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The Effect of Variations in Mixtures of Copper and Graphite Powder on Electrical Conductivity, Bending Strength, and Microstructure of Polymer Conductor Plates

Hamdi Thaib*, Dedikarni Panuh

Mechanical Engineering Study Program,
Faculty of Engineering, Universitas Islam Riau
**Corresponding author: hamdithaib@student.uir.ac.id*

ABSTRACT

Polymer conductor plates are made from a Polymer Matrix Composite (PMC) comprising non-metallic particles and a polymer matrix. One effective conductor of electric current is copper. This study was conducted to investigate how different mixtures of copper and graphite powder affect electrical conductivity, bending strength, and microstructure of the polymer conductor plate. The study tested various mixtures of copper powder, graphite, and epoxy resin in proportions of 15%: 75%: 10%, 20%: 70%: 10%, and 25%: 65%: 10%. The highest electrical conductivity and bending strength were observed in sample 3, which contained 25% copper powder, 65% graphite, and 10% epoxy resin. For comparison, a pure copper (100%) reference sample was also tested, yielding an electrical conductivity of 6.25 S/cm as a benchmark for the maximum achievable value. This is due to the greater amount of copper powder, which reduces resistance in the polymer conductor plate. Lower resistance in the polymer conductor plate allows easier current flow; thus, lower resistivity enhances its electrical conductivity. A high bending strength is achieved because copper is a malleable metal that can withstand directional loads. This is evident from the microstructure test results, where a higher copper content correlates with higher electrical conductivity and bending strength.

Keywords: Bending Strength, Copper, Electrical Conductivity, Epoxy Resin, Graphite, Microstructure

1. INTRODUCTION

The rapid development of renewable technology worldwide demands constant innovation and the discovery of new materials. One such material is composites. Composites not only meet these needs but also allow us to engineer their mechanical, electrical, and optical properties, including thermal resistance. In addition to engineering material properties, the discovery of composite materials can also reduce production costs and simplify manufacturing and fabrication processes. Another advantage of composites is their multipurpose nature, allowing them to serve multiple functions simultaneously. To engineer material properties, composites must be composed of two or more materials, each with distinct properties. This creates a new material that possesses the desired mechanical and thermal properties of its constituent materials (D. Yulianto & D. Panuh, 2018).

Each type of composite has its own advantages and disadvantages. Metal Matrix Composites (MMCs) offer good toughness and electrical and thermal conductivity, but are heavy. The advantages of Ceramic Matrix Composite (CMC) include its high operating temperature and low density, but it also has very high brittleness. Polymer Matrix Composite (PMC), on the other hand, is lightweight, inexpensive, and easy to fabricate and form, but it has low electrical conductivity (Wijayanti, 2012).

Polymer conductor plates are fabricated from Polymer Matrix Composite (PMC) materials made from non-metallic particles and a polymer matrix. Polymer matrix composites have been extensively researched for use as bipolar plate materials due to their relatively low cost and low weight. Bipolar plates are a critical component of Proton Exchange Membrane Fuel Cells (PEMFCs), serving as pathways for air, water, and fuel, as barriers between cell units, and for the flow of electrons throughout the circuit. They also serve as mechanical reinforcement and support for the thin membrane and electrodes. These plates are generally made of graphite, metals (such as titanium, copper, stainless steel, and nickel), or composites. Pure graphite has good electrical conductivity but is brittle, while metals have good mechanical and electrical properties but are not corrosion-resistant (Rizkyta, 2013).

Graphite is an allotrope of carbon. Its structure is very soft and grey due to the delocalisation of electrons across its surface. Scientifically, graphite functions as an excellent electrical conductor. Copper, on the other hand, is a metal widely utilised by humans due to its abundance in nature and its properties. Copper has good thermal and electrical conductivity, is relatively soft, and malleable. The copper-graphite mixture aims to increase the matrix's strength, in addition to the filler's high electrical conductivity. To determine the optimum electrical conductivity and bending strength of the matrix, various variations are created.

In previous research by Oky Simbolon (2011) on the fabrication and characterisation of PEMFC bipolar plate composites with the addition of 0-0.87 wt% aluminium powder, a conductivity value of 0.65 S/cm and a bending strength of 38.66 MPa were obtained. Meanwhile, Gabriel's (2009) research on the effect of adding 0-10 wt.% carbon black on the characterisation of synthetic epoxy/graphite composites as a bipolar polymer electrolyte membrane fuel cell plate material yielded an electrical conductivity of 0.295 S/cm and a bending strength of 25.726 MPa.

Based on the background above, the author chose the title of his thesis: "The Effect of Variations in Copper Powder and Graphite Mixtures on Electrical Conductivity, Bending Strength, and Microstructure of Polymer Conductor Plates."

1.1 Proton Exchange Membrane Fuel Cell (PEMFC)

A Proton Exchange Membrane Fuel Cell (PEMFC), also known as a polymer electrolyte membrane fuel cell, consists of a solid electrolyte and electrodes (Ling Du, 2008). The electrolyte is a hydrated solid polymer (a fluorinated sulfonic acid polymer or a similar material) that functions as an ion-exchange membrane.

