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Mechanical Properties of Electric Arc Furnace Dust Filled Epoxy Composite

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Abstract: *In this work, mechanical properties of Electric Arc Furnaces (EAF) dusts filled epoxy composite were studied. Water absorbent test, Hardness, Tensile and impact test were conducted respectively on samples with varying volume of EAF dust reinforcement, ranging from 10% volume fraction to 40% volume fraction of the EAF dust, and the pure epoxy. All the samples showed no changes in weight and physical appearance after submersion in water for 30 days. Sample with 20% volume fraction recorded the highest impact strength (2.79 Joules), the impact strength of the pure epoxy was 2.1 Joules. There was gradual reduction in tensile strength from 176MPa, recorded for the pure epoxy to 155MPa for the 40 vol. % EAF dust reinforcement, while the hardness value increased from 195HB for the pure epoxy to 217HB for composite with 40 vol. % reinforcement.*

Keywords : *adhesion force, cohesion force, curing, debonding, particle to particle interaction/ aggregation*

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I. Introduction

Over the past decade, quest for materials with low density, higher specific strength and stiffness, higher corrosion resistance and improved fatigue has driven research into study of composite materials. Composites are advanced materials produced by assembling two or more components with fillers or reinforcing fibers which are compacted within a matrix [1]. They usually possess combined properties of the matrix and filler material(s) used.

Researches on these materials have brought about advancement that has made it increasingly used as replacement for engineering components. Polymer composites are easy to process into different sizes and shapes, they have low cost, achieved by replacing the volume of costly resins with cheap fillers which are incorporated to enhance properties like modulus, strength, heat deflection temperature, and tribological properties. For example, studies have shown that particulate filled epoxy is a preferred choice in applications involving nonstructural materials like bearings, and seals [2]. Also, in aviation, naval and automotive industries, metallic fiber reinforced polymer (FRP) composites are being introduced as replacement for metallic component [3]. Some examples of these components include cams, seals, brakes, bearings. Common matrices used for composite materials include mud, cement (concrete), polymers (fiber reinforced plastics), metals and ceramics, while common fillers of various sizes and shapes being used and or researched on include carbon fiber, calcium carbonate, talc, mica, zinc oxide, kaolin, copper-oxide, titanium dioxide.

In this work, Epoxy resins were used as the matrix, while EAF dust was used as the reinforcement. Epoxy resins belong to a category of reactive prepolymers and polymers that contain epoxy group which may be cross linked either with each other or with other co-reactant to form thermosetting polymer. They are widely used in engineering and structural applications such as electrical industries, automotive and aircrafts industries. EAF dusts on the other hand are small particles consisting partly of entrained drops of metal, slag, and other volatile metals, which are fumed from the steel melt, oxidized, and later captured as airborne particles. EAF dusts are hazardous waste produced during the production of iron and steel by means of an arc melting furnace. Their composition may vary with respect to the type of steel being manufactured. Common EAF dust components from production of steel may include iron and iron oxides, Aluminum, zinc, chromium, Cadmium, Magnesium, Lead, nickel oxide and other metals used for alloys.

Studies have shown that with the right combination of filler and matrix, composite materials can be very effective especially if applied in a suitable operating environment [4,5,6]. Adeosun et al. [7] found out that refractory properties of steel dust sintered at 1000ºC are strongly influenced by the amount of bentonite content. Shao-Yun et al. [8] noted that the strength and toughness of composite materials are strongly affected by particle size, particle/matrix adhesion and particle loading, while the stiffness depends significantly on particle loading. Onitiri and Adedayo [9] discovered alteration in the value of the impact strength as the size and volume of the iron ore tailings in the composite was varied. Adeosun et al. [10] also discovered that the presence of 10 wt. %

steel dust in 6063 Aluminum/ steel dust composite resulted in a tremendous improvement in the UTS and hardness.

Chang et al. [11] found that short carbon fibre (SCF), graphite flakes, and sub-micro particles of TiO_2 and ZnS influence both the wear resistance and the load-carrying capacity of polyetheretherketone (PEEK) and polyetherimide (PEI) significantly. Xiang et al. [6] also observed that incorporation of kaolin particles in PTFE reduced the wear rate by two orders of magnitude as compared to the unfilled PTFE. Jogi et al. [12] observed that the mechanical behavior of blend with 6-amino hexanoic acid Na-AHA modified multiwall carbon nanotubes (MWNT) was strongly influenced by the carbon nanotubes, its dispersion, the morphology developed during compounding, as well as the interfacial adhesion between the phases. Extensive study on the application of nanoparticles for modifying epoxy matrix has also led to improvement in the mechanical properties of fibre reinforced polymer composites [3].

