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Research on the Electrical and Mechanical Properties of Conductive Epoxy Composite

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Abstract

This paper reported on the possibility of using organic materials in the production of green epoxy conductive composites. Epoxy composite samples were produced through the hybridization of carbonized coconut fibre filler (CCS), raffia palm fibre (RPF), carbon black (CB), and carbon fibre (CF), using the simple hand lay-up technique. Then the electrical properties (electrical resistivity and electrical conductivity) and the mechanical properties (tensile strength) of the composite samples were tested accordingly, using the ASTM D6343 – 14, ASTM B193 and ASTM D 3039 approved methods. Results obtained from the laboratory tests revealed that both the CCS and RPF (organic materials) have significant influence on the mechanical and electrical properties of the composite samples. It was observed that the electrical conductivity of the composite samples increased ($4.34x10^{-3}$ S/cm to $4.48x10^{-3}$ S/cm) as the CCS loading increased from 3% to 6% (by mass); before it started to decline after 9% (by mass) CCS loading, recording lowest conductivity of $9x10^{-4}$ S/cm at 15% CCS volume. The electrical resistivity of the composite samples was noted to decline from $2.90x10^{7}$ Ωcm to $2.83x10^{7}$ Ωcm as the CCS content in the composite increased from 3% to 6%, before it started to increase after 9% CCS quantity, with the S5 composite sample (15% CCS quantity) having the highest electrical resistivity of $3.80x10^{7}$ Ωcm. Regarding the composite's mechanical properties, the study depicted that the S1 composite sample had the highest tensile strength of 98.3 MPa, while the S5 composite developed the lowest tensile strength of 62.7 MPa, portraying that the CCS and RAF has a substantial effect on the composites samples' tensile strength. This study's results portrayed the possibility of producing lightweight, high-tensile strength conductive composite from organic waste materials, which can be utilized in several engineering applications.

Keywords: *Green composite, coconut fibre, hybridization, raffia palm fibre, synthetic materials*

INTRODUCTION

Composites are made by incorporating reinforcement materials into a matrix material (binder), resulting in the production of a new material with superior characteristics to either of the raw materials. The demand for composites is increasing due to their vast applications in various sectors. Conductive composite, a special type of composite with significant electrical properties, are becoming vital electrical and electronic components in several electrical applications. The application of green conductive composites is increasing mostly in aerospace and automobile industries, due to high electrical conductivity and eco-friendliness, compared to ordinary composites (Singha and Thomas, 2008; Islam *et al*., 2018; Obukoeroro and Uguru, 2021a). Islam *et al*. (2018) reported that conductive composites can be used as semiconductors, pressure sensors and self-regulated heating materials. Obukoeroro and Uguru (2021a) stated that apart from appreciable electrical properties, conductive composites must have good mechanical properties, for them to withstand the tension and tensile stresses they are subjected to in the field. Altering the matrix – to – reinforcement material(s) ratio, to accommodate more reinforcement materials tends to increase the mechanical and electrical behaviours of most composites. When used in excess, reinforcement materials can result in composites with poorer mechanical and electrical properties due to weak bonding between the matrix and the reinforcement materials (Ayatollahi *et al*., 2011; Edafiadhe *et al*., 2019; Akpokodje *et al*., 2021).

Recently, there have been studies into the effect of organic and inorganic materials on the electrical conductivity of various electronic components (Igbologe and Okieke, 2022). The amounts and types of reinforcing materials have a significant impact on the electrical properties of conductive composites. Activated carbon, copper nitride (Cu_3N) and aluminum nitride (AlN) are some of the commonly utilized fillers (reinforcement materials) employed during the production of conductive composites. According to Shu-Hui *et al*. (2004) and Yung *et al*. (2010), aluminum nitride has the ability of improving the electrical properties of polyimide composites, Dutta *et al*. (2007) in their investigation into the electrical properties of polypyrrole–silica reinforced composites, observed that the electrical conductivity of the composites increased non-linearly with an increment in polypyrrole–silica quantity. Kristin *et al*. (2014) reported that composites produced from a low volume of multi-walled carbon nanotubes have good electrical properties, and can be used in antistatic coatings and batteries.

Additionally, Uguru and Obukoeroro (2020) and Odoh *et al.* (2022) reported that impurities in molten copper matrix composites, are responsible for the poor electrical conductivity and high electrical resistivity exhibited by such copper wires. It was also noted by Omah *et al.* (2018) that the electrical resistivity of carbonized bone - epoxy composites tend to decline as the volume of the filler increases. According to Tepsila and Suksri (2018), the electrical properties of composites produced with organic fillers/fibres tend to be better, compared to those produced with synthetic fillers/fibres. In a study carried out by Aleksandra *et al.* (2014), they observed that the capacitive behaviour of the activated carbon-reinforced composite was superior to plain composite; thus the carbonized composite can be effectively used as capacitors in the automobile and electronic industries. Furthermore, Choi *et al.* (2019) stated that carbon black (CB) can improve the conductivity of polymer resin, and the composite's electrical conductivity is a factor of the percentage of CB incorporated into the matrix.

