# DEVELOPMENT OF COPPER FIBER BASED COMPOSITE BIPOLAR PLATES FOR PEM FUEL CELLS

A PROJECT REPORT

submitted by

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to

APJ Abdul Kalam Technological University, Kerala
In partial fulfilment of the requirements for the award of the Degree

of

Bachelor of Technology

In

*Mechanical Engineering*


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MAY 2024

# DECLARATION

I, undersigned, do hereby declare that the project report " **DEVELOPMENT OF COPPER FIBER BASED COMPOSITE BIPOLAR PLATES FOR PEM FUEL CELLS** ", submitted for partial fulfilment of the requirements for the award of degree of Bachelor of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of Dr. CIJO MATHEW. This submission represents my ideas in my own words and where ideas or words of others have been included, I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

Kothamangalam ALEN JAIMON

09-05-2024

**DEPARTMENT OF MECHANICAL ENGINEERING**
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# CERTIFICATE

This is to certify that the report entitled "**DEVELOPMENT OF COPPER FIBER BASED COMPOSITE BIPOLAR PLATES FOR PEM FUEL CELLS"** submitted by **ALEN JAIMON(Reg .No. MAC20ME025)** to the APJ Abdul Kalam Technological University in partial fulfilment of the requirements for the award of the Degree of Bachelor of Technology in Mechanical Engineering is a bonafide record of the project work carried out by him under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

| | | |
|---|---|---|
| Dr. Cijo Mathew<br>Project Guide | Dr. Bobin Cherian Jos<br>Project Coordinator | Dr. Soni Kuriakose<br>Head of Department |

Dept. Seal

09-05-24

# ACKNOWLEDGEMENT

It is a great pleasure to acknowledge all those who have assisted and supported me for successfully completing my project.

I thank God Almighty for his blessings as it is only through his grace that I was able to complete my project successfully.

I take this opportunity to extend sincere thanks to my project guide **Dr. Cijo Mathew,** Department of Mechanical Engineering for his constant support and immense contribution for the success of my project.

I extend our sincere thanks to my project coordinator **Dr. Bobin Cherian Jos**, Mechanical Engineering Department, project in-charge **Prof. George Mathew** , Mechanical Engineering Department and all other members of the Department of Mechanical Engineering for sharing their valuable comments during the preparation of the project.

I am also grateful to **Dr. Soni Kuriakose** , Head of Mechanical Engineering Department, for the valuable guidance as well as timely advice which helped me a lot during the preparation of the project.

I am deeply indebted to **Dr. Bos Mathew Jos** , Principal, Mar Athanasius College of Engineering for his encouragement and support.

I whole- heartedly thank all my classmates, for their valuable suggestions and for the spirit of healthy competition that existed between us.

09-05-2024 ALEN JAIMON

# ABSTRACT

This research focuses on the development of a polymer composite material using carbon and metallic fillers that has the potential to be used for the production of bipolar plates (BPs). Bipolar plates are an integral component of proton exchange membrane fuel cells (PEMFC), utilized in hydrogen powered electric vehicles. In this study we developed a polymer carbon composite bipolar plate (PCCBP) using epoxy resin (ER) as the primary binder and natural flake graphite (NFG), carbon black (CB), and copper fiber as filler materials. The research focuses on understanding the influence of Cu-fiber on the electrical conductivity and flexural strength of the developed composite by varying the length of Cu fiber incorporated in each composition. The composite plates fabricated were characterized for electrical conductivity, flexural strength, hardness, density, contact angle and water absorption. The composite sample prepared with 44 vol% NFG, 40 vol% ER, 8 vol% CB and 8 vol% 3 mm Cu fibers exhibited flexural strength of 43.6 MPa and electrical conductivity of 172 S/cm. The composite also showed appreciable values for shore D hardness, bulk density, and water absorption. This composite was capable of meeting the proposed level of electrical conductivity and flexural strength as per US DoE standards for bipolar plates.



**Keywords:** Proton Exchange Membrane Fuel cell, Polymer Carbon Composite Bipolar plate, Flexural strength, Electrical conductivity, Copper fiber, Carbon fillers.

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# ABBREVIATIONS & NOTATIONS

## ABBREVIATIONS

| Abbreviation | Definition |
|---|---|
| ASTM | American Society for Testing and Materials |
| A | Area of cross-section |
| BP | Bipolar plate |
| CB | Carbon black |
| $CO_2$ | Carbon dioxide |
| CF | Carbon Fibre |
| CNT | Carbon nanotube |
| Cu | Copper |
| DOE | Design of experiment |
| DSC | Differential Scanning Calorimeter |
| $Wt_d$ | Dry weight |
| EIS | Electrochemical impedance spectroscopy |
| ER | Epoxy resin |
| Gr | Graphene |
| HDP | High density polyethylene |
| L | Length |
| LLDPE | Linear low-density polyethylene |
| LDPE | Low-density polyethylene |
| MWNT | Multi-walled carbon nanotubes |
| NFG | Natural flaked graphite |
| $NO_x$ | Nitrogen oxides |
| PPS | Poly phenylene sulphide |
| PET | Polyethylene terephthalate |
| PCBP | Polymer composite bipolar plates |
| PEMFC | Proton exchange membrane fuel cell |
| R | Resistance |
| SEM | Scanning Electron Microscopy |
| $SO_x$ | Sulphur oxides |

| Abbreviation | Definition |
|---|---|
| vol%. | Volume percentage |
| W | Weight |
| wt%. | Weight percentage |
| $Wt_w$ | Wet weight |
| XRD | X-Ray Diffraction |

## NOTATIONS

| Notations | Definition |
|---|---|
| σ | Conductivity |
| $^0$C | Degree Celsius |
| g | Gram |
| g/cm$^3$ | Gram per cubic centimeters |
| MPa | Megapascal |
| m$^2$/g | Metersquare per gram |
| mm | Millimeters |
| nm | Nanometer |
| $\rho$ | Resistivity |
| rpm | Rotations per minute |
| S/cm | Siemens per centimeter |
| $\rho_{th}$ | Theoretical Density |
| W/mK | Watt per meter kelvin |

# CHAPTER 1
# INTRODUCTION

## 1.1 PROTON EXCHANGE MEMBRANE FUEL CELLS

Proton Exchange Membrane fuel cells (PEMFC), also known as polymer electrolyte membrane (PEM) fuel cells, are a type of fuel cell being developed mainly for transport applications [1]. They are advanced devices that convert the energy stored in hydrogen into electricity through a process called electrochemical reactions. These cells use a specialized membrane to allow protons to move between positive and negative sides, creating electrical energy in the process.

The key components of a PEM fuel cell include proton exchange membrane which is a thin polymer membrane that allows protons to pass through while blocking electrons. Anode, which is the electrode here hydrogen molecules are oxidized, releasing protons and electrons. These electrons travel through the circuit towards the cathode establishing current flow in the circuit. The cathode is the electrode where oxygen molecules combine with protons and electrons to form water. The working of a typical PEMFC is shown in Fig 1.1.

