



## Evaluation of the Electrical Characteristics of Recycled Iron Reinforced Polystyrene Composites

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### ABSTRACT

The prospective reuse of iron fillings from the milling machine and polystyrene in the solid waste streams in the production of plastic composites were considered in this study. The preparation, electrical properties, density, void fraction and particle distributions of the solvated polystyrene filled composites were all investigated as a function of recycled iron fillings concentration. The composites were developed by hand layup technique and cured by casting under ambient conditions ( $25 \pm 2^\circ\text{C}$ ) for 7 days. The compared micrographs confirmed well-dispersed recycled iron fillings in polystyrene matrix and decreasing void fraction as iron filling increases in the composites. The highest electrical conductivity and density values of the composites were obtained at the highest iron filling composition of 40 wt% as  $5.91 \times 10^{-07}$  S/cm and  $1.31 \text{ g/cm}^3$ , respectively. The developed iron polystyrene composite has good electrical properties, making it suitable to be an alternative material for metals.

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### INTRODUCTION

Plastic composites filled with metal are of immense industrial impact in many areas of engineering applications [1]. Their significance hinges on the fact that their processing methods and eventual mechanical properties are generally plastics related while their emerging electrical properties are metallic [1, 2]. The achievement of this property mix in such composites depends on many factors like type, concentration, aspect ratio, and conductivity of the additive, as well as plastic materials selected [3, 4]. The influence of the type of plastic matrix and filler on the electrical characteristics of the composite has been studied in many works [5, 6]. Although in some reports, it was observed that the percolation behaviour of the developed conductive composite depends on both filler particle shape and spatial distribution within the plastic matrix, it is generally accepted that the filling of plastic with metallic particles results in an increase of electrical conductivity of the composites obtained [5].

Acquiring metallic material for the production of conductive composite material often involves a huge investment in the material and a direct increase in the cost of production [7]. One way of reducing the production cost but still maintaining the properties of the composite is by using a waste metallic material such as iron filings from the waste stream [8]. Iron filings had been chosen due to their availability, low cost and high specific strength [9, 10]. The iron fillings and polystyrene resins used in this study were obtained directly from solid waste streams. This bears significant implications for solid waste management efforts. As effort is being explored to convert waste to wealth [11-13], more intricate technologies for doing so are invariably important. Development of composites in one such important way of using these waste materials [14, 15].

Several researchers have been carried out investigations on the development of composites from the mixture of polystyrene and various fillers like starch, aluminium, copper and clay using injection moulding technique, hot press method and many more [16, 17].

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Researchers have investigated the electrical properties of metal-reinforced polymer materials given the application in electrical circuits and also to determine their potential as dielectrics and semiconductors. The electrical properties of plastics composites have been investigated in cases where aluminium [8], clay [17], natural fibres [18, 19], silicon oxide [20] and boron nitride [21, 22] were used as fillers.

In a recent review paper on the current research area, Adeniyi and Ighalo [23] observed that the electrical properties of pure metals in polystyrene composites have not been sufficiently investigated. Most studies focused on epoxy composites. Because polystyrene is another important polymer for composites development [24-26]. It is important to evaluate the electrical properties of her pure metal composites. This, therefore, presents an important gap in knowledge that this study intends to fill. This work is based on using waste solid materials as materials of conductive composite production; iron filings powders as filler and solvent-based polystyrene resin as a matrix to form a composite of desired properties using the hand lay-up method, entirely in cold processing without recourse to thermal treatment at any stage of its processing.

In the present study, iron filing powder was used as conductive filler while solvated polystyrene resin synthesized from waste polystyrene was used as a matrix. The selected materials will aid in the study of the influence of iron filing content on the electrical conductivity of the composites. Also, this research will assist in the reduction of problem associated with waste discharged in the environment and thus, reducing the cost of waste management as well as the developed composites.

## MATERIALS AND METHODS

### Preparation of iron filings

The iron filings used in this study was directly obtained from the Central Engineering Workshop, the University of Ilorin after some metallic jobs of steel of known properties (Table 1) were ground. This was done to avoid

the use of rusted iron fillings which could affect the results of the research. The iron filings were dried in an oven for 24 h at 50°C to remove the free water present in it [8]. The dried sample was graded to obtain the powder particle size of 150 µm [1].