Choosing the appropriate materials is inevitable in composite production in order to achieve desired goals. The engineering properties of green conductive composites are influenced by crop varieties (Eboibi *et al.*, 2019), pre-harvest treatment (Akpokodje and Uguru, 2019; Edafeadhe and Uguru, 2020), post- harvest treatment (Navdeep *et al.*, 2012; Nyior *et al.*, 2018), hybridization (Bao, 2008; Bratte and Uguru, 2021), and the maturation (Oghenerukewve and Uguru, 2018) of the reinforcing materials. Lopattananon *et al.* (2008) reported that the chemical treatment of pineapple leaf fibre (PALF) improves the mechanical properties of composites produced from them. It has been observed that modification of natural fibres increases their contact surface areas and interface cross linkages (Uguru and Umurhurhu, 2018; Obukoeroro and Uguru, 2021a); hence enhancing its electrical and mechanical properties in the process. Green composites with poor engineering properties have very little applications in the engineering sector (Li *et al.*, 2008; Agbi *et al.*, 2020).

Though several researches have being done on conductive composites, a related literature search revealed that very little work had being done on the hybridization of green materials in conductive composite production. Therefore, this study was aimed at the production of composite through hybridization of carbonized coconut fibre, raffia palm fibre, carbon fibre and carbon black; with appreciable mechanical and electrical properties.

MATERIALS AND METHODS

Materials

The raffia palm fibre (RPF), carbon black (CB), carbon fibre (CF), epoxy resin (type: LY 556) and hardener (type: HY951) were procured from the local markets and chemical shops in Delta State, Nigeria.

Methods

Carbonization of the coconut fibre

The coconut fibre was carbonized in accordance with AOAC procedures to obtain the carbonized coconut fibre. Then the carbonized fibre was pulverized and sieved using a 150 μm gauge fabric sieve to obtain the carbonized coconut fibre filler (CCS).

Composite samples production

The matrix was prepared by mixing the hardener and epoxy resin at a ratio of 3:7; while the quantity of the enforcement materials used for the various composite samples production is given in Table 1. All materials were batched by mass.

Table 1: Composite samples composition

Sample Code	Reinforcement materials (%)				Matrix
	CCS	CB	CF	RPF	
S1	3	15	7	6	70
S2	6	12	6	8	70
S3	9	9	5	7	70
S4	12	6	4	8	70
S5	15	3	3	9	70

The composite samples were prepared in accordance with the simple hand lay-up technique, as described by Umurhurhu and Uguru (2019). After production, all the composite samples were kept under a constant weight (10 kg) for 20 hours to expel all the entrapped air, before they were left to cure at room temperature (24±4^{0}C) for one week.

Electrical conductivity determination

The electrical conductivity was determined in accordance with ASTM D6343 – 14 (2018) procedures, as described by Obukoeroro and Uguru (2021a). Then the electrical conductivity of each sample was calculated by using the formula shown in Equation 1.

$$Electrical\ conductivity\ (s/m\,m) = \frac{1}{R} = \frac{L}{rA} \quad 1$$

Where:
R = resistivity of the composite (Ω m),
r = resistance of the composite (Ω),
A = cross-section area of the composite (m^2),
L = length of the composite (m)

Electrical Resistivity determination

The electrical resistivity was determined in accordance with ASTM B193 (2020) as described by Obukoeroro and Uguru (2021a). Each composite sample's electrical resistivity was calculated through the formula given in Equation 2 (Omah *et al.*, 2018).

$$\text{Electrical resistivity} = \frac{R \times A}{L} \quad 2$$

Where:
R = Resistance (Ω),
A = Cross-sectional area (m^2),
L = Length of the composite sample

Tensile strength determination

The samples' tensile strength were measured by using the Universal Testing Machine [UTM (Testometric model)], in accordance with ASTM D 3039 (2017) procedures; at a loading rate of 1 mm/min. At the end of each test, a force-deformation curve was plotted automatically by the UTM, and the tensile strength was calculated using the expression shown in Equation 3 (Abdullah-Al-Kafi *et al.*, 2006).

