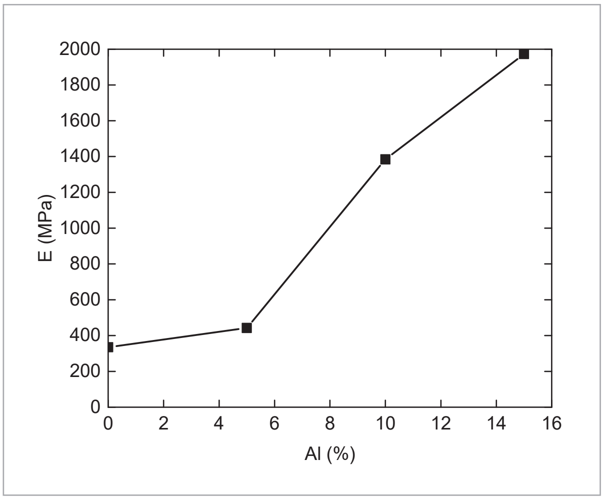
Mechanical

Tensile test of Polystyrene composite reinforced by Aluminium particles showed that the Load-Strain curve behaviour of the composite changed from low strength and brittle at 0% Aluminium powder to increased hardness and strength when the weight fraction of aluminium powder increased to 15 % in the composite materials developed. This is quantitatively explained by the load-strain profile in each of the plots in Figures 6 a-d.

The tensile characteristics which include Young modulus (E) elongation (ε), and time to break, relative to the aluminium content of the composites in the PBR matrix, are equally shown in Figures 7 to 9 respectively. It is shown that there was a decrease in elongation (ε), and Time to break with the increase in the weight fraction of Al powders in the composites until the weight fraction reached 15%. The elongation at break decreased from 47.6% at 0% Aluminium powder to 7.9% at 15% Aluminium powder. Likewise, the time to break decreased from 57.13 sec 0% Aluminium powder to 9.52 sec at 15% Aluminium powder reinforcement. These observations are the distinctive characteristic of Aluminium/metal filled plastic composites (Sihama *et al.,* 2015)

Fig. 7

Young modulus (E) relative to the Aluminium content of the composites



The increased Young modulus values is related to the effective dispersion of Al micro particles into the

Fig. 8

Elongation (ε) relative to the Aluminium content of the composites

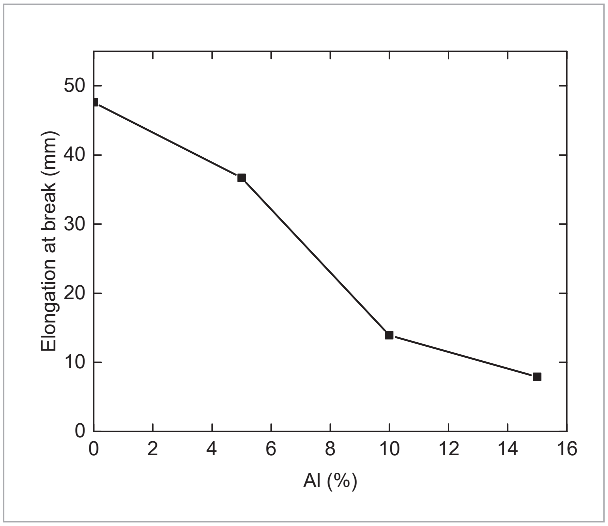
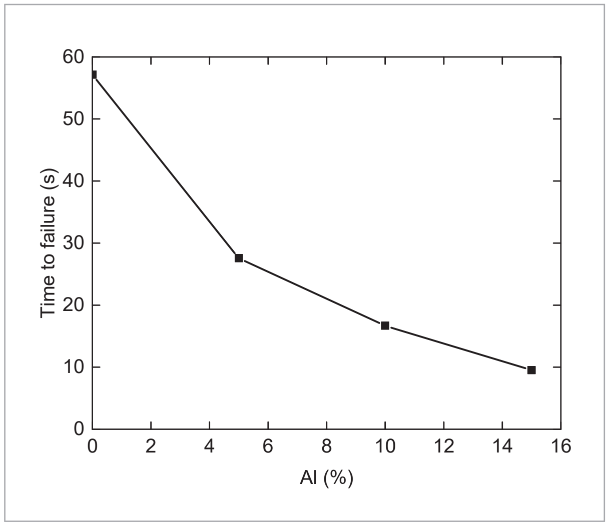


Fig. 9

Time to break relative to the Aluminium content of the composites



Polystyrene matrix to fill the open structure of the crystalline crosslink structure of aluminium powder content in composites samples. It is clear from these plots that the mechanical properties improved with increasing filler content up to 15% Al powder considered in this study. The range is between 335.24MPa for 0% Aluminium to 1972.70 MPa for 15% reinforcement. This can be equally related to the interfacial adhesion and physical bonding between the Aluminium filler and Polystyrene matrix prepared in form of PBR. The interfacial adhesion is possible due to the usage of petroleum solvent in the preparation of PBR, which eliminated the adhesion problem mentioned in previous studies (Chung *et al.,* 2005; Alwan *et al.,* 2016; Hachani and Meghezzi, 2015).

Conclusions

In the present work, the use of aluminium powder and polystyrene from waste streams were used to produce metal filled plastic composites. The following conclusions were drawn:

1. Investigation by optical microscope reveals that the distribution of aluminum particles in the matrix of PBR is uniform and even.
2. There is a significant increase in the tensile strength and modulus with an increase in the filler concentration up to15% of mass fraction considered.
3. XRD studies showed that there is a good structural interaction between the Aluminium particles and the PBR matrix and no chemical reaction was found.

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Aliuminiu užpildytų polistirolo kompozicijų sintezė ir struktūrinė analizė iš perdirbtų atliekų

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Šiame tyrime buvo analizuojamas aliuminio miltelių (Al) kaip polistirolo pagrindo dervos (PBR) užpildų poveikis, remiantis mechaninių ir struktūrinių savybių analize. Mėginiai buvo paruošti rankiniu būdu išdėstytais metodais, naudojant vieną ritinį. PBR buvo sustiprintas aliuminio milteliais (μm) pasirinktose (0, 5, 10 ir 15%) svorio dalyse ir tirtas rentgeno difrakcijos (XRD) fizikiniais ir mechaniniais bandymais. Mechaninių savybių tyrimas apima: pailgėjimo pertrauką, laiką iki gedimo. XRD tyrimai nepatvirtino jokios cheminės reakcijos, o kristalinės struktūros įvedimas į polistirolo matricą, remiantis aliuminio kiekiu ir lygiu aliuminio miltelių paskirstymu matricoje. Tempimo stipris padidėjo didėjant užpildo kiekiui; tačiau pailgėjimas pertraukoje ir laiko tarpas parodė sumažėjimą, nes aliuminio miltelių svorio dalis kompozicijose padidėja. Mechaninė ir XRD analizė parodė, kad aliuminio mikro dalelių buvimas PBR matricoje padidina kompozitų struktūrines savybes.

Raktiniai žodžiai: kompozitai, polistireninės dervos (PBR), mechaninės savybės, aliuminis.