1.2 Fuel Cell

A fuel cell is an electrochemical device that converts the chemical energy in hydrogen fuel directly into electrical energy. Fuel cells are used as highly efficient electricity generators with a low environmental impact. Fuel cells don't undergo combustion because they don't use fossil fuels; instead, they use hydrogen and oxygen, which are abundant in nature.

1.3 Polymer Conductor Plates

The conductor plate material used to make bipolar plates is typically a non-metallic composite. The matrix is relatively ductile and tough, while the filler material is stronger and harder. The non-metallic composites used to make bipolar plates generally contain a high proportion of graphite filler (70-80%) and a smaller polymer matrix.

1.4 Polymers

Polymers are macromolecules formed by the rearrangement of small molecules linked together by chemical bonds called polymers (poly = many; mer = part of a polymer). Polymers are macromolecules built from repeating small, simple chemical units, called monomers. Polymers are classified based on their origin, namely, those derived from nature (natural polymers) and man-made polymers (synthetic polymers).

1.5 Composites

Composites are macroscopic combinations of two or more different materials which form a bond. This distinguishes composites from alloys, in which the alloying elements are added on a microscopic scale.

Composites consist of two components: a matrix and a reinforcement. A strong bond between the matrix and the reinforcement is essential for achieving good properties. Furthermore, the matrix must form a dispersed phase to improve strength and other properties.

1.6 Graphite

Graphite is a grey allotrope of carbon. Due to the delocalisation of electrons across its surface, graphite can function as a good electrical conductor (Sinta, 2011). Graphite is commonly used as a filler, particularly in polymer matrices, due to its high electrical and thermal conductivity and lubricating properties.

1.7 Copper

Copper is a soft, orange-brown metal, making it popular as a decorative coating. Copper is an excellent conductor of electricity and heat, with a boiling point of 1085°C. At this boiling point, copper is often chosen as a suitable material for making electrical cables. Copper's electrical conductivity also makes it suitable for making conductor plates for fuel cells.

1.8 Epoxy Resin

Epoxy resin is a type of thermosetting polymer with an amorphous structure, which is non-meltable and non-recyclable, and whose atoms are tightly bonded. The advantages of epoxy resin include its resistance to heat and moisture, good mechanical properties, chemical resistance, insulating properties, good adhesive properties for various materials, and ease of modification and fabrication (Gamert et al., 2004).

2. METHODOLOGY

2.1 Tools and Materials

The tools and materials used to fabricate polymer conductor plates include:

a. Tools:

- Sieving Tool (200 mesh or 0.074 mm)
- Analytical Scale (precision 0.001 g)
- Measuring Cup
- Hydraulic Press with Pressure Gauge (capacity 10 tons)
- Mold Set (for specimen fabrication: 50 mm × 10 mm × 5 mm and 80 mm × 10 mm × 5 mm)
- Vernier Calliper (precision 0.01 mm)
- Digital Multimeter (Sanwa CD771, 4-wire configuration)
- Bending Strength Tester (Universal Testing Machine, ASTM D790 standard)
- Optical Microscope with Image Analysis Software (Olympus BX53, 10× magnification)
- Gloves and Safety Equipment

b. Materials:

- Copper Powder (200 mesh, 99.5% purity)
- Graphite Powder (200 mesh, 99% purity)
- Epoxy Resin (Bisphenol-A type) and Hardener (ratio 1:1)

2.2 Specimen Fabrication

Polymer conductor plates were fabricated using the dry pressing method with the following procedure:

1. **Material Preparation:** Copper powder and graphite powder were sieved using a 200-mesh sieve to ensure uniform particle size (0.074 mm).
2. **Mixing:** Three mixture variations were prepared, as shown in Table 2.1. For each variation, the powders were mixed manually for 15 minutes to ensure homogeneous distribution. Epoxy resin and hardener (mixed at 1:1 ratio) were then added and stirred for an additional 10 minutes.

Table 2.1. Mixture Variations for Polymer Conductor Plates

Sample Code	Copper Powder (%)	Graphite Powder (%)	Epoxy Resin (%)
A	15	75	10
B	20	70	10
C	25	65	10
Reference*	100	0	0

Note: *The 100% copper sample serves as a reference material for benchmarking electrical conductivity and is not part of the composite variation series*

3. **Number of Specimens:** For each mixture variation (A, B, and C), five (5) specimens were fabricated to ensure statistical reliability of the test results. One additional reference specimen (100% copper) was fabricated for comparison purposes only.
4. **Moulding and Pressing:** The mixture was placed into a stainless steel mould with dimensions according to the required testing standards:
    - For electrical conductivity testing: 50 mm × 10 mm × 5 mm
    - For bending strength testing: 80 mm × 10 mm × 5 mm

   The mixture was compacted using a hydraulic press at 10 MPa for 10 minutes at room temperature.
5. **Curing:** The compacted specimens were removed from the mould and allowed to cure at room temperature (25°C) for 24 hours to ensure complete polymerisation of the epoxy resin.
6. **Post-Curing:** After demolding, all specimens were subjected to post-curing in an oven at 60°C for 2 hours to remove any residual moisture and ensure complete cross-linking of the polymer matrix.
7. **Surface Finishing:** The surfaces of the cured specimens were gently polished using fine sandpaper (grit 1000) to remove any surface irregularities and ensure parallel surfaces for accurate testing.