II. Materials And Methods

2.1. Materials

The Epoxy resins and polyamine hardener employed in this study was obtained commercially, from a private dealer of raw materials in Aba, Abia state, Nigeria. The EAF dusts particles employed in this study was obtained from Delta Steel Company (DSC.), an integrated steel plant located in Ovian-Aladja, Delta State, Nigeria. Delta Steel Company utilizes a fume extraction System for the filtration of their furnace off-gases.After sieving, the particle size of the dust was found to range between 47µm (300 BSS) to 95 µm (150 BSS), and 75% of the dust particle was found to be in the range of 95 µm. The sieving was done with a standard test sieve (with vibrator attached).

Average size of the dust particle employed was 47µm.

2.2. Sample Preparation:

- Closed cylindrical mold of diameter 20mm was employed.
- The inner surface of the mold was lined with PVC for easy parting of the thermoset.
- Control samples were prepared using 100% epoxy compounds.
- Four samples with varying volumes (10 – 40%) of EAF dusts respectively were prepared by the addition of the EAF dust at an interval of 10%.
- Mixtures poured in the mold where adequately rammed and then sealed to prevent expansion during curing.
- Curing was done at a controlled temperature with the aid of a water bath, to ensure uniform curing and prevent entrapped volatiles or voids.
- Prepared samples were machined to desired shape/ dimension as per ASTM standard for required tests.

2.3. Theory

The EAF dust particles are assumed to be spherical in shape and of uniform size. The density of the composite (D_c) is a function of both the density of the matrix and the filler.

The governing equation is given as;

$$D_c = \left(1 - V_p\right)d_e + d_m V_p \quad (1)$$

Where; V_p is volume fraction of EAF dust particle and $(0<V\leq1)$, d_e is density of pure epoxy with experimentally obtained value of $1.04gcm^{-3}$, and d_m is mean value of density of EAF dust particle with experimentally obtained value of $2.9765\ gcm^{-3}$.

The strength of a material is the maximum stress that can be sustained under uniaxial tensile loading by the material. For micro- and nano-particulate composites, the strength relies on the effectiveness of stress transfer between the matrix and reinforcement. These stress transfer between the components of the composite largely depend on the particle– matrix interface adhesion and particle loading [13,14]. In composite materials, the load-bearing capacity depends on the strength of the weakest path within the microstructures, while the strength is determined by their fracture behaviors which are associated with the extreme values of several parameters which include interface adhesion, stress concentration size/spatial distributions and defect. Hard particles also weaken the strength due to their stress concentration, while they strengthen the composite by their reinforcing effects since they may act as barriers to crack growth. Hence, the overall strength of the composite will be determined by the predominant effect [8]. Pukanszky et al [15] proposed a model which includes the assumption that the matrix cross section is zero when the volume fraction of the filler is less than 1;

$$\sigma_c = \left[\frac{1 - V_p}{1 + 2.5V_p}\sigma_m\right] exp\left(BV_p\right) \quad (2)$$

B is a constant, and it depends on the surface area of particles, particle density, interfacial bonding energy and the nature of interfacial bonding existing. $4 > B \geq 0$.
For this model, the value of B was taken as 2.98.

III. Result

3.1. Water Absorbent Test
The composites showed no difference in weight and physical appearance after submerging all samples separately in a water bath, at ambient temperature for 30days.
3.2. Density
From Fig. 1 below, the density of the composite gradually increased as the Volume fraction of the EAF dust particle was increased.

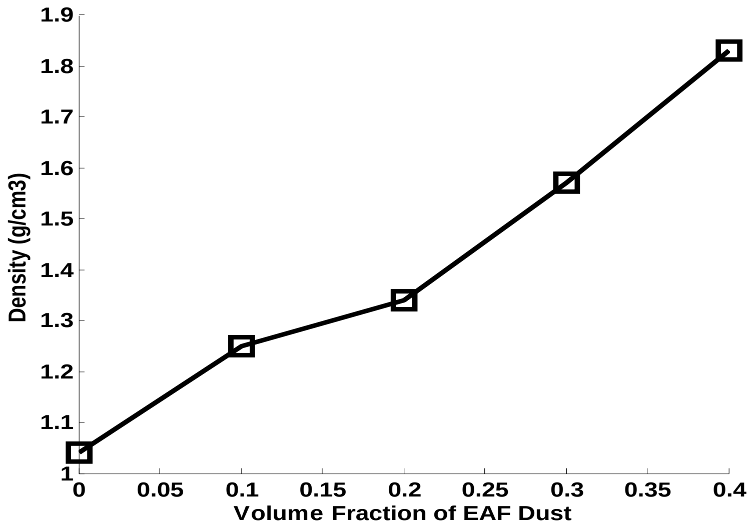

Figure 1: Density of different volume fraction of eaf dust filled composites

3.3. Hardness
Fig. 2 below showed gradual increase in the hardness value as the volume of the reinforcement in the composite was increased.

