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Mechanical Properties of Steel-making Slag Reinforced Polyester Composites

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Abstract: *In order to assess the viability of utilising steelmaking slag for reinforcing polyester matrix to form composites with improved mechanical properties, slag was obtained from an indigenous steel production plant and prepared by crushing and pulverizing. This was followed by sieving into 75, 106 and 300 µm sizes and, varied masses of the particles were used to develop the composites by reinforcing the unsaturated polyester resin with the steelmaking slag particles. The homogeneous mixtures were poured into the flexural and tensile tests moulds and allowed to cure before being stripped from the moulds. The samples were further allowed to cure for 30 days before carrying out the mechanical tests. The results showed that the composites produced have indeed gained increment in these properties compared to the unreinforced polyester material. The optimum results were obtained from the use 106 µm and 2 wt% slag particles.*

Keywords: *Steelmaking slag, reinforcement, composites, mechanical properties.*

1. Introduction

To cope with the obvious limitations of polymers, for example, low stiffness and low strength, and to expand their applications in different sectors, inorganic particulate fillers, such as micro-/nano-SiO_2, glass, Al_2O_3, Mg $(OH)_2$ and $CaCO_3$ particles, carbon nanotubes and layered silicates, are often added to process polymer composites, which normally combine the advantages of their constituent phases. Particulate fillers modify the physical and mechanical properties of polymers in many ways (Fu *et al*., 2008).

It has been shown that dramatic improvements in mechanical properties can be achieved by incorporation of a few weight percentages of inorganic exfoliated clay minerals consisting of layered silicates in polymer matrices (Kim *et al*., 2004). Commonly used layered silicates have a thickness of ≈1 nm and lateral dimensions of ≈30 nm to several microns or larger. The large aspect ratios of layered silicates are thought to be mainly responsible for the enhanced mechanical properties of particulate-polymer nano-composites.

Many studies have been conducted on the mechanical properties of these particulate-filled polymer composites. Stiffness or Young's modulus can be readily improved by adding either micro- or nano-particles since rigid inorganic particles generally have a much higher stiffness than polymer matrices (Zhu *et al*., 1999; Fu and Lauke, 1997; Wang *et al*., 1998). However, strength strongly depends on the stress transfer between the particles and the matrix. For well-bonded particles, the applied stress can be effectively transferred to the particles from the matrix; this clearly improves the strength (Reynaud *et al*., 2001; Ou *et al*., 1998). However, for poorly bonded micro-particles, strength reductions occur by adding particles (Liang *et al*., 1997; Tjong and Xu, 2001). The drawback of thermosetting resins is their poor resistance to crack growth. But inorganic particles have been found to be effective tougheners for thermosetting resins. In contrast, most studies on thermo plastics filled with rigid particulates reported a significant decrease of fracture toughness compared to the neat polymers (Jancar and Dibenedetto, 1995; Fu and Lauke, 1998). There are, however, several studies that show toughness to have increased with the introduction of rigid particles in polypropylene and polyethylene, respectively (Pukanszky, 1995). Impressively, enhanced impact toughness has been reported for polyethylene filled with calcium carbonate particles. Enhancement of impact properties of some pseudo-ductile polymers by the introduction of inorganic particles has also been achieved (Fu and Wang, 1993; Bartczak *et al.*, 1999).

Slag is the by-product of iron and steel production processes and, has been used in civil engineering for more than 100 years. Rapidly water-cooled Electric Arc Furnace Slag (EAFS), due to its relative high amorphous silica content which has pozzolanic activities, is to be employed in the production of blended cement. Even there are some research works about the properties of concretes, in which air-cooled and ground granulated EAFS were used as aggregates. The conclusions of these studies indicate that there is a great likelihood to use

EAFS instead of natural aggregate in concrete. It has been widely employed as aggregate, mainly in base, sub-base and bituminous pavement for road construction, in which steel slag provides many advantages in comparison with natural aggregates (Chaurand *et al.*, 2007).

Although many studies have been conducted on the evaluation of steel slag to be used in road construction, there are rare researches regarding the utilisation of steel slag in concrete. ASTM C336 gives specifications for the use of blast furnace slag as aggregates in concrete, while there is not such a standard for steel slag (Frias and Sanchez, 2004).