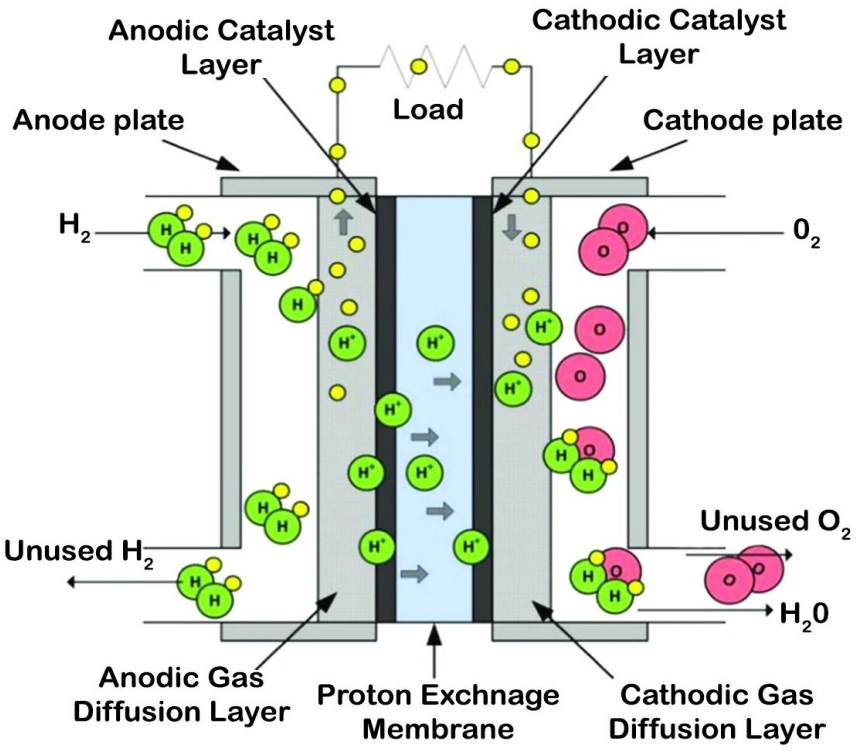


**Fig.1.1** Fuel cell system.

PEMFCs are highly efficient at converting hydrogen power into electricity, making them ideal for various applications, especially in powering vehicles. Remarkably, these cells operate at

moderate temperatures, typically between 60 and 80 degrees Celsius, allowing for quick start-ups and ensuring long-lasting performance. Their ability to rapidly start and stop, well-suited for applications like cars, adds to their appeal. Furthermore, their compact and lightweight design makes them perfect for portable devices such as phones and even vehicles.

Major components of PEMFC fuel cells (Fig 1.2) include- bipolar plates- which are conductive plates that distribute reactants to the respective electrodes and collect the electrical current produced and help remove excess water from the cell; gas diffusion layer- which are porous materials that facilitate the even distribution of reactant gases over the surface of the electrodes; catalyst- which aid in increasing the rate of production of hydrogen and oxygen ions; proton exchange membrane- which acts as a medium for travel of protons from one cathode to anode. A significant environmental advantage lies in the fact that PEMFC only produce water as a byproduct when generating electricity, making them environmentally friendly with zero harmful emissions. Additionally, their scalability is another notable feature that allows stacking of these cells to generate more power, catering to various energy needs.

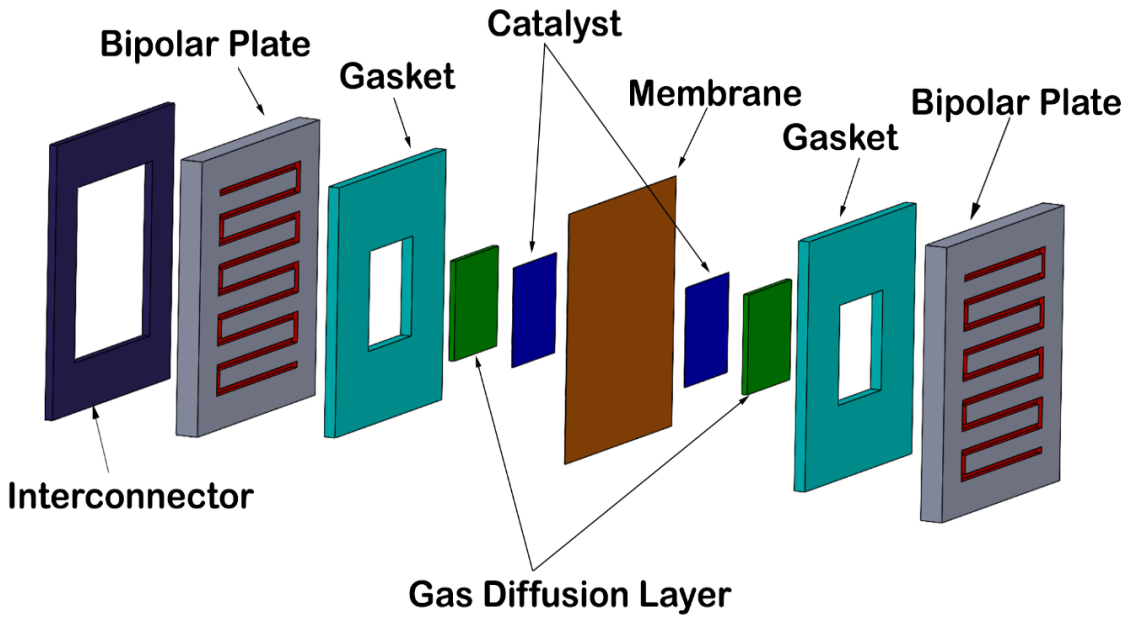


**Fig.1.2** Components of PEMFC

## 1.2 NEED FOR BIPOLAR PLATES IN PEMFC

Bipolar plates (Fig 1.3) serve as multifunctional components within PEMFC, playing a critical role in the efficient operation of the system [2]. These conductive elements establish a pathway

for the flow of electrons to establish current flow. Additionally, bipolar plates play a major role in the distribution of reactant gases, typically hydrogen and oxygen, evenly across the surface of the electrodes. This uniform distribution is essential for optimizing the electrochemical reactions at the anode and cathode, thereby promoting the overall efficiency of the fuel cell. As electrons are generated at the anode and traverse the external circuit to the cathode, bipolar plates function as collectors, efficiently gathering and channelling the electrical current.

Beyond their electrical roles, these plates provide crucial structural support to the fuel cell

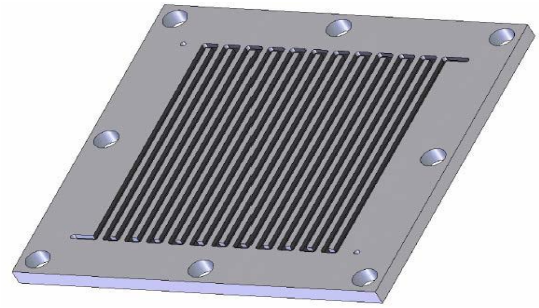

**Fig.1.3** Bipolar Plate

stack, where multiple cells are stacked together to achieve the desired power output. This mechanical support is vital for maintaining the integrity of the stack and preventing deformation or damage during operation. Efficient heat dissipation is another key contribution of bipolar plates to PEM fuel cells. By conducting excess heat away from the fuel cell, these plates play a crucial role in preventing overheating and ensuring consistent performance. Moreover, bipolar plates contribute to gas sealing within the stack, preventing the mixing of reactant gases and ensuring the separation of hydrogen and oxygen streams. This gas sealing is essential for maintaining the integrity of the electrochemical reactions and preventing unwanted side reactions that could compromise performance. Controlling the water balance is critical for PEM fuel cell performance, and bipolar plates actively contribute to water management. They facilitate the removal of excess water produced during electrochemical reactions, preventing flooding within the cell and maintaining optimal conditions for proton transport through the membrane. Additionally, bipolar plates act as barriers to prevent the permeation of hydrogen gas, safeguarding the purity of the hydrogen stream and addressing safety concerns associated with potential hydrogen leakage.