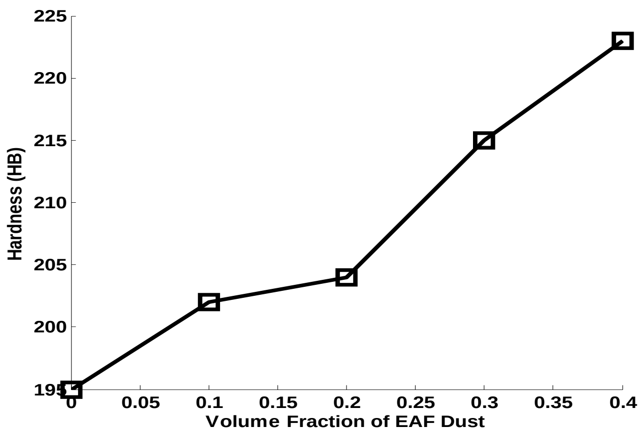

Figure 2: Hardness of EAF dust filled Composite

3.4. Tensile Strength
In Fig. 3 below, there was a gradual reduction in the tensile strength (UTS) of the composite as the volume fraction of the filler increased from 10% to 40%. It was observed that the pure Epoxy sample (0% EAF dust) recorded a UTS value higher than that of all the composites.

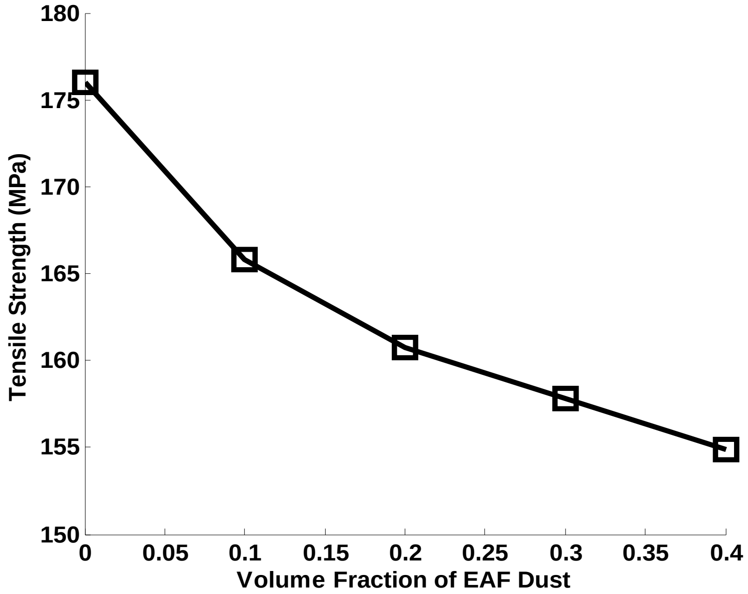

Figure 3: Tensile Strength of EAF dust filled composite

Fig. 4 gives a comparison of Pukanszky et al. [15] model with the experimental trend. The figure showed that the model gives a good prediction of the experimental trend for the ultimate tensile strength of the composites, as volume fraction of EAF dust particles was gradually increased.

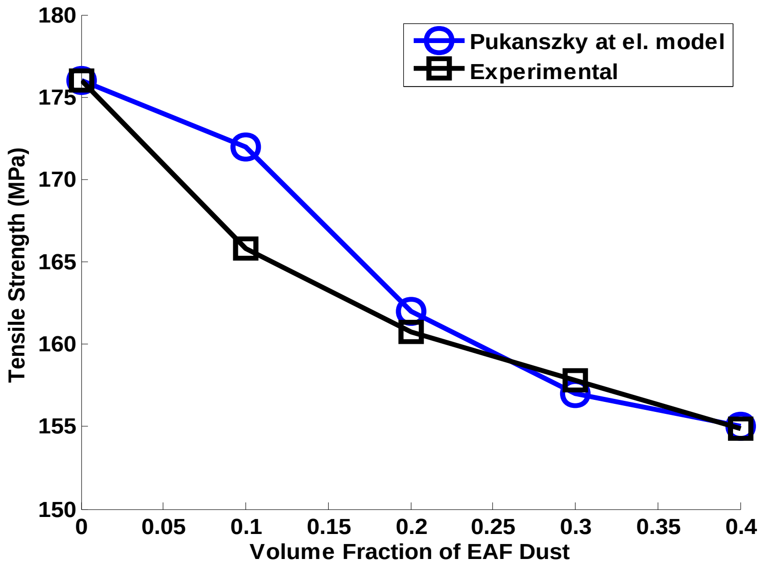

Figure 4: Experimental result and proposed model of Pukanszky and others (1988), for Tensile Strength of composite.