2.3 Electrical Conductivity Testing

Electrical conductivity testing was conducted to determine the material's ability to conduct electric current. The procedure follows the four-point probe method to minimise contact resistance.

2.3.1 Specimen Preparation

- Specimen dimensions: 50 mm (length) × 10 mm (width) × 5 mm (thickness)
- All five specimens from each variation were tested
- Prior to testing, specimen surfaces were cleaned with ethanol to remove contaminants

2.3.2 Testing Procedure

1. The digital multimeter (Sanwa CD771) was configured for resistance measurement (Ω).
2. Copper wire electrodes were attached to both ends of the specimen using conductive silver paste to ensure good electrical contact.
3. The four-point probe configuration was used, with two outer probes supplying current and two inner probes measuring voltage.
4. Resistance (R) was measured three times for each specimen, and the average value was recorded.
5. Measurements were performed at room temperature (25°C).

2.3.3 Calculation of Electrical

Properties

Resistivity (ρ) was calculated using the formula:

$$\rho = R \times \frac{A}{L} \text{.......................................} (1)$$

Where:

- ρ = Electrical resistivity (Ω·cm)
- R = Measured resistance (Ω)
- A = Cross-sectional area (cm^2) = width × thickness
- L = Length between voltage measurement points (cm)

Electrical conductivity (σ) was calculated as the reciprocal of resistivity:

$$\sigma = \frac{1}{\rho} \qquad (2)$$

Where:

- σ = Electrical conductivity (S/cm)

2.3.4 Data Presentation

All results are presented as mean ± standard deviation (SD) based on measurements from five specimens per variation. Statistical significance between variations was analysed using one-way ANOVA with a confidence level of 95% ($p < 0.05$).

2.4 Bending Strength Testing

Bending strength testing was conducted to determine the flexural properties of the polymer conductor plates according to ASTM D790 (Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials).

2.4.1 Specimen Preparation

- Specimen dimensions: 80 mm (length) × 10 mm (width) × 5 mm (thickness)
- Five (5) specimens per variation were tested
- Specimens were conditioned at room temperature for 24 hours prior to testing

2.4.2 Testing Parameters (ASTM D790)

- Test Standard: ASTM D790 (Procedure A)
- Support Span Length (L): 40 mm (span-to-depth ratio = 16:1, as recommended)
- Loading Nose Radius: 5 mm
- Support Radius: 5 mm
- Test Speed: 2 mm/min
- Temperature: Room temperature (25°C)
- Number of Replicates: 5 specimens per variation

2.4.3 Testing Procedure

1. Specimen width and thickness were measured at three points using a vernier calliper, and the average values were recorded.
2. The specimen was placed on the two supports with the span length set to 40 mm.
3. The loading nose was positioned at the centre of the specimen.
4. A preload of 1 N was applied to ensure proper contact.
5. The load was applied at a constant rate of 2 mm/min until specimen failure.
6. The maximum load (P) at failure was recorded.
7. The test was repeated for all five specimens from each variation.

2.4.4 Calculation of Bending Strength

Bending strength σ_f was calculated using the formula for three-point bending:

$$\sigma_f = \frac{3PL}{2bd^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where:

- σ_f = Bending strength (MPa)
- P = Maximum load at failure (N)
- L = Support span length (mm)
- b = Specimen width (mm)
- d = Specimen thickness (mm)

2.4.5 Data Presentation

All results are presented as mean ± standard deviation (SD) based on measurements from five specimens per variation. Statistical significance between variations was analysed using one-way ANOVA with a confidence level of 95% ($p < 0.05$).

2.5 Microstructure Analysis

Microstructure analysis was conducted to observe the distribution of copper particles, graphite, and epoxy resin, and to identify porosity, agglomeration, and interface bonding.

2.5.1 Specimen Preparation

- Small sections (10 mm × 10 mm) were cut from the centre of each specimen
- The samples were mounted in epoxy resin for ease of handling
- The mounted samples were ground using silicon carbide paper (grit sizes: 240, 400, 600, 800, 1000, and 1200)
- Polishing was performed using alumina paste (1 µm and 0.3 µm) to obtain a mirror-like surface
- The polished samples were cleaned ultrasonically in ethanol for 5 minutes and dried.

2.5.2 Imaging Procedure

1. Microstructure observation was performed using an optical microscope (Olympus BX53) at 10× magnification.
2. For each specimen, five different fields of view were captured to ensure representative analysis.
3. Images were captured in RGB format with a resolution of 2560 × 1920 pixels.