$$Tensile\ Strength\ (\sigma) = \frac{F_{Max}}{Area} \quad 3$$

Where:
F_{max}= Maximum force absolved by the sample at the rupture point

RESULTS AND DISCUSSION

Electrical conductivity of the samples

The results of the electrical conductivity of the composites are presented in Figure 1. It was observed that the activated carbon had substantial effects on the electrical conductivities of the composite samples. The conductivity of the composite generally declined non-linearly as the CCS volume increased from 3% to 15% in the presence of varying quantities of the other constituents. However, from the results, it can be deduced that 6% of the CCS caused a minimal increment in the composite's electrical conductivity. As presented in Figure 1, as the CCS volume was increased from 3% to 6% (S1 to S2), and the CB and CF quantities declined from 15% to 12% and 7% to 6% respectively, the conductivity inclined by 3.12%. Whereas, as the CCS volume was increased from 9% to 15% (S3 to S5), and the CB and CF quantities declined from 9% to 3% and 5% to 3% respectively, the conductivity fell sharply with 80.53%. The dramatic decrement noted in the conductivities of the samples as the CCS volume was increased above 9%, and the CB and CF volumes decreased below 9% and 5% respectively, can be linked to the increase in CCS and the associated poor bond formation within the composite, as well as the lower volumes of CF and CB in the composite. Obukoeroro and Uguru (2021a) and Omah *et al.* (2018) reported similar trends in results for carbonized bone filler epoxy composites.

Similarly, Bahaa *et al.* (2011) observed that increasing the quantity of carbonized filler during composite production, results in the formation of composites with better electrical conductivity. Bahaa *et al.* (2011) attributed this to increasing body contact between the fillers, which will enhance the electrical properties of the composites. Notwithstanding variations that may exist in the electrical conductivities of different green composites can be linked to the maturity stage of the materials, carbonization methods, age of the CB, chemical composition of the reinforcing materials and hybridization pattern of the reinforcing materials (Lee *et al.,* 2009; Edafeadhe *et al.*, 2020; Eboibi *et al.*, 2021). According to Radzuan *et al.* (2017), though CB enhances the conductive behavior of polymer materials, its concentration must be within the percolation threshold to achieve optimal results.

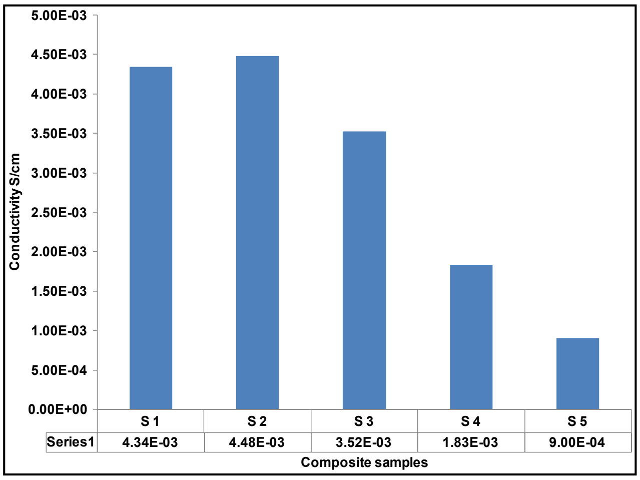

Figure 1: Electrical conductivity of composites produced with different quantities of CCS, CB, CF and RPF

Electrical resistivity of the samples

The results of the electrical resistivity of the composite samples are shown in Figure 2. The resistivity ranged between 2.90x10^{7} Ωcm and 3.8x10^{7} Ωcm, with CCS considerably influencing the composite's electrical resistivity. It can be seen in Figure 2, that there was a minute decrement (2.41%) in the composite's resistivity, as the CCS volume increased from 3% to 9%; compared to the drastic increment (98.8%) in the resistivity as the CCS increased from 9% to 15%. This indicates that the specific combination (6%, 12%, 6% and 6% of CCS, CB, CF and RPF respectively) in this setup, relatively/slightly hinders the resistance of eth composite, while generally, larger volumes of CCS and PRF increased the resistance of the epoxy composite to current flow. Furthermore, the results portrayed that the carbon black filler and carbon black fibre degraded the ability of the CCS and RPF in the epoxy composite to resist current flow; as it was observed that the resistivity developed by the composite declined non-linearly, as the CB quantity increased from 3 wt% to 15 wt%. This conforms to earlier observations of Obukoeroro and Uguru (2021a) and Omah *et al.* (2018) that a large quantity of green carbonized materials encourages the resistivity of current flow through composites.

According to Melnyk (2017), the resistivity of CNT reinforced composite declined significantly, as the quantity of the non-conductive reinforcement material increased. A composite's electrical resistivity is dependent on the effective surface area of the reinforcing non-conductive materials, the concentration of the conductive reinforcement materials, prevailing temperature, composting production method and the relative humidity (Melnyk, 2017). Desai and Njuguna (2012) and Zhou *et al.* (2009) in their studies stated that, if the quantity of non-conductive reinforcement materials inside a composite is increased, then dielectric constant will decrease proportionally; hence, the electrical resistivity will rise accordingly.