Chemical composition and temperature during manufacturing determines the structure of the slag which further influences other properties. Granulated slag aggregate is currently utilised mainly in earthworks of linear transport communications, as backfill in retaining structures, backfill of roads and pipeline structures, in motorway rugs and groundwork layers, for terrain modification works, during manufacturing of burnt brick products, and also for revitalisation of depleted mines. Beside granulated slag aggregate, which is not yet so widely used, slag is generally utilised in form of fine grounded blast furnace slag which is used as active and filler admixture to concrete.

Utilisation of finely ground slag is an established method of reusing of this metallurgical by-product, mainly in concrete and cement industries. Special attention has been directed at investigating the possibilities of it being used as substitute for natural mineral aggregates when producing asphalt mixtures. Results of analyses usually conducted when testing physical and chemical characteristics of natural mineral aggregates intended for the same purpose have been demonstrated (Motz and Geiseler, 2001).

Having noticed from previous works that particulate fibres are good source of reinforcement materials to fill and enhanced the properties of matrixes. And considering the wide application of steelmaking slag in ceramic matrix, this work was carried out to investigate the influence of steelmaking slag on unsaturated polyester material. This was done with the aim of turning waste to wealth by using slag for engineering applications.

2. Materials and Methods

This research was carried out with the following materials; Unsaturated polyester resin, Ethyl Ethyl Ketone Peroxide (MEKP), Cobalt 2% in solution, polyvinyl acetate and ethanol. The steelmaking slag that was a waste product of electric arc furnace was sourced from universal steel Ikeja Lagos Nigeria. XRD was carried out to examine the composition of the slag, and it was as shown in Table 1.

2.1 Material Preparation

The steelmaking slag that was obtained in lumps form was crushed with hammer and finally pulverized using Denver laboratory ball mill. The particle from the process was sieved with sieve shaker 16155 Model into 75, 106 and 300 µm sieve sizes. XRD was carried out with Fluxana-HD Elektonik Vulcan Fusion Technology.

Table 1. XRD analysis for the steelmaking slag

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O
36.79	10.55	21.05	5.79	2.58	0.06	0.4

NaO	LOI	LSF	SR	AR	Mn	Ti
1.39	0.08	5.73	1.01	0.4	11.01	2.26

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2.2 Mould Production

Tensile mould of gauge length 90 x 5 x 3 mm of a dumb-bell shape and flexural mould of 150 x 50 x 3 mm were used for the production of tensile and flexural samples respectively from where the hardness samples were obtained.

2.3. Production of Composites

To develop the composites, 1.5 g each of catalyst and accelerator was added to 120 g of the unsaturated polyester resin while the steelmaking slag particulate was varied in a predetermined proportion of: 2, 4, 6, and 8 wt%. After proper stirring, the homogenous slurry is poured into the mould and allowed to cure inside the mould at room temperature before it is removed. The cured sample is left for 3 weeks before the mechanical tests were carried out.

2.4.Mechanical Property Tests

Cured composite samples were prepared for tensile and flexural tests after which Scanning Electron Microscope (SEM) was used to investigate the miscibility between the filler and matrix at the fractured surfaces. These tests were carried out as follows;

(a) Determination of the tensile properties of the materials - In the present study, tensile tests were performed on INSTRON 1195 at a fixed Crosshead speed of 10 mm min^{-1}. Samples were prepared according to ASTM D412 and tensile strength of the standard and conditioned samples were calculated.

(b) Determination of the flexural property of the materials - Flexural test was carried out by using Testometric Universal Testing Machine in accordance with ASTM D790. To carry out the test, the grip for the test was fixed on the machine and the sample that has been cut into the test piece dimension of 150 x 50x 3 mm, was hooked on the grip and the test commenced. As the specimen is stretched the computer generates the required data and graphs. The Flexural Test was performed at the speed of 100 mm/min.