### Preparation of polystyrene resin

The waste polystyrene was sorted from the solid waste stream of the University of Ilorin, cleaned and subjected to solvolysis to obtain a solvent-based resin of 855 kg/m<sup>3</sup> density at room temperature. The preparation methodology of the petroleum solvent based polystyrene resin has been previously described in detail [28]. The use of a petroleum solvent does not bear negative consequence on the environment because it is entirely used up during the dissolution process of waste polystyrene. Though the eventual composite developed is non-biodegradable, this is mainly because of the metal fillers used and not the resin itself. Biodegradability has been reported when biomass fillers were used for polymer composites [29]. Based on these considerations, the current approach can be considered to not have a deleterious effect on the environment.

### Composite development

The composites were developed by hand layup technique. The required mass of the solvent-based polystyrene resin and prepared iron filling particles were dispensed into the mixer and mixed rigorously in one step mixing process for 5 minutes before discharging onto the roller plate for further pressing and shape forming unto a uniform cross-section. Composites with 0, 10, 20, 30 and 40 wt% metallic fillers were prepared. Filler concentration did not exceed 40 wt% because of the aspect ratio. Because a solid powder is going into a polymeric resin, there is usually a maximum amount of the solid the resin can hold to form a composite material of consistent physical integrity (this is 40%). Above this value, the two components will not stick together to form a heterogeneous solid. Oil was smeared on the metal surface to prevent the composite from sticking and to achieve easy composites removal. The fabricated composite was spread and made to cure by casting under ambient conditions (25 ± 2°C) for 7 days [30].

### Measurement of resistivity

Electrical resistances of conductive composites were measured by employing the standard four-point probe method under laboratory conditions [1]. The narrow sides of the composite film were covered with aluminium foils to facilitate measurement with the four-point probe. This technique measures resistivity by applying a constant current (in the range of 0 to 10 A) and measuring the voltage drop over the center 3 mm thick sample. A Keithley 224 Programmable Current Source and Keithley 182 Digital Sensitive Voltmeter were used. The composite resistivity (R) was calculated by using the

**Table 1.** Chemical composition of iron filings [27]

Elements	Composition (wt%)
Carbon	3.53
Silicon	2.67
Magnesium	0.05
Sulphur	0.01
Phosphorus	0.03
Manganese	0.31
Iron	93.4

relation in Equation (1) [6].

$$R = \frac{\rho l}{A} \tag{1}$$

where R is the measured resistance, L is the length of the specimen, which is also the length of the glass slide, w is the width of the specimen, which corresponds to the gap between the two adhesive strips, and h is the thickness of the conductive paste. Three specimens were tested for each experimental condition. An average bulk resistivity for each sample was calculated for each sample.

**Measurement of density**

The experimental densities of the iron filling, solvated polystyrene and composites were obtained using the laboratory-made density setup [1]. The rule of the mixture was used to calculate the theoretical densities of the solvated polystyrene/iron filling composites by using the densities of the solvated polystyrene and iron fillings as 0.855 g/cm<sup>3</sup> and 7.87 g/cm<sup>3</sup>, respectively. Theoretical densities of the composites were evaluated by using Equation (2) [6].

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

where,  $w_f$  and  $w_m$  are weight fraction of the filler and matrix, respectively while  $\rho_f$  and  $\rho_m$  are densities of the filler and matrix, respectively. The void content in the composites was estimated by using the theoretical and experimental densities as presented in Equation (3) [6].

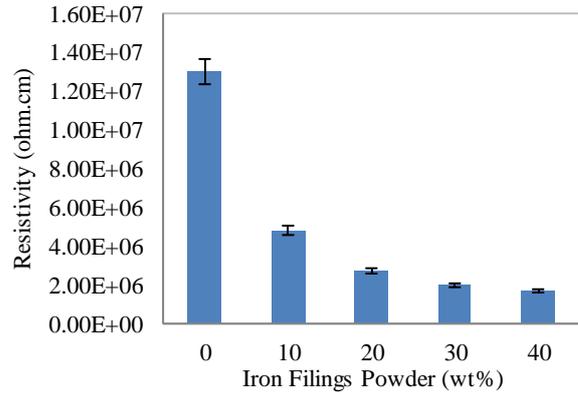
$$v_{void} = \left(\frac{\rho_{td} - \rho_{ed}}{\rho_{td}}\right) \times 100 \tag{3}$$

where,  $\rho_{td}$  - theoretical density of the composite material,  $\rho_{ed}$  - Experimental density of the composite materials. Morphological analysis was done with a Metallurgical microscope (Olympus BX-60 M) at a magnification of  $\times 100$ .