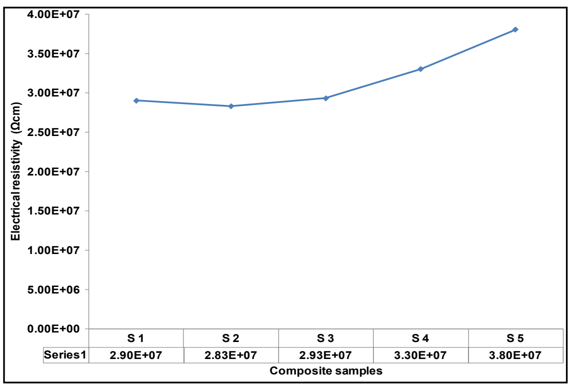

Figure 2: Electrical resistivity of composites produced with different quantities of CCS, CB, CF and RPF

Electrical resistivity and conductivity of materials are vital factors that determine the application of material in the electrical field. This is because the electrical resistance of material is highly influenced by its electrical resistivity (Omah *et al.*, 2018). Materials with low resistivity indicate that they readily allow electric current to pass through them. Odoh *et al.*, 2022; Obukoeroro and Uguru (2021b) reported that materials with high resistivity tend to build up high thermal energy within their bodies, when subjected to current flow. This heating up can lead to electrical fires, which is one of the major reasons why electrical fires are common in substandard electrical wires and cables. These results reveal that a low quantity of carbonized coconut shell filler can be used as a substitute for carbon black in conductive composite production.

Composite tensile strength

The tensile strengths of the conductive samples are presented in Figure 3. It was noted that the S1 composite had the highest tensile strength of 98.3 MPa, while the S5 composite developed the minimum tensile strength 62.7 MPa. Then the S2, S3 and S4 composites recorded tensile strengths of 94.8 MPa, 87.9 MPa and 75.1 MPa respectively. The findings shown in Figure 3 depicted that the tensile strength of the composites declined continuously as the CCS quantity increased in the composites. Though CCS may be a good reinforcement material, however the large quantity (resulting in lower density and poorer bonding) in the composite can be responsible for the poorer tensile strength recorded in the S3, S4 and S5 composites samples. Poor intercalation of fillers with the matrix, resulting from high fillers volume can lead to production of composite with poor tensile properties (Bera *et al.*, 2018; Umurhurhu and Uguru, 2019; Agbi *et al.*, 2020). A large fillers volume in epoxy resin matrix, hinders easy interaction of the fillers with the matrix; hence, resulting in poor interface bond between the resin and the fillers, thus compromising the composite's tensile strength in the process (Bera *et al.*, 2018).

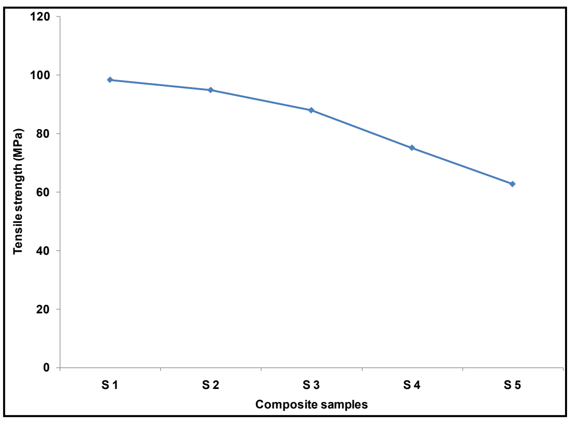

Figure 3: Tensile strength of composites produced with different volumes of CCS, CB, CF and RPF

This study's finding is an indication that the hybridization of CCS, RPF, carbon black powder and carbon fibre can produce composites with appreciable mechanical and electrical properties. Carbon fibre and RPF (though better at reduced quantities) are lightweight fibres with high tensile strength; thus they are ideal for the production of composites for applications in areas that demands high stiffness and lightweight.

CONCLUSION

This study tends to investigate the possibilities of using green materials in the production of conductive composites. The tensile strength, electrical conductivity and electrical resistivity of composite samples produced through the hybridization of CCS, CB, CF and RPF were determined using standard (ASTM D 3039, ASTM B193 and ASTM D6343 – 14) procedures. Findings obtained from study revealed that the organic materials (CCS and RPF) have a substantial influence on the mechanical and electrical properties of the composite. It was noted that the electrical conductivity of the composites tends to generally decrease with an increase in the CCS volume; while the electrical resistivity tends to increase with an increase in the volume of CCS incorporated into the composite. Regarding the mechanical properties of the composite, it was observed that the CCS and RPF were able to stabilize the tensile strength of the composite produced. This study's results indicated the possibility of producing lightweight conductive composite from organic waste materials, which can be utilized in several engineering applications.

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