(c) SEM Observation - SEM of the composites was observed using Zeiss SEM: Zeiss Ultra Plus 55 FECSEM, Zeiss, Oberkochen Germany. Before the examination, the samples were prepared by cutting with bench vice and hacksaw followed by gluing on sample holder and finally coated with carbon using Carbon Coater: EMITECH K950X, EM Technologies, Kent, England.

3. Results and Discussions

The mechanical properties of particulate–polymer composites depend strongly on the particle size, particle–matrix interface adhesion and particle loading. Particle size has an obvious effect on these mechanical properties. Various trends of the effect of particle loading on composite strength have been observed due to the interplay between these three factors, which cannot always be separated.

Figures 1-3 show the results of the tensile properties for the various samples. It was noticed that the reinforcements bring about improvement in all the tensile properties compared to the unreinforced polyester. The results revealed that steelmaking slag particulates would actually be utilised to improve the tensile properties of unsaturated polyester.

From Figure 1, it was observed that 8 wt% of 300 µm slag particle addition gave the best ultimate tensile strength result with a value of 61.03 MPa compared to the unreinforced polyester material (control) with a value of 50.76 MPa. This implies that the property has been enhanced by 20 %.

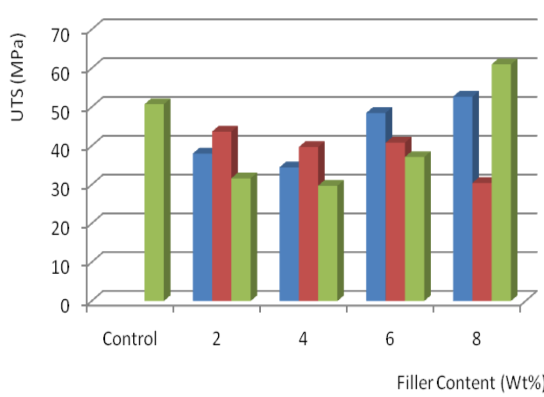

Figure 1. Variation of ultimate tensile strength with filler content for the varied steelmaking slag particles

Figure 2 shows the ultimate tensile strain results for the samples. From the results, it was observed that, 6 wt% from 106 and 300 µm particle sizes gave the best values of 0.028 and 0.027 mm/mm, respectively compared to the unreinforced polyester with a value of 0.016 mm/mm. These culminate to 75 % and 69 % enhancements, respectively.

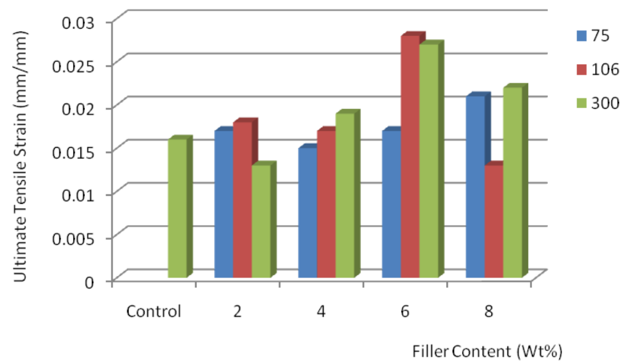

Figure 2. Variation of ultimate tensile strain with filler content for the varied steelmaking slag particles

The results of the Young's modulus in Figure 3 show that 2 wt% of 300 µm particle size reinforced sample gave the best result with a value of 4084.26 MPa compared to the unreinforced polyester matrix which has a value of 3966.15 MPa. This amounts to 2 % increment in this property. The results revealed that 300 µm particle size followed by 106 µm particle size would be the best particle size for tensile property enhancement.

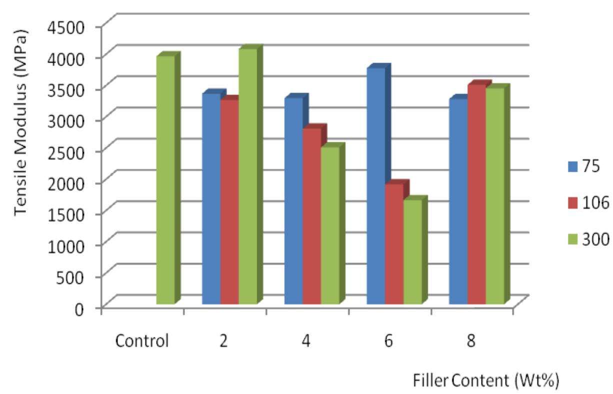

Figure 3. Variation of tensile modulus with filler content for the varied steelmaking slag particles

Figures 4 and 5 show the flexural properties results from where it was observed that, the reinforcement also brings about enhancement in flexural properties of the composites compared to the unreinforced polyester material. From Figure 4, it was observed that 2 wt% from 106 µm particle size gave the best flexural strength at peak with a value of 69.91 MPa compared to the unreinforced polyester sample with a value of 43.25 MPa. This amounts to 62 % enhancement compared to the neat polyester.

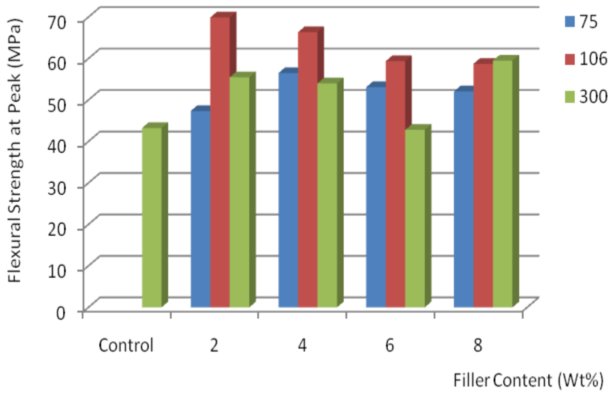

Figure 4. Variation of flexural strength at peak with filler content for the varied steelmaking slag particles

Also from Figure 5, the flexural modulus results showed that 2 wt% from 106 µm particle size gave the best flexural modulus with a value of 11957 MPa compared to the unreinforced polyester sample with a value of 7452MPa. This amounts to 60 % enhancement compared to the neat polyester. These results show that flexural properties were highly improved with 106 µm particle sizes addition. This was in agreement with the tensile test results where it was noted that 106 µm particle sizes gave the best enhancement in tensile strain property. Tensile strain property is a measure of similar mechanical property in terms of flexural strength properties which is the ability of the materials to be stress for long time before fracture. They both relate to the ductility nature of a material. However, these properties tend to decreases as the filler content increases from 2-8 wt% considering the particle size (106 µm) that gave the best results in flexural property investigation.

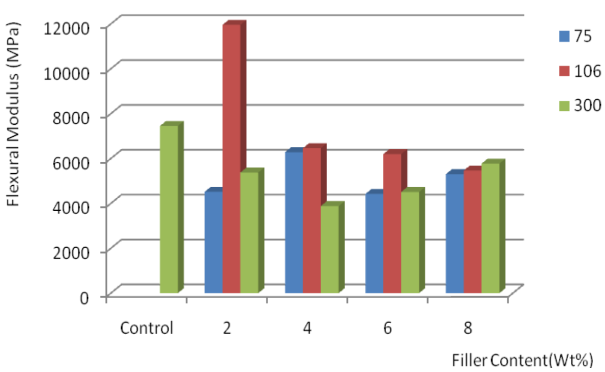

Figure 5. Variation of flexural modulus with filler content for the varied steelmaking slag particles

From Figures 6-8, it was observed that as the particle size increases, the number of particles that are present decreases due to weight increase.

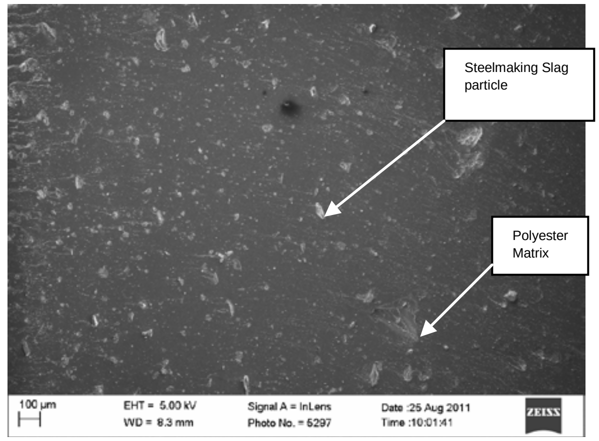

Figure 6. SEM of Fractured surface of 8 wt % from 75 µm particle size steelmaking slag filled polyester composites