3.5. Impact Strength

In Fig. 5, there was an increase in impact strength as the volume of the reinforcement in the composite was increased to 20%. On further increase of the volume fraction of the reinforcement in the composite beyond 20%, there was gradual reduction in the impact strength. The impact strength of the reinforced composites respectively was higher than that of the pure epoxy. Among the reinforced composites, composite with 10% EAF dusts reinforcement had the lowest impact strength of 2.15 joules while composite with 20% EAF dusts reinforcement recorded the highest value (2.79 joules). The pure epoxy had impact strength of 2.10 Joules.

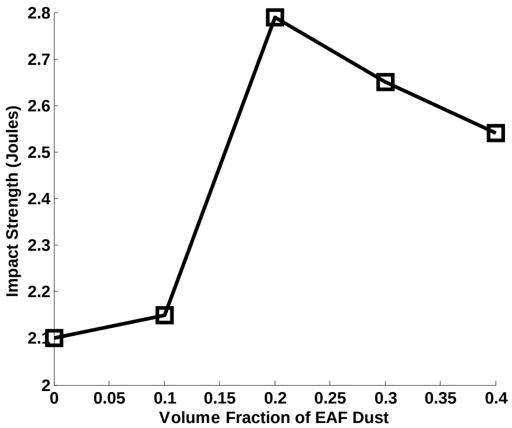

Figure 5: Impact strength

IV. Discussion

The strength of composite material is a function of the cohesion force within the matrix, adhesion force between the filler and matrix, and the concentration of particle to particle interaction/aggregation. At any given volume fraction of reinforcement in the composite, the magnitude of the mechanical property depends on the effect of the predominant binding force, and also on the effect of particle to particle interaction/aggregation. Particle to particle interaction/aggregation is a form of defect in particulate composite. They are potential sites for initiation of debonding as a result of their weak bond, due to nonexistence of adhesive force at the interface between the particles. Their effect on the strength of composite may be negligible, when their concentration is below certain critical value, but beyond this value they tend to weaken the strength of the composite due to increase in the number of potential weak paths and thus, increase in the amount of weak bonds. The effect of particle to particle interaction was observed in the tensile strength as shown in Fig. 3. As the concentration of the particle to particle interaction increases due to increase in the volume fraction of EAF dust, there was reduction in the strength of the composites. This trend is due to an increase in available weak paths that can result to discontinuity in form of debonding, which then leads to inefficient stress transfer at the EAF dust/epoxy interface.

However, there was remarkable increase in hardness of the composite, compared to that of the pure epoxy, as shown in Fig. 2. This is partly as a result of the cohesion and adhesion forces which were sufficient to produce compactment that do not debond under the influence of indentation. Hence, as the volume fraction of EAF dust particle is increased, there is increase in the resistance to indentation due to increase in density. The impact strength of the composite depends largely on the cohesion and adhesion force, and on the ability of the composite to arrest cracks initiated by impact. In Fig. 5, as the EAF dust particles was increased to 20% volume fraction, there was increase in the impact strength of the composite. Within the range of 20% volume fraction EAF dust, the cohesion and adhesion force is significantly high and the effect of particle to particle interaction becomes negligible, hence as the density increased due to increase in vol. % of EAF dust particles the impact strength also increased. However, as the volume fraction of the EAF dust particles was further increased beyond 20%, there was reduction in the impact strength. This reduction is partly due to the adhesion force which gradually becomes subsidiary, and also partly due to increase in the concentration of particle to particle interaction which provides more weak paths that causes accelerated growth rate of micro cracks initiated by the impact force.

V. Conclusion

In this study, the mechanical property of Electric Arc Furnace dust filled epoxy composite was presented. The Hardness, Tensile and impact strength are found to be influenced by the volume fraction of the EAF dust particles. Sample with 20% volume fraction recorded the highest impact strength of 2.79 Joules, the impact strength of the pure epoxy was 2.1 Joules. Though, the ultimate tensile strength of composite with 10% volume fraction was the highest (172MPa) among the composites, composite with 20% reinforcement also recorded an appreciable value (162MPa). The value recorded by the pure epoxy was higher (176MPa) than that of the composites. Sample A (pure epoxy) recorded the lowest hardness value of 195HB, while composite with 40% volume fraction reinforcement recorded the highest value of 223HB. The hardness value of composite with 20% reinforcement was considerable (204HB).

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