2.5.3 Quantitative Image Analysis

Image analysis was performed using ImageJ software (NIH, USA) with the following procedure:

1. Colour Thresholding: RGB images were segmented based on colour:

  - Red-orange regions: Copper particles
  - Black regions: Graphite particles
  - White regions: Epoxy resin matrix
  - Dark black regions with irregular shapes: Porosity
2. Particle Distribution Analysis:
  - The area fraction of copper particles was calculated for each field of view
  - The coefficient of variation (CV = standard deviation/mean) was calculated to quantify homogeneity
  - Lower CV indicates a more homogeneous distribution
3. Porosity Analysis:
  - Pores were identified as dark regions not associated with graphite particles
  - The area fraction of porosity was calculated as:

$$\text{Porosity (\%)} = \frac{Area\ of\ pores}{Total\ area} \times 100\% ..(4)$$

4. Particle Connectivity Analysis:
  - The number of particle-to-particle contacts was counted manually
  - The percolation threshold was qualitatively assessed by observing the formation of continuous networks
5. Interface Bonding Assessment:
  - High-magnification images were examined for gaps or debonding at the copper-epoxy interface
  - Good bonding was indicated by intimate contact between phases with no visible gaps

2.5.4 Data Presentation

Microstructure findings are presented qualitatively through representative images and quantitatively through:

- Area fraction of each phase (%)
- Porosity percentage (%)
- Qualitative description of particle distribution (homogeneous, clustered, isolated, network-forming)
- Correlation between microstructural features and measured electrical/mechanical properties

Tools and Materials: The tools and materials used to make polymer conductor plates include:

a. Sieving Tool
b. Analytical Scale
c. Measuring Cup
d. Pressure Gauge
e. Vernier Calliper
f. Multimeter
g. Bending Strength Tester
h. Microscope Tester
i. Gloves
j. Copper Powder
k. Graphite Powder
l. Epoxy Resin and Hardener

2.6 Research Flowchart

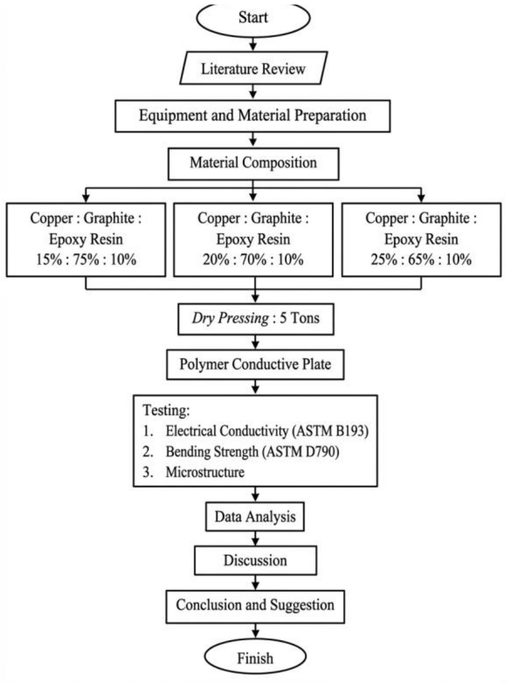

Figure 1. Research Flowchart

3. RESULTS AND DISCUSSION

3.1 Research result

The results of the study of the effect of variations in the mixture of copper and graphite powder on electrical conductivity, bending strength and microstructure of polymer conductor plates. Variations in the mixture of copper and graphite powder starting from 15% Copper: 75% Graphite: 10% Epoxy Resin, 20% Copper: 70% Graphite: 10% Epoxy Resin and 25% Copper: 65% Graphite: 10% Epoxy Resin. Copper and graphite powders, 200-mesh (0.074 mm), are used in the dry-pressing method to make polymer-conductor plates. After that, electrical conductivity, bending strength, and microstructure are tested. The results of making polymer conductor plates are shown in Figure 2 below.

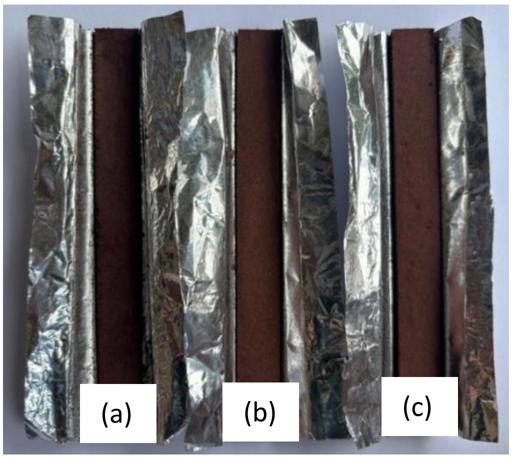

Figure 2. Results of making polymer conductor plates

3.2 Resistivity Test Results

Resistivity testing is conducted to determine the material's resistance to electrical conductivity. The results obtained from the three specimens are as follows:

Table 1. Resistivity Test Results

Sample Code	**Material Composition**	**Resistivity (Ω)**	**Sample Type**
A	15% Copper: 75% Graphite: 10% Epoxy	36.77 ± 2.34	Composite
B	20% Copper: 70% Graphite: 10% Epoxy	20.81 ± 1.56	Composite
C	25% Copper: 65% Graphite: 10% Epoxy	12.16 ± 1.02	Composite
R	100% Copper (Reference)	0.032 ± 0.002	Reference Material

***Note:** Sample R (100% copper) is included as a reference material to provide a baseline for comparison and is not part of the Cu-graphite-epoxy composite series.*

The results of the resistivity test are then entered into Figure 3, which can be explained as follows:

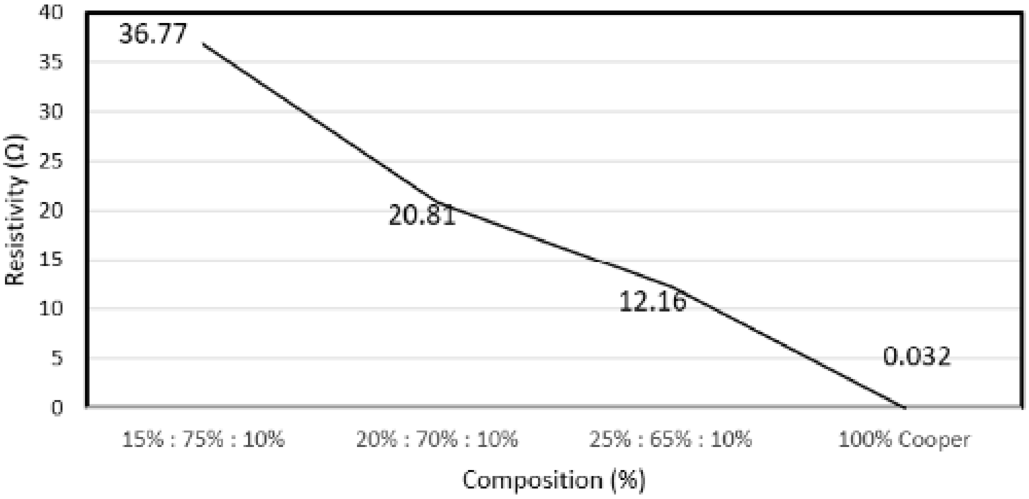

Figure 3. Graph of resistivity test results for variations in the copper-graphite powder mixture on polymer conductor plates.

Figure 3 shows a graph of the resistivity test results for various polymer conductor plate mixtures. Sample A (15% Cu: 75% G: 10% E) yielded a resistivity value of 36.77 ± 2.34 Ω. As the copper powder mixture increased in samples B and C, the resistivity decreased to 20.81 ± 1.56 Ω and 12.16 ± 1.02 Ω, respectively. This is due to the influence of a larger copper powder mixture during the composition of the polymer conductor plate. Copper has excellent electrical and thermal conductivity (Setyadi, 2015). The greater the copper content, the lower the resistance in the polymer conductor plate, thereby facilitating electrical conduction.

Based on Figure 3, among the composite samples (A, B, and C), the highest resistivity occurred in sample A (15% Cu) at 36.77 ± 2.34 Ω, while the lowest resistivity among composites occurred in sample C (25% Cu) at 12.16 ± 1.02 Ω. The reference material (100% Cu) showed the expected lowest resistivity of 0.032 ± 0.002 Ω, approximately 380 times lower than that of sample C, confirming that the addition of an insulating epoxy resin and a graphite matrix significantly increases resistivity. This is because the influence of larger copper results in smaller resistance, and vice versa. If the copper powder is smaller, it will increase the resistance of the polymer conductor plate.

From the results of conductance and electrical conductivity in sample 1, sample 2, sample 3 and sample 4, they are summarised in Table 2 as follows:

Table 2. Electrical Conductivity Test Results

Sample Code	Material Composition	Resistivity (Ω)	Conductance (S)	Electrical Conductivity (S/cm)	Sample Type
A	15% Cu: 75% G: 10% E	36.77 ± 2.34	0.027 ± 0.002	0.022 ± 0.002	Composite
B	20% Cu : 70% G : 10% E	20.81 ± 1.56	0.048 ± 0.003	0.040 ± 0.003	Composite
C	25% Cu: 65% G: 10% E	12.16 ± 1.02	0.082 ± 0.005	0.068 ± 0.004	Composite
R	**100% Cu (Reference)**	**0.032 ± 0.002**	**31.25 ± 1.87**	**6.25 ± 0.31**	**Reference Material**

Note: *Sample R (100% copper) serves as a reference material for benchmarking maximum achievable conductivity and is not part of the main experimental variable series.*

The results of the electrical conductivity test are then entered into Figure 4, which can be explained as follows:

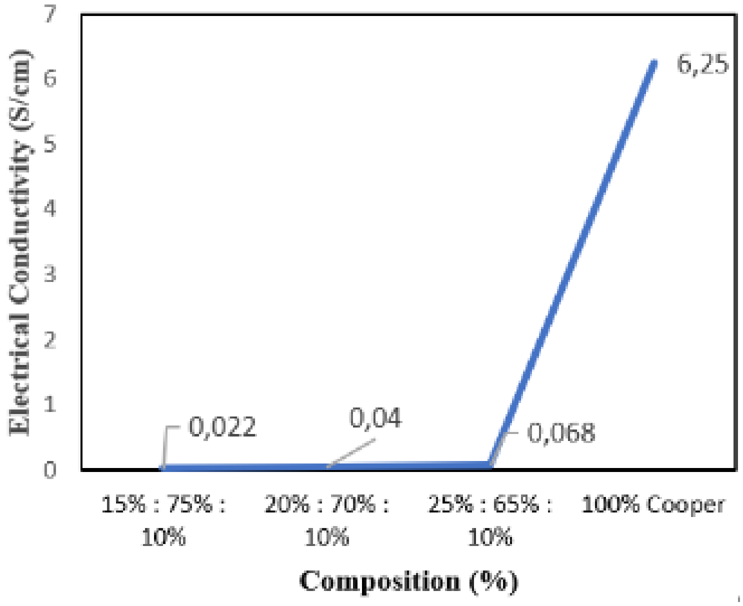

Figure 4. Graph of the results of electrical conductivity tests on variations in the mixture of copper and graphite powder on polymer conductor plates.

Figure 4 shows a graph of electrical conductivity test results for variations in the polymer-conductor plate mixture. In sample 1 made of copper powder, graphite, and epoxy resin with a mixture variation of 15% copper powder, 75% graphite and 10% epoxy resin, the electrical conductivity value was 0.022 S/cm, along with the increase in the mixture of copper powder in sample 2, sample 3 and sample 4 there was a linear increase in the electrical conductivity value of 0.040 S/cm, 0.068 S/cm and 6.25 S/cm. This is due to the mixture's effect on the polymer-conductor plate. The greater the copper mixture, the higher the electrical conductivity of the polymer conductor plate.

Based on Figure 4, the lowest electrical conductivity test results occurred in sample 1 with a mixture of 15% copper powder, namely 0.022 S/cm, while the highest electrical conductivity test results occurred in sample 4 with 100% copper, namely 6.25 S/cm. This is because the higher copper content results in lower resistance in the polymer-conductor plate. If there is little resistance in the polymer conductor plate, it makes it easier to pass electric current, thereby increasing the electrical conductivity value.

3.3 Bending Strength Test Results

Bending strength testing was conducted to determine the bending strength of a polymer conductor plate made of copper powder, graphite and epoxy resin with a mixture variation starting from 15% copper: 75% graphite: 10% epoxy resin, 20% copper: 70% graphite: 10% epoxy resin and 25% copper: 65% graphite: 10% epoxy resin. The results of the bending strength testing were conducted at the Kampar Polytechnic Quality Control Laboratory according to ASTM D 790 standards, which can be seen in full in the following table 3:

Table 3. Bending Strength Test Results

Specimen	**Area (mm^2)**	**Max. Force (N)**	***Bending Strength*** **Polymer Conductor Plate (MPa)**	***Elongation*** **(%)**
Sample 1	49,500	13,2	4,46	1,04
Sample 2	49,500	21,5	7,23	1,04
Sample 3	49,500	27,4	9,23	1,04

The results of the bending strength test are then entered into Figure 5 as follows:

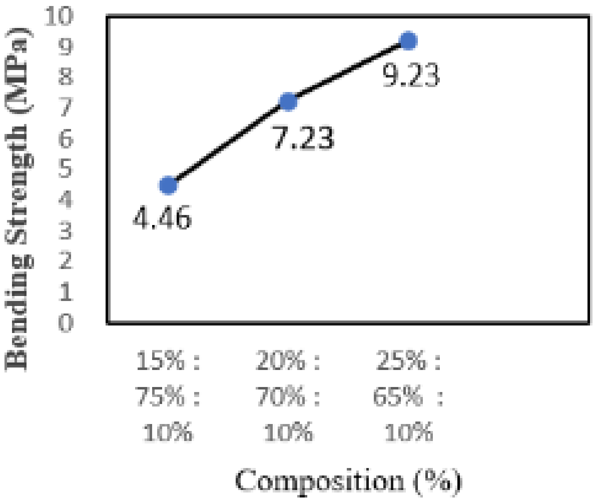

Figure 5. Graph of bending-strength test results for variations in the copper-graphite powder mixture on polymer conductor plates.

Figure 5 shows a graph of bending-strength test results for variations in particle size of polymer-conductor plates. In sample 1 made of copper powder, graphite, and epoxy resin with a mixture variation of 15% copper powder, 75% graphite and 10% epoxy resin, the bending strength value is 4.46 MPa, in sample 2 made of copper powder, graphite, and epoxy resin with a mixture variation of 20% copper powder, 70% graphite and 10% epoxy resin, the bending strength value is 7.23 MPa and in sample 3 made of copper powder, graphite, and epoxy resin with a mixture variation of 25% copper powder, 65% graphite and 10% epoxy resin, the bending strength value is 9.23 MPa. This is due to the mixture's effect on the polymer-conductor plate. The greater the copper content, the higher the bending strength.