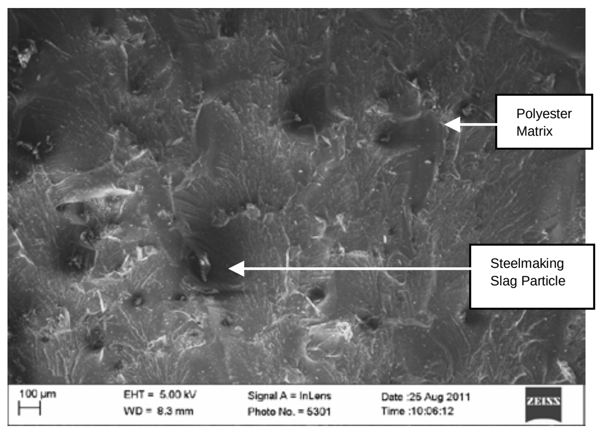

Figure 7. SEM of Fractured surface of 8 wt % from 106 µm particle size steelmaking slag filled polyester composites

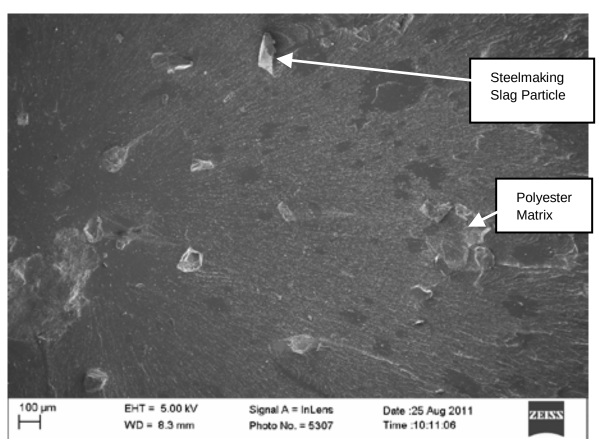

Figure 8. SEM of Fractured surface of 8 wt % from 300 µm particle size steelmaking slag filled polyester composites

The images revealed that there is proper bonding between the steelmaking slag particles (white part) and the unsaturated polyester matrix (dark part) which was responsible for the good mechanical properties that was obtained from the mechanical tests results. As a result of the good interfacial bonding strength between the slag and the polyester matrix, as well as adequate particle dispersal in the polyester matrix, better enhancement of properties was obtained for the composites for both tensile and flexural properties compared to the neat polyester matrix. Despite these good observations with respect to the interaction between the steelmaking slag particles and the unsaturated polyester, 75 µm particle size performed less compared to 106 and 300 µm particle sizes. This may be due to low strength from the fine particles compared to others.

4. Conclusion

The desire to ensure that there is proper utilisation of every materials and the drive for zero waste have motivated the use of steelmaking slag as a reinforcement in unsaturated polyester matrix in order to develop polymer based composites for different applications in areas like automobile and structural industries. As a result of the capability of particulate materials to reinforce and bring enhancement in polymer properties, steelmaking slag has also confirmed the suitability of its use as a filler and reinforcement in unsaturated polyester material.

From this work, it was observed that;

(a) The mechanical properties; flexural and tensile, were highly enhanced by the addition of 106 µm particle sizes of the steelmaking slag. While the addition of 2 wt% of this particle sizes gave the best flexural property results, the addition of 6 wt% gave the best tensile strain result.

(b) The use of 300 µm particle sizes of the steelmaking slag led to the enhancement of the tensile properties of unsaturated polyester matrix where it was observed that 2 wt %and 8 wt % gave the best results for modulus and ultimate tensile strength respectively.

(c) The work shows that the addition of these steelmaking slag particles in small quantity, that is, low fibre content is the best for optimum results. This was the case since both properties were highly enhanced by the addition of 2 wt% fibre content compared to others.

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