## 1.3 LIMITATIONS OF CONVENTIONAL BPs

Bipolar plates are generally made of graphite and metals. Graphite, while a lightweight and conductive material, has limitations in terms of mechanical strength. Bipolar plates made from graphite may be susceptible to mechanical stress and deformation, especially in applications where there are high-pressure conditions or frequent temperature variations. This limitation can affect the overall durability and structural integrity of the fuel cell [3]. Manufacturing bipolar plates from high-quality graphite can still contribute to the overall cost of PEM fuel cell production. The limited mechanical strength of graphite may impose restrictions on the load-bearing capacity of bipolar plates. This limitation can impact the suitability of graphite-based plates in applications where higher mechanical strength is a critical requirement. Achieving the necessary precision in manufacturing graphite bipolar plates can be challenging, especially when intricate designs are required. Complex machining processes can contribute to increased manufacturing costs.

Metallic BP has attractive properties like excellent electrical and thermal conductivity, good mechanical properties, reduced gas permeability and better machinability. However, metallic BP's major drawback is its poor corrosion resistance. PEMFC is operated at moderately high temperatures of 60-80 $^{0}$C and at a pH of 2-3 in the presence of water. This working atmosphere results in the corrosion of metallic BP, which negatively affects the lifetime and power output of the fuel cell. Hence special coatings are needed to be made to the metallic BP, which adds to the expense and is time-consuming [4]. Moreover, this protective coatings are vulnerable to damage in the future.

## 1.4 POLYMER COMPOSITE BIPOLAR PLATE

PCCBP is another emerging alternative to graphite and metallic BP. They are fabricated by moulding techniques either by thermoplastic or thermosetting resin along with electrically conductive fillers like graphite, carbon black (CB), carbon fibres (CF), graphene (Gr), etc. PCCBP has many advantages like low density, excellent corrosion resistance, and low cost compared to graphite and metallic BP. However, the PCCBP's electrical conductivity is very low. Adding conductive fillers over a specific limit to increase electrical conductivity reduces its mechanical properties.

This research explores the scope of utilizing copper fibres of various lengths with carbon black and natural flake graphite in a matrix of epoxy resin to produce a composite of high electrical conductivity and mechanical strength. Along with this we study the influence of variation of

Cu-fibre length on the electrical conductivity and flexural strength of the composite. Composite plates are much thinner and lighter than conventional graphite plates. This would help in reducing the size and weight of individual fuel cells, thus, allowing us to design a fuel stack that can be used for commercial automobiles.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 LITERATURE SURVEY

Ahmed et al. (2016), [5] discusses about hydrogen as a promising solution to curb greenhouse gas emissions, and certain nations are taken as examples like Canada, Japan, the US, and Germany. However, In Malaysia certain challenges are being faced such as high production costs and limited adoption of fuel cell vehicles. In case of Japan, it leads in universal hydrogen system development due to its lack of fossil fuel resources. Malaysia aims to emulate this but encounters economic hurdles. The study emphasizes the need for scientific innovation, technological advancement, and sustained commitment to realize a hydrogen-based energy future in Malaysia.

Mathew et al. (2022), [6] developed a PCCBP using copper fibre, epoxy resin, natural flake graphite, and carbon black using compression moulding. Copper fibre addition resulted in the increase of electrical conductivity and flexural strength. The composite containing 8% Cu fibre, 10% carbon black, and 42% natural flake graphite exhibited remarkable electrical conductivity (169 S/cm), flexural strength (43 MPa), thermal conductivity (17 W/mK), and corrosion resistance. The study offers insights for advancing metal based PCCBPs in fuel cell applications.

Soleimani et al. (2019), [7] discusses about how cost-effective bipolar plates for PEMFCs are synthesized using epoxy, graphite, and nano-copper using bulk moulding. Epoxy mainly provides us cost-effectiveness, while graphite and nano-copper increase the overall conductivity of the composite. Different ratios are carefully studied, and properties are evaluated as per industry standards, confirmed by SEM and XRD ,It showed that the composite had enhanced efficiency and performance.

Kakati et al. (2010), [8] developed composite bipolar plates for fuel cells were made using compression moulding where novolac type phenol formaldehyde resin was used as a binder, with natural graphite, carbon black, and carbon fibre as reinforcements. Characterization included electrical conductivity, mechanical strength, and corrosion resistance. The optimum composition (PF:30%; NG:60%; CB:5%; CF:5%) yielded a flexural strength of 55.28 MPa, with 5.2% deflection at mid-span, along with in-plane and through-plane electrical conductivities of 286 and 92 S/cm, respectively

Luyt et al. (2006), [9] fabricated a composite using low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) with varied copper concentrations, by melt mixing. Uniform copper distribution was observed, though clustering increased at higher concentrations, forming percolation paths. DSC revealed about minimal melting temperature impact. Here Copper acts as a nucleating agent, enhancing the crystallinity of the composite. LDPE-Cu showed high thermal stability, while LLDPE showed better stability at lower copper content. The Thermal and electrical conductivities were much greater than pure polyethylene.

Banerjee et al. (2020), [10] studied the impact of graphite loading by developing high density polythene(HDP)/copper composites, with varying copper volumes and graphite using melt blending and injection moulding. Thermal conductivity had increased with 40 vol.% copper and graphite, showcasing synergistic efficiency. Graphite lowered percolation threshold, indicating synergy with copper. Resulting composites had the properties of corrosion-resistant, mechanically robust, electrically and thermally conductive which are ideal for fuel cell devices.

Huang et al. (2005), [11] proposed a method for producing cost-effective bipolar plates with high electrical conductivity and mechanical strength is outlined. Thermoplastic composite materials, made of graphite particles, thermoplastic fibres, and glass or carbon fibres, are created using a wet-lay process, forming highly malleable sheets. These sheets were stacked and compression moulded to form bipolar plates with gas flow channels. Poly phenylene sulphide (PPS) based wet-lay composite plates exhibit exceptional in-plane conductivity (200–300 S/cm) and mechanical properties, surpassing industry and Department of Energy requirements.

Wu et al. (2005), [12] explains about the triple-continuous structure which was achieved through injection moulding of carbon nanotube-filled PET blend that enhances the electrical conductivity and tensile strength. Compared to CNT-filled PET, the blend exhibits remarkable improvements, promising cost-effective, high-performance conductive polymers for PEM fuel cell bipolar plates.