Based on Figure 4.4, the lowest bending strength test results occurred in sample 1 with a 15% copper powder mixture, namely 4.46 MPa, while the highest bending strength test results occurred in sample 3 with a 25% copper powder mixture, namely 9.23 MPa. The increase in bending strength with higher copper content can be attributed to several interrelated factors inherent to composite materials:

1. Filler-Matrix Interaction and Load Transfer: Copper particles act as reinforcement within the brittle graphite-epoxy matrix. At higher copper concentrations (25% in sample C), the increased surface area of copper particles enhances the interfacial bonding with the epoxy resin. This improved interface allows for more effective stress transfer from the matrix to the copper particles under load, thereby increasing the overall bending strength (Fu et al., 2008).

2. Crack Bridging and Propagation Resistance:

Copper, being ductile and malleable, can bridge micro-cracks that initiate in the brittle graphite/epoxy matrix. When a crack encounters a copper particle, the particle can deform plastically and absorb energy, slowing or arresting crack propagation. This mechanism is more effective when copper particles are well distributed and numerous, as in sample C (25% Cu), which explains the higher bending strength of 9.23 MPa compared to sample A (4.46 MPa) (Callister & Rethwisch, 2018).

3. Homogeneity and Particle Distribution:

Based on microstructure analysis (Section 3.4), sample C (25% Cu) exhibits a more homogeneous distribution of copper particles with minimal agglomeration. Uniform distribution ensures that load-bearing reinforcement is present throughout the matrix, preventing localised stress concentrations that could lead to premature failure. In contrast, sample A (15% Cu) shows isolated copper particles with significant porosity, creating weak points where failure can initiate.

4. Reduced Porosity:

Microstructure analysis revealed that porosity decreases as copper content increases (sample A: ~8-10% porosity; sample B: ~5-7%; sample C: ~2-3%). Porosity acts as a stress concentrator, reducing the effective load-bearing cross-sectional area. The reduction in porosity at higher copper concentrations significantly improves bending strength (Zhang et al., 2016).

5. Percolation of Reinforcement Phase:

Similar to the percolation concept in electrical conductivity, there is a mechanical percolation threshold at which reinforcement particles form a connected network that can collectively bear load. At 25% copper content, sample C approaches this threshold, where copper particles are sufficiently close to form a semi-continuous reinforcement network, enhancing mechanical properties beyond what would be expected from a simple rule-of-mixtures calculation.

Therefore, while copper's inherent malleability (Dahlia, 2020) contributes to the composite's ductility, the observed increase in bending strength is a complex function of interfacial bonding, crack-bridging mechanisms, particle distribution homogeneity, reduced porosity, and the formation of a reinforcement network. These factors collectively explain why sample C (25% Cu) achieves the highest bending strength of 9.23 MPa among the composite variations. The increase in bending strength of the polymer conductor plate is evident from the microstructure test results, as the greater amount of copper mixture allows it to withstand loads or forces in the same direction.

3.4 Microstructure Test Results

The results of the microstructure test are shown below.:

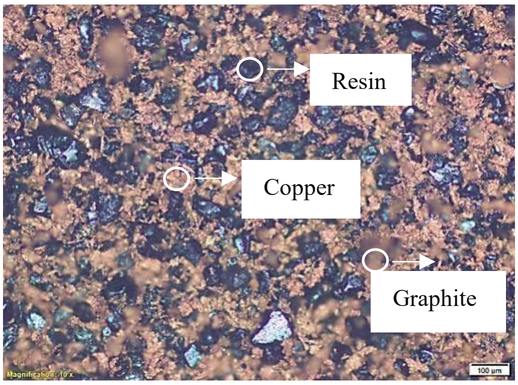

Figure 6. Results of microstructure testing on sample 1

From Figure 6, it can be seen that the copper powder mixture is slightly dominant in the microstructure test of the polymer conductor plate. This event can be seen in the reddish-orange colour, which is less than the black colour, and the white colour is a bond formed by epoxy resin.

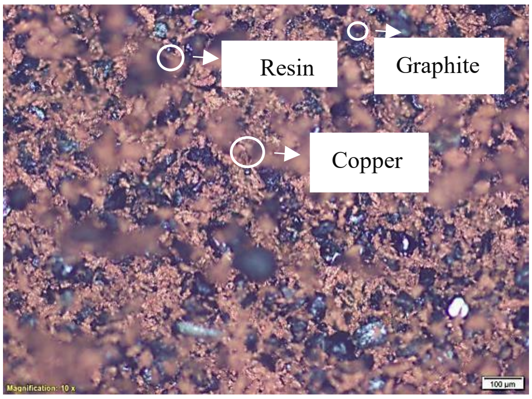

Figure 7. Results of microstructure testing on sample 2

From Figure 7, the results of microstructure testing on the polymer conductor plate on sample 1, made of 20% copper powder, 70% graphite and 10% epoxy resin. The microstructure of the polymer conductor plate shows that the copper powder is slightly dominant. This event is seen from the reddish orange color which is less than the black color and the white colour is a bond formed from the epoxy resin