**RESULTS AND DISCUSSION**

**Electrical resistivity and conductivity of the composites**

The resistivity of Iron filings/polystyrene composites containing various mass fractions of recycled iron filing powder with the size of 150  $\mu\text{m}$  is presented in Figure 1. It was seen that even at a lower concentration of filler the resistivity of composite is lower than that of cured virgin solvated polystyrene without iron filing powder, which is  $1.3 \times 10^8$  ohm-cm and decreased progressively at a higher percentage of iron filler as shown in Figure 1. A similar observation of the filler loading effect has been made for copper [31] and aluminium [8] reinforced polystyrene composites. The iron filler has lesser resistivity when compared to the polymer resin [23]. Hence, increasing its proportion in the composites will invariably lead to lesser resistivity.



**Figure 1.** Effect of iron filling powders on resistivity

The electrical conductivities of the iron filling composites are shown in Table 2. As a comparison, iron filling content in polystyrene at 10 wt% results in  $2.08 \times 10^{-7}$  S/cm. The conductivity reaches  $5.91 \times 10^{-07}$  S/cm for 40 wt% iron content in this study. The results showed a considerable increase in the electrical conductivity as the iron filling content increases, which is a confirmation of the impact of the addition of the iron fillings to the solvated polystyrene matrix. This is an enhanced conductivity achieved as compared to other studies of thermosetting matrix [32]. Also, As the amount of iron filling in the polystyrene increases more conductive paths in the composite are created. Low concentrations and poor dispersion may lower the conductivity at low wt% of metallic content as reported by Osman and Mariatti [5]. However, local enhancement of electrical conductivity is achieved in this study as a result of the good adhesive property of solvated polystyrene that allowed better dispersion of the iron filling and the good formation of an interconnected network of iron filings in the polystyrene matrix [1].

**Density of the composites**

The effect of different iron filing loading in the solvated polystyrene matrix on density was investigated. Table 3 shows that polystyrene composites with 40% Iron filing content have the highest density followed by 30, 20 and 10 wt% iron filling content, respectively. The same trend is observed with the theoretical density prediction. Since

**Table 2.** Effects of iron filling content on conductivity of the composites

Filler content (wt %)	Conductivity (S/cm)
0	$7.69 \times 10^{-08}$
10	$2.08 \times 10^{-07}$
20	$3.67 \times 10^{-07}$
30	$5.05 \times 10^{-07}$
40	$5.91 \times 10^{-07}$

the iron filling has a higher density ( $7.87 \text{ g/cm}^3$ ) than solvated polystyrene ( $0.855 \text{ g/cm}^3$ ), therefore, the density of composites tends to increase as the iron filling content increases. However, the effects of the void fraction on the experimental values of density became evident by comparing the theoretical and experimental densities of the composites.

The densities of the composites compared with the theoretical values were used to find out the pore volume since it explains the air gaps (micro-voids) in the composite developed as presented in Table 3. It was observed in Table 3 that the higher the filler content, the lower the voidage fraction become; this is between 5.3% and 1.4% in the range. The void percentage decreased by the addition of iron filling filler. A higher percentage of micro-voids formed at a lower percentage of iron filling filler got decreased as the percentage of filler increased [1]. This implies that interfacial interaction is strengthened in iron filling-solvated polystyrene composite as the distance between metal particle decreases. The effective density profile obtained in this study is lighter when compared with composites developed by using other materials [32, 33]. Similar observations have also been reported in other studies [1, 23].