Roncaglia et al. (2021), [13] explored graphite-epoxy composites for fuel-cell bipolar plates, comparing wet and dry mixing methods. Their study, published in the International Journal of Hydrogen Energy, also investigated about the impact of design of experiment (DOE) techniques on optimizing moulding parameters. By assessing different mixing approaches and utilizing DOE, the research aims to enhance the fabrication process and performance of

graphite-epoxy composites for fuel-cell applications, contributing to advancements in sustainable energy technologies.

Lee et al. (2009), [14] explained about the weight and cost in fuel cell stacks, polymer composite materials with carbon conducting fillers are explored for use as bipolar plates. Composites, comprising graphite and low vol.% of carbon black (CB), multi-walled carbon nanotubes (MWNTs), or carbon fibers (CF) in epoxy resin, are evaluated. The highest electrical conductivity is achieved at 75 vol.% total conducting filler content. Incorporating a small hybrid conducting filler amount improves conductivity until specific thresholds, enhancing overall properties compared to single filler systems.

Lopes et al. (2014), [15] investigated the corrosion resistance of polyphenylene sulphide (PPS) and carbon black-graphite composites for potential use as bipolar plates in polymer electrolyte membrane (PEM) fuel cells. Scanning electron microscopy (SEM) examines cross-sectional views. Electrochemical impedance spectroscopy (EIS) and polarization tests characterize their response in simulated PEM fuel cell environments. Results indicate corrosion resistance decreases with higher carbon black content, likely influenced by composite porosity and electrical conductivity.

Zakaria et al. (2015), [16] studied carbon composite bipolar plates fabricated via compression moulding, employing synthetic graphite and milled carbon fibers as conductive fillers within an epoxy polymer matrix. The composite achieves a high electrical conductivity of 69.8 S/cm (in-plane) and 50.34 S/cm (through-plane) at 2 wt.% carbon fiber and 80 wt.% filler loading, surpassing typical graphite/epoxy composites by 30%. Flexural strength increases to 36.28 MPa compared to single filler systems (25.22 MPa). The General Effective Media (GEM) model accurately predicts electrical conductivities for both single and multiple filler composites.

Alavijeh et al.(2019), [17] successfully synthesized an economically viable nanocomposite for bipolar plates in proton-exchange membrane fuel cells (PEMFCs). Epoxy/graphite/nano-copper nanocomposite plates are prepared via bulk moulding compound process, where graphite serves as the primary filler and nano-copper as the secondary filler. The addition of nano-copper enhances conductivity throughout the composite, dispersed effectively due to its nanoscale size. Various filler percentages are tested, and resulting composites undergo rigorous testing for electrical resistance, flexural strength, and density. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) confirm filler dispersion. Notably, this

innovation improves composite properties and efficiency by incorporating metal nanoparticles (copper).

## 2.2 RESEARCH GAP

It has been observed that research works on metal doped composite BPs are limited. Only a few works have been conducted on the use of metallic fibre fillers for improving the conductivity and flexural strength of BPs. Currently no works are reported on the study of influence of length of metallic fibre in BPs.

## 2.3 PROJECT OBJECTIVES

- To develop a composite BP using carbon fillers, metallic fibers and conductive polymer.
- To study the effect of Cu fiber length on electrical, mechanical and morphological properties BP.
- To characterize the developed composite based on the measured mechanical properties and electrical conductivity.

# CHAPTER 3

# MATERIALS

## 3.1 EPOXY RESIN

Epoxy resin (ER) is a synthetic polymer known for its versatility and strong adhesive properties. When mixed with a curing agent or hardener, such as Araldite Epoxy CY 230-1 and Aradur HY951 acquired from Huntsman, Texas, US, respectively, it undergoes a chemical reaction resulting in a hardened, durable material suitable for various applications. The specific resin used in this research, Araldite Epoxy CY 230-1, exhibits a viscosity of 1350 mPa s and a specific gravity of 1.1 $g/cm^3$, providing important characteristics for its application. ER serves as the base matrix to which different fillers can be added, allowing for customization based on specific project requirements. Its widespread use in adhesives, coatings, casting, and moulding makes it a valuable material in industries ranging from construction to manufacturing. By understanding the properties of this resin and its curing process, researchers can optimize its performance for specific applications, contributing to advancements in material science and engineering.

## 3.2 CARBON BLACK

Carbon black (CB) is a finely powdered substance primarily composed of elemental carbon, characterized by its deep black colour. Its production involves the incomplete combustion or thermal decomposition of hydrocarbons, which can include oil or natural gas. This process results in the formation of small carbon particles that aggregate to form the distinctive fine powder known as carbon black. In various industries, carbon black serves as a secondary filler material, chosen for its relatively low cost compared to other additives. Additionally, carbon black contains functional groups such as phenols, carboxyl, lactones, and quinones. These functional groups facilitate effective blending and amalgamation with the resin matrix, leading to improved composite properties. Due to its spherical shape, carbon black particles are adept at filling the voids between larger conductive particles within a composite material. This characteristic enables carbon black to form a conductive network, enhancing the electrical conductivity of the composite. Consequently, in applications where electrical conductivity is essential, such as in battery electrodes or electromagnetic shielding materials, carbon black is a valuable component. The specific properties of carbon black, such as its high surface area of 254 $m^2/g$ and small particle size of 30 nm, contribute to its effectiveness in enhancing the performance of composite materials. By incorporating carbon black into composite

formulations, manufacturers can achieve desired electrical conductivity levels while maintaining mechanical strength and other desired properties. Therefore, carbon black plays a crucial role in various industries, including automotive, electronics, and construction, where composite materials are utilized for their unique combination of properties.

**Fig 3.1:** Carbon black

## 3.3 NATURAL FLAKE GRAPHITE

Natural flake graphite is a crystalline form of carbon that occurs in nature as graphite flakes, which are flat, thin, and hexagonally arranged. It is one of the naturally occurring allotropes of carbon, along with amorphous carbon, diamond, and fullerenes. Natural flake graphite is mined from graphite deposits and is known for its distinct structure and properties. NFG is used as the primary conductive filler as many literatures reported that elongated flake-like particles form an excellent electrically conductive path through the composite. NFG with carbon content >=98% and +50 mesh >=80%.

**Fig 3.2:** Natural flake graphite

## 3.4 COPPER FIBER

In this project, copper in the form of small tin fibers serves as the filler material, selected for its widespread availability, exceptional electrical conductivity, which is nearly 90% as efficient as pure silver, and its outstanding mechanical properties and malleability. The choice of copper fibers with a diameter ranging from 100 to 200 micrometers, a density of 8.96 g/cm$^3$, and a purity of 99% is deliberate, as these specifications ensure optimal performance for the intended application. Leveraging the high electrical conductivity of copper enhances the

efficiency of electrical and electronic components, making it an ideal choice for various industrial and technological applications. Additionally, the mechanical robustness and malleability of copper fibers facilitate their incorporation into composite materials, providing strength and flexibility where needed. Overall, the utilization of copper fibers underscores their versatility and suitability for diverse engineering and manufacturing endeavours, contributing to the advancement and innovation of materials science and technology.

**Fig 3.3:** Copper fiber

# CHAPTER 4

# METHODOLOGY

## 4.1 PREPARATION OF ER/NFG/CB/Cu COMPOSITE

Compression moulding technique was used to fabricate the composite bipolar plate. Dimensions of the mould used for the moulding process is 12 cm×3 cm×0.3 cm. Liquid ER and filler materials were homogeneously mixed in a three-step process before compression moulding. In the first step, solid filler materials such as flakes, powders, and fibers are homogeneously mixed by a ball mill machine at 200 rpm for 1 h. Stainless steel balls are used with a balls-to-powder weight ratio of 4:1. In the second step, ER was mixed with the hardener in a ratio of 10:1 by volume, as suggested by the resin manufacturer. The resin and hardener are mixed by a high-speed mechanical mixer at a speed of 1400 rpm for 2 min. Mixing is done intermittently, preventing premature polymerization and condensation reactions due to frictional heat generated by the mixer blades. In the next stage, the epoxy-hardener mixture and solid fillers are blended together by a mechanical mixer at 50 rpm for 20 min. Finally, the composite plate is made by compression moulding with this mixture. The plates are compressed at a pressure of 20 MPa, initially at room temperature for 6 h and then at 65 C for 6 h. Fig 4.1 provides a pictorial representation of the fabrication process.

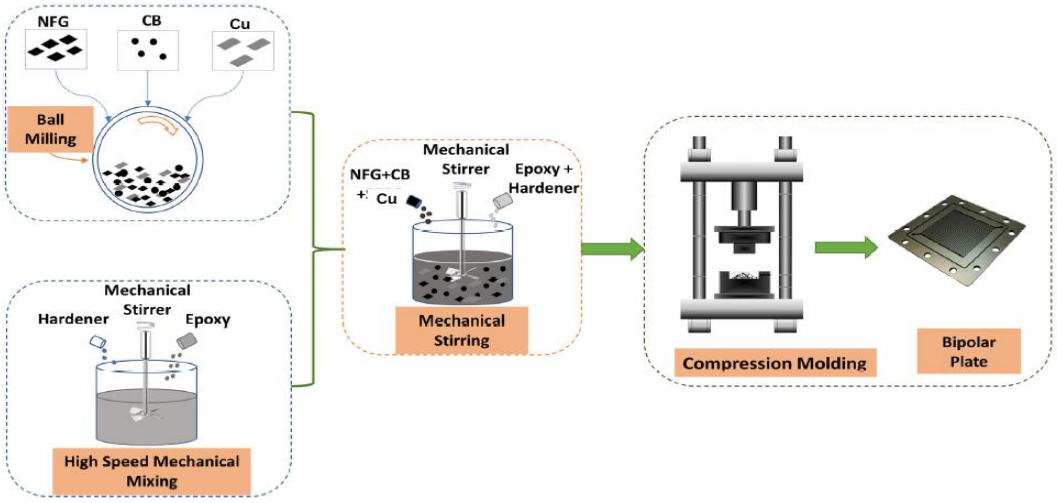


**Fig.4.1** Fabrication process of BP

The composite is prepared with ER as binder and Cu, NFG and CB as fillers. 6 samples are produced by following the same production process. In each sample the length of the sample is varied from 1-6 mm. The variation of electrical conductivity and mechanical strength with length of fibre is studied and the sample with most desirable properties is subjected to further analysis.

## 4.2 RELATED CALCULATIONS

Theoretical density ($\rho_{th}$) of the composite is calculated using the equation 4.1,

$$\rho_{th} = \frac{1}{\frac{W_1}{\rho_1}+\frac{W_2}{\rho_2}+\frac{W_3}{\rho_3}+\frac{W_3}{\rho_4}} \ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

where, $w_1, w_2, w_3, w_4$ are the individual weight percentage of ER, NFG, CB, Cu and $\rho_1$, $\rho_2$, $\rho_3$, $\rho_4$ are the individual densities. results. Theoretical density was found to be 2.1784 g/cm$^3$.

By multiplying this total density with the volume of the mould, the overall weight of the composite is obtained.

Total weight= Theoretical density ×Mould volume …… …… (4.2)

The total weight was found to be 28 g. Subsequently, the weight of each component can be calculated by multiplying its weight percentages to the total weight. Table 4.2 showcases the volume percentage (vol%) and weight (g) of ER, NFG, CB and Cu in the composite.

**Table 4.1**: Weight of ER, NFG, CB and Cu in the composite

| Name of components | Percentage by volume (%) | Density or specific gravity (g/cm$^3$) | Percentage by Weight (%) | Weight (g) |
|---|---|---|---|---|
| NFG | 44 | 2.213 | 44.70 | 12.156 |
| ER | 40 | 1.2 | 22.03 | 6.618 |
| CB | 8 | 0.1 | 0.37 | 0.1035 |
| Cu | 8 | 8.96 | 32.90 | 9.21 |

## 4.3 SAMPLE CHARACTERIZATION

### 4.3.1 Three Point Bending Test

The three-point bending test evaluates how a material responds to bending forces, providing insights into its flexural strength and deformation behaviour. Following the guidelines of ASTM D790 standards, the test involves supporting a sample at its ends while applying force at the center, causing the material to bend, as shown in Fig 4.2. By measuring the resulting stress and strain data, crucial mechanical properties such as modulus of elasticity and fracture toughness can be determined. This test method offers a standardized approach to assessing the bending characteristics of materials, making it easier to compare and analyse their performance. Understanding these mechanical properties is essential for various industries, including manufacturing, and aerospace, as it helps engineers select materials that can withstand bending loads and maintain structural integrity under different conditions. Overall,

the three-point bending test is a valuable tool for characterizing the mechanical behaviour of materials and ensuring their suitability for specific applications.

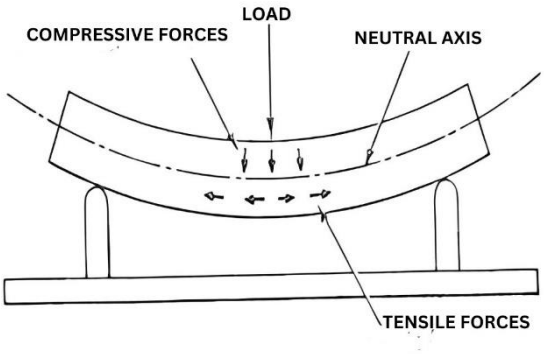


**Fig 4.2** 3-Point bending test

### 4.3.2 Electrical Conductivity

In the four-probe method using the Keithley Sourcemeter 2450, conductivity is measured indirectly by first determining the resistivity of the material being tested. Conductivity (σ) is the reciprocal of resistivity (ρ), so once the resistivity is known, conductivity can be calculated.

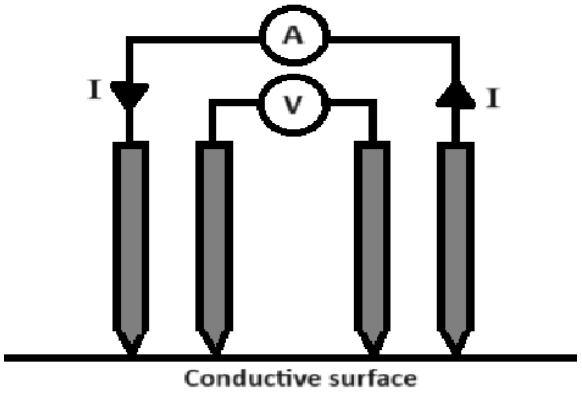


**Fig 4.3:** 4-point probe conductivity measurement

The material sample is placed between the four terminals of the Sourcemeter 2450, with two terminals used for current injection (Source) and the other two for voltage measurement (Sense). The Sourcemeter applies a known current (I) through the material using the Source terminals. The voltage drop (V) across the material is measured using the Sense terminals. This voltage corresponds to the resistance (R) of the material. Using Ohm's Law (V= I * R), the resistance (R) of the material is calculated. Once R is known, ρ is calculated using the relation 4.3,

$$R = \rho \times \frac{L}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

where, L is length of sample being tested and A is its cross-sectional area.
σ can be calculated using the equation 4.4,

$$Conductivity, \sigma = \frac{1}{\rho} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

### 4.3.3 Shore D Durometer

The Digital Type Shore D Durometer is a device that measures the hardness of polymers and elastomers. It's designed to meet the standards outlined in ASTM D2240, ensuring accurate and reliable results. The durometer utilizes a pointed indenter to penetrate the surface of the material being tested. Once the measurement is taken, it provides a digital readout, making it easy to record and interpret the hardness value. This standardized testing process ensures consistent assessment of hardness across different materials. This information is valuable for industrial applications where material selection is critical. By knowing the hardness of a material, manufacturers can make informed decisions about which materials to use for specific purposes. Understanding hardness helps ensure that materials can withstand the required stresses and strains. Overall, the Digital Type Shore D Durometer provides a simple and effective way to measure hardness, contributing to the quality and reliability of manufactured products

### 4.3.4 Water Absorption Test

The water absorption test, following ASTM D570 standards, assesses how well a material can soak up moisture. To conduct the test, samples of the material are submerged in water, and their weight changes are tracked over a specified period. Water absorption of the samples was then calculated using equation 4.5,

$$Water\ absorption = \frac{(Wt_w - Wt_d)}{Wt_d} * 100\% \ldots\ldots\ldots\ldots\ldots\ldots (4.5)$$

where $Wt_w$ is wet weight and $Wt_d$ is dry weight of the specimen. This method helps in gauging how prone a material is to deterioration caused by water.

Understanding a material's ability to absorb water is crucial because excessive moisture absorption can lead to structural weaknesses, dimensional changes, and other forms of degradation over time. In manufacturing, products like electronic components or packaging materials need to withstand moisture to ensure their functionality and durability. Therefore, the water absorption test provides valuable insights into a material's performance in real-world

conditions, aiding in informed decision-making for selecting the most suitable materials for specific applications.

### 4.3.5 Water Contact Angle

A contact angle meter is a device used to measure the angle formed at the interface between a liquid droplet and a solid surface. This angle, known as the contact angle, plays a crucial role in understanding the surface wettability and adhesion properties of materials. In material science and surface chemistry, contact angle measurement is a common technique employed to assess surface interactions. By accurately determining the contact angle, researchers can evaluate the effectiveness of surface treatments, coatings, and modifications. This information is invaluable for quality control purposes, ensuring that surfaces meet desired specifications and performance requirements. Additionally, contact angle measurement aids in the optimization of coatings and treatments by providing insights into how different surface modifications affect the wetting behaviour of liquids. Overall, contact angle meters are indispensable tools for characterizing surface properties and advancing research in various fields, including materials science, nanotechnology, and biomedical engineering.

### 4.3.6 Bulk Density

Bulk density measurement, following ASTM C559 standards, was conducted to assess the density of prepared samples. This involved determining the mass-to-volume ratio of the samples, a critical parameter in understanding their physical properties.

$$Bulk\ density = \frac{Mass\ of\ sample}{Volume\ of\ sample} \ldots\ldots\ldots\ldots\ldots\ldots (4.6)$$

By measuring bulk density, we gain insights into how tightly packed the material is, which has implications for various applications, such as construction, agriculture, and pharmaceuticals. The ASTM C559 standards ensure consistency and accuracy in the measurement process, allowing for reliable comparisons between different materials and batches. This information aids in material characterization and selection, enabling engineers and researchers to make informed decisions about the suitability of the samples for specific purposes. Overall, the bulk density determination serves as a fundamental aspect of material testing, providing valuable data for optimizing processes and ensuring product quality.

# CHAPTER 5

# RESULTS AND DISCUSSION

The composite samples prepared are shown in Fig 5.1. The variation in fiber length is observable on the surface of developed samples.

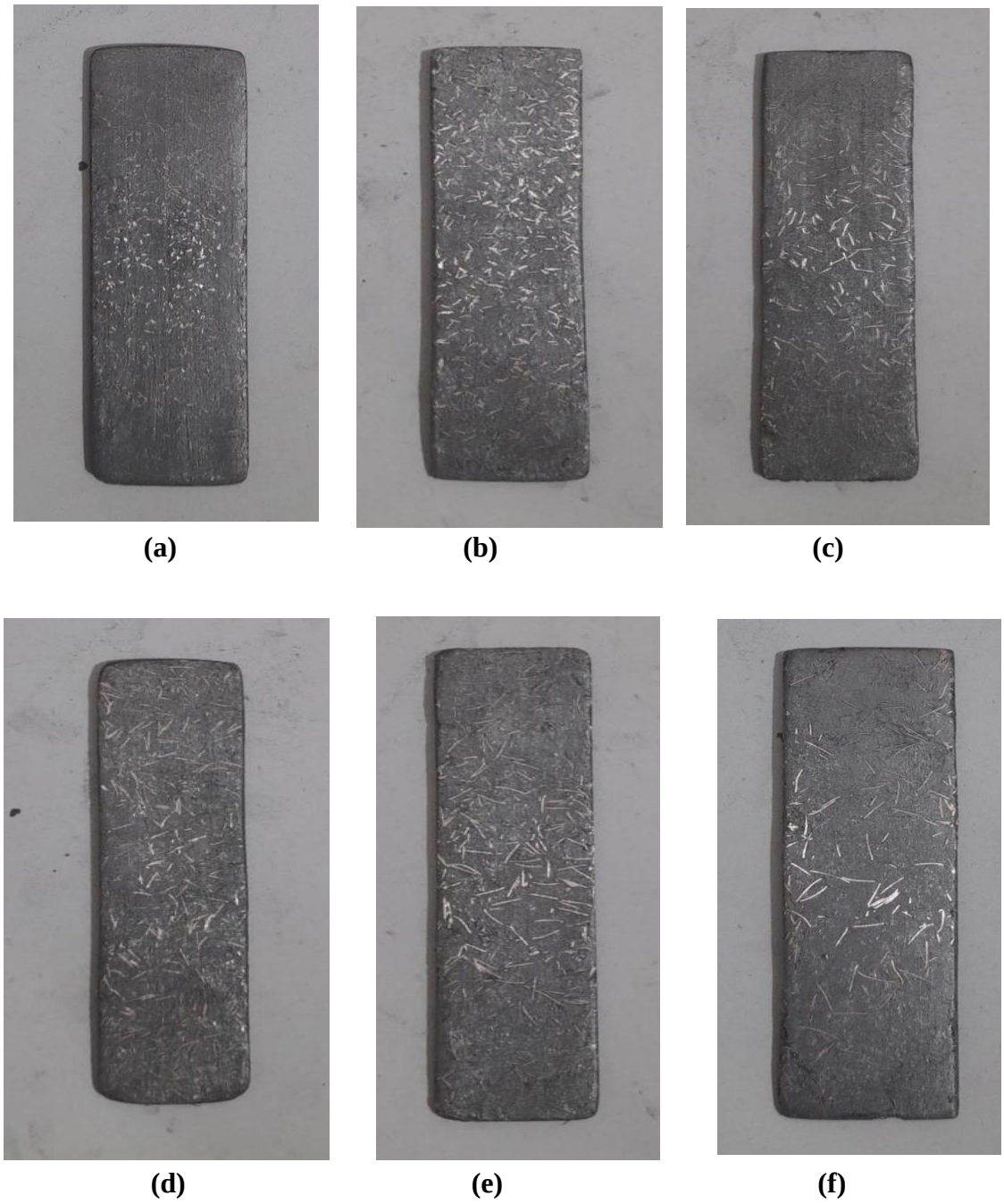


**Fig 5.1:** ER/NFG/CB/Cu samples of different fiber lengths
(a) 1mm, (b) 2mm, (c) 3mm, (d) 4mm, (e) 5mm, (f) 6mm

## 5.1 FLEXURAL STRENGTH

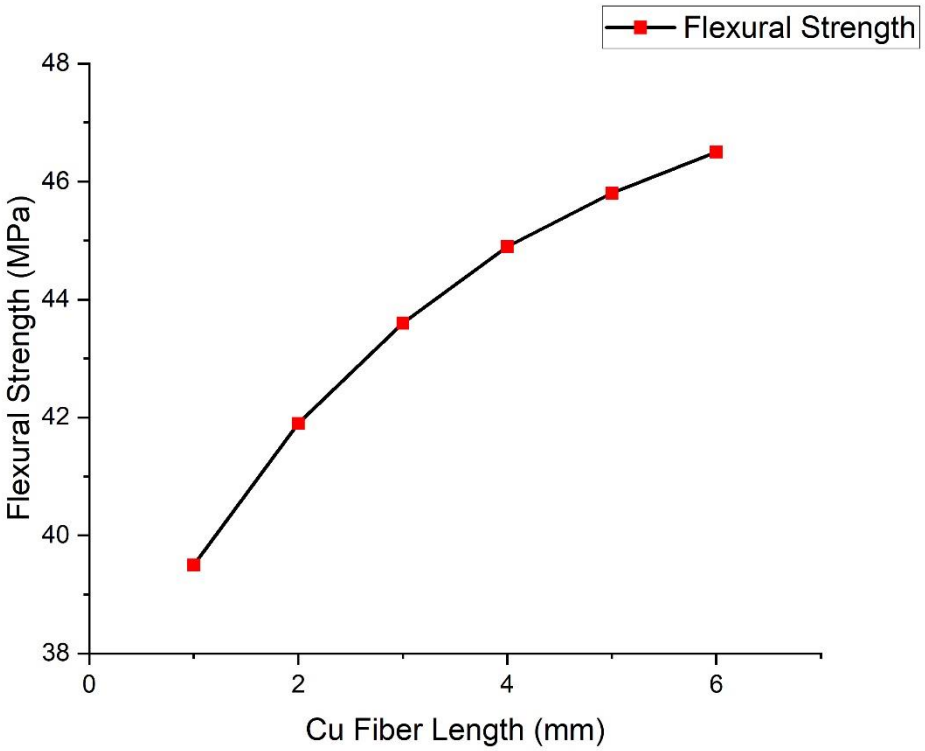


**Fig 5.2:** Variation of flexural strength of composite with Cu fiber length.

When fiber length increases, flexural strength tends to increase as well. This relationship can be attributed to the improved stress distribution within the material. At shorter fiber lengths, stress distribution may be improper, leading to lower flexural strength. This occurs because shorter fibers may not effectively bridge the gaps between load-bearing points, resulting in localized stress concentrations and weaker regions within the material.

**Table 5. 1**: Variation of flexural strength of composite with Cu fiber length.

| Fiber length (mm) | Hardness |
|---|---|
| 1 | 39.5 |
| 2 | 41.9 |
| 3 | 43.6 |
| 4 | 44.9 |
| 5 | 45.8 |
| 6 | 46.5 |

However, as fiber length increases, fibers have more space to interlock and cross each other, forming a mat-like structure. This structural arrangement enhances the ability of the material to distribute stresses more uniformly, thereby increasing flexural strength. The longer fibers effectively span across multiple load-bearing points, providing greater reinforcement and resistance to bending forces. Consequently, materials with longer fiber lengths exhibit higher flexural strength due to the improved stress distribution facilitated by the formation of a cohesive mat-like structure. The samples produced exhibited flexural strength in the range of 39.5 to 46.5 MPa.

## 5.2 ELECTRICAL CONDUCTIVITY

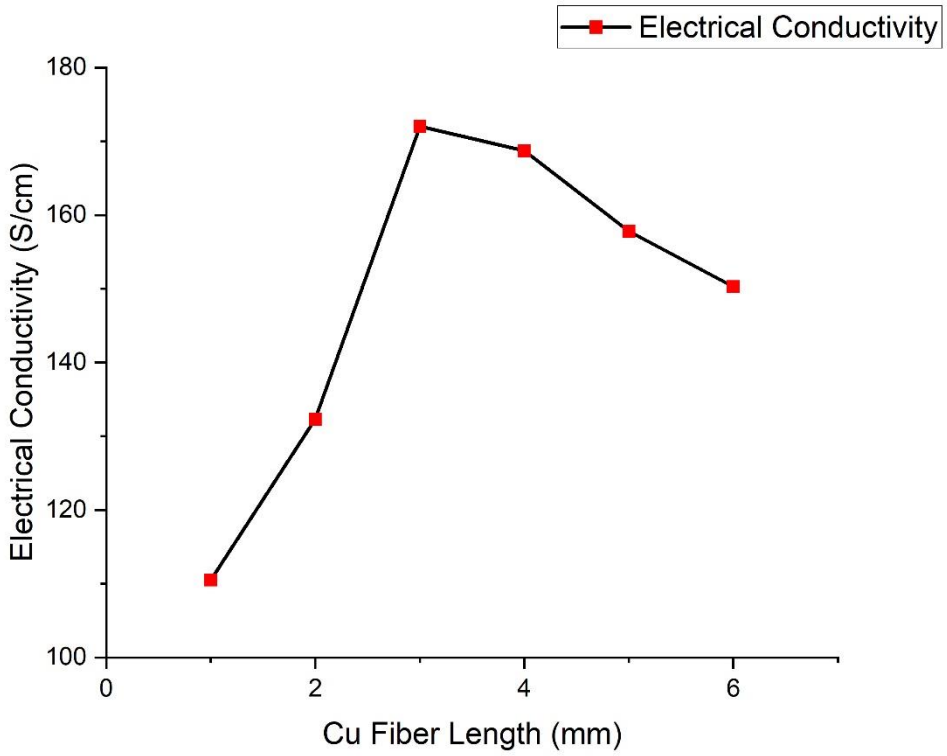


**Fig 5.3:** Variation of Electrical conductivity of composite with Cu fiber length.

Initially, the electrical conductivity showed an increase up to a fiber length of 3 mm, attributed to the even distribution of metallic fibers and carbon fillers within the composite material. This even distribution facilitated efficient electron transport, leading to enhanced conductivity. However, beyond the 3mm length of fibre, there was a noticeable decrease in conductivity. The initial low conductivity can be attributed to the agglomeration of CB which results in micro voids. Beyond 3mm there is effective filling of voids by CB, forming efficient conductive paths. The slight decline in conductivity beyond 3 mm can be attributed to the increased resistance offered by longer metallic fibers. This observation underscores the importance of fiber length in determining the electrical properties of composites, highlighting

the need for careful optimization of fiber distribution to achieve desired conductivity levels in composite materials.

**Table 5.2:** Variation of Electrical conductivity of composite with Cu fiber length.

| Fiber length (mm) | Electrical conductivity (S/cm) |
|---|---|
| 1 | 110.5 |
| 2 | 132.3 |
| 3 | 172 |
| 4 | 168.7 |
| 5 | 157.8 |
| 6 | 150.3 |

## 5.3 SHORE D HARDNESS

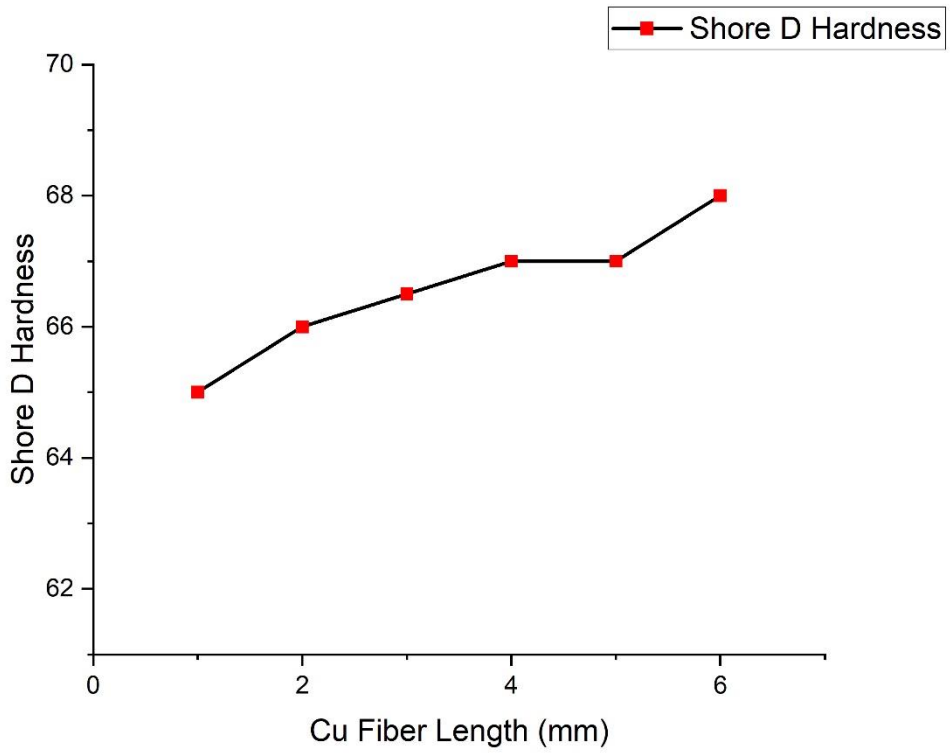


**Fig 5.4:** Variation of Shore D Hardness of composite with Cu fiber length.

When examining the relationship between hardness and length, it becomes evident that hardness tends to increase as the length of the fiber material increases. This phenomenon can be explained by the support provided to the carbon fillers by the interlocking long fibers. In instances where the fiber length is smaller, the underlaying fibers are not capable of providing

adequate support to the surface of the composite. At shorter lengths CB particles may also agglomerate resulting in formation of micro-voids. Therefor it is easier to remove material from the surface. Conversely, at higher fiber lengths, it is observed that the sample surface is fully supported by the inter winding fibers, and most voids are effectively filled by carbon particles. Thus the surface becomes more resistant to abrasions and indentations. This observation underscores the importance of fiber length in determining the mechanical properties of materials, particularly in relation to hardness. Understanding this relationship is crucial for optimizing material processing and improving the overall performance of engineered materials in various industrial applications.

**Table 5.3:** Variation of Shore D Hardness of composite with Cu fiber length.

| Fiber length (mm) | Hardness |
|---|---|
| 1 | 65 |
| 2 | 66 |
| 3 | 66.5 |
| 4 | 67 |
| 5 | 67 |
| 6 | 68 |

## 5.4 WATER CONTACT ANGLE

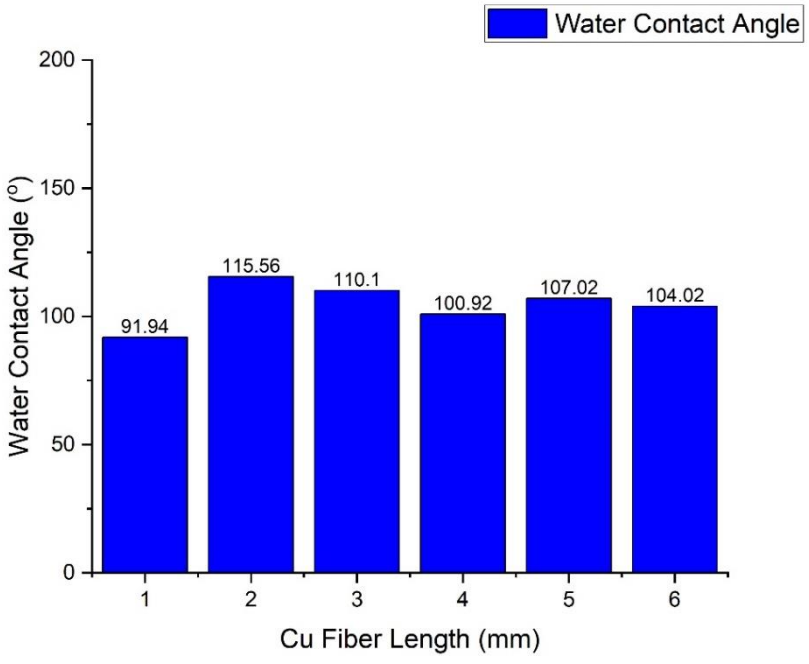


**Fig 5.6** Variation of water contact angle with Cu fiber length

A water contact angle exceeding 80 degrees indicates a material's hydrophobic nature, meaning it repels water. In our study, samples exhibited contact angles in the range of $91^0$-$116^0$, with the sample of 2mm fiber exhibiting the highest angle of $115.56^0$ and 1mm with the least angle, $91.94^0$. This suggests that the material effectively resists wetting by water droplets, which could be