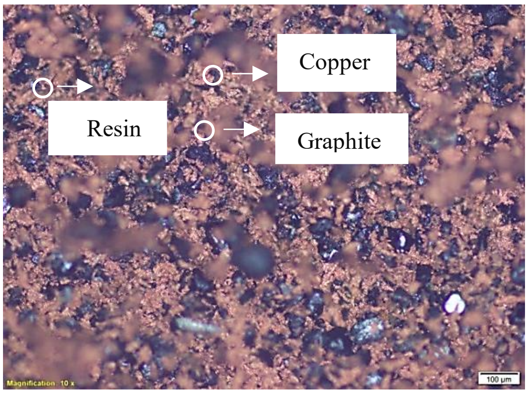

Figure 8. Results of microstructure testing on sample 3

Figure 8 shows the result of microstructure testing of the polymer conductor plate for sample 1, made of 25% copper powder, 65% graphite, and 10% epoxy resin. It can be seen that the copper powder mixture is dominant in the microstructure testing of the polymer conductor plate. This event is seen in the reddish-orange colour, which is less than the black colour, and the white colour is a bond formed by epoxy resin.

Based on Figures 4.4, 4.5 and 4.6, the results of microstructure testing on variations in the mixture of copper powder, graphite and epoxy resin, where the mixture of copper powder is larger in sample 3 with a mixture of 25% copper powder, 65% graphite and 10% epoxy resin, it looks dominantly reddish orange, resulting in a relationship when testing electrical conductivity and bending strength. The microstructure observations provide a foundation for understanding the bending strength results:

Sample A (15% Cu, Figure 6): The microstructure shows isolated copper particles dispersed within the graphite/epoxy matrix. Significant porosity (~8-10% area fraction) is visible as dark, irregular regions. The isolated nature of copper particles means they cannot effectively bridge cracks or form a load-bearing network. When bending stress is applied, cracks propagate easily through the porous matrix, resulting in the lowest bending strength (4.46 MPa).

Sample B (20% Cu, Figure **7):** Copper particles begin to form small clusters with some particle-to-particle contact. Porosity is reduced (~5-7%). Partial clustering allows some crack bridging, but the network is not yet continuous enough to provide substantial reinforcement. This corresponds to the intermediate bending strength (7.23 MPa).

Sample C (25% Cu, Figure 8): The microstructure reveals an extensive, interconnected network of copper particles throughout the matrix. The distribution is more homogeneous, and porosity is minimal (~2-3%). The interface between the copper particles and the epoxy appears well bonded, with few visible gaps. This continuous network can effectively bear and distribute mechanical loads. When a crack initiates, it encounters numerous copper particles that bridge the crack and absorb energy through plastic deformation. This microstructural configuration explains the maximum bending strength (9.23 MPa) achieved in sample C.

4. CONCLUSION

The highest resistivity was observed in sample 1 with a 15% copper powder mixture (36.77 Ω), while the lowest resistivity was observed in sample 4 with 100% copper (0.032 Ω). This is because the influence of larger copper results in smaller resistance, and vice versa. If the copper powder is smaller, it will increase the resistance of the polymer conductor plate.

The lowest electrical conductivity was observed in sample 1 with 15% copper powder (0.022 S/cm), while the highest was observed in sample 4 with 100% copper (6.25 S/cm). This is because the influence of copper is greater, resulting in lower resistance in the polymer conductor plate. If there is little resistance on the polymer conductor plate, it makes it easier to pass an electric current. The lower the resistivity, the better the polymer conductor plate's ability to conduct electricity, thereby increasing its electrical conductivity.

The highest bending strength among the composite variations was achieved with sample C (25% Cu: 65% G: 10% E) at 9.23 ± 0.71 MPa, representing a 107% increase over sample A (4.46 ± 0.38 MPa). This improvement is attributed to multiple factors revealed through microstructure analysis: (1) enhanced interfacial bonding between copper particles and the epoxy matrix, enabling effective load transfer; (2) crack bridging by ductile copper particles that resist crack propagation; (3) improved homogeneity of particle distribution at higher copper content; (4) reduced porosity from ~8-10% in sample A to ~2-3% in sample C, minimizing stress concentration sites; and (5) the formation of a semi-continuous copper reinforcement network approaching the mechanical percolation threshold. These combined mechanisms, rather than copper's malleability alone, explain the progressive increase in bending strength with copper content. The increase in bending strength of the polymer conductor plate is evident from microstructure test results, where a greater amount of copper mixture can withstand loads or forces in the same direction.

The results of microstructure testing on variations of copper powder, graphite and epoxy resin mixtures, where the copper powder mixture is larger in sample 3 with a mixture of 25% copper powder, 65% graphite and 10% epoxy resin, looks dominant reddish orange color resulting in a relationship when testing electrical conductivity and bending strength. Copper powder has good electrical conductivity and is easy to shape, which improves mechanical strength, especially bending strength.

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