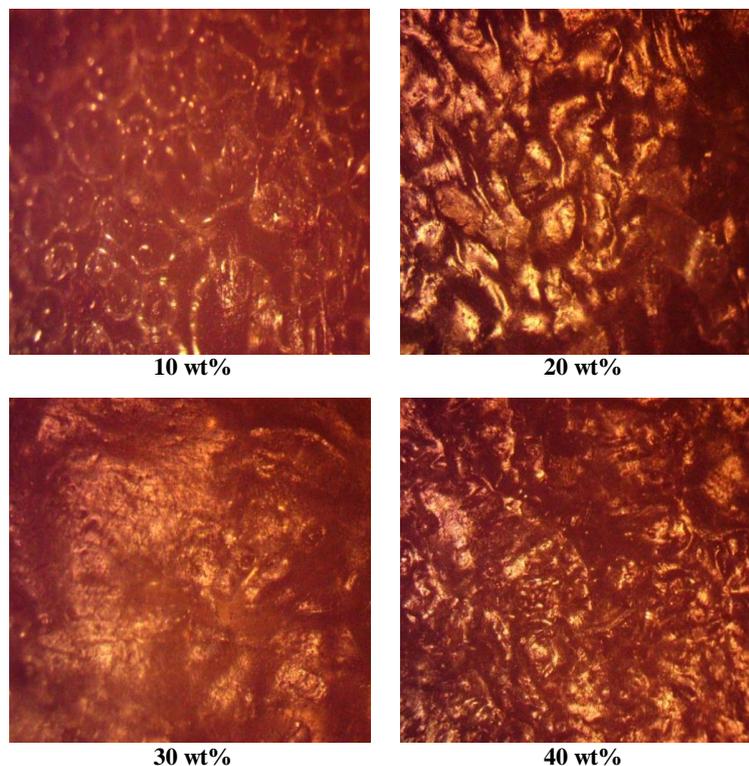
#### Morphological analysis

Microscopic examination (micrographs) on the developed conductive composites at different iron filling

percentages are shown in Figure 2. It shows optical microscope images of the composites for 10 wt% to 40 wt% contents of iron filling particle in the solvated polystyrene matrices. These micrographs also support the concept that the composites have better conductive networks as iron filling contents increases. The smoothness of the composite surface reveals a good dispersion of the filler in the matrix and the absence of any agglomerations [34]. In all of the composites produced, effective mixing is observed. It could be summarized from the analysis that the distribution of the iron filling in the sample is uniform at all content percentage used, with no exception; this confirms the effectiveness of the preparation method employed.

**Table 3.** The variation in the density of poly styrene/iron fillings composites

Filler content (wt %)	Density of composite ( $\text{g/cm}^3$ )		Void fraction (%)
	Theoretical	Experimental	
0	0.8550	0.8100	5.2632
10	0.9387	0.9120	2.8412
20	1.0405	1.0200	1.9693
30	1.1671	1.1500	1.4642
40	1.3288	1.3100	1.4120



**Figure 2.** Micrographs of the composites at different iron filling percentages (magnification  $\times 100$ )

## CONCLUSION

The development of conductive composites has been achieved by mechanical mixing of solvated polystyrene and iron fillings. Several key conclusions were derived from the current investigation. Comparisons of micrographs in low and high magnification showed that iron-fillings in all higher fractions are well dispersed in their respective solvated polystyrene matrixes. The composites also exhibit conducting properties comparable to other similar works.

The highest electrical conductivity of the composites was obtained at the highest iron filling composition of 40 wt% as  $5.91 \times 10^{-07}$  S/cm. The highest density of the composites was obtained at the highest iron filling composition of 40 wt% as  $1.31 \text{ g/cm}^3$ .

Thus, the Iron filling-polystyrene composites prepared by simple mechanical mixing method afforded acceptable density and comparable electrical conductivity as to other related composites reported previously. The developed iron fillings-polystyrene composite has good electrical properties, making it suitable to be an alternative material for metal materials. For future work, methods of treating and modifying the fillers and/or resins can be explored to achieve improved electrical and density properties. It will be also important to try other eco-friendly solvents in the resin development process.

## CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

## COMPLIANCE WITH ETHICAL STANDARDS

This article does not contain any studies involving human or animal subjects.

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#### Persian Abstract

#### چکیده

استفاده مجدد احتمالی از پرکننده‌های آهن از دستگاه فرز و پلی استایرن در جریان زباله‌های جامد در تولید کامپوزیت‌های پلاستیکی در این مطالعه در نظر گرفته شد. آماده‌سازی، خصوصیات الکتریکی، تراکم، کسر فضای خالی و توزیع ذرات کامپوزیت‌های پلی استایرن محلول، همه به عنوان تابعی از غلظت پرکننده های آهن بازیافتی بررسی شد. کامپوزیت‌ها با استفاده از روش چیدمان دستی تولید و با ریخته‌گری تحت شرایط محیط (۲۵ درجه سانتیگراد) به مدت ۷ روز بهبود یافتند. میکروگراف‌های مقایسه شده پر شدن آهن بازیافتی پراکنده در ماتریس پلی استایرن و کاهش کسر فضای خالی را با افزایش پر شدن آهن در کامپوزیت‌ها تایید می‌کنند. بیشترین مقادیر هدایت الکتریکی و چگالی کامپوزیت‌ها در بالاترین ترکیب پرکننده آهن ۴۰ درصد وزنی به ترتیب  $5/91 \times 10^{-7}$  S/cm و  $1/31$  g/cm<sup>3</sup> به دست آمد. کامپوزیت آهن پلی استایرن توسعه یافته از ویژگی‌های الکتریکی خوبی برخوردار است، و این ماده را به عنوان ماده جایگزین برای فلزات مناسب می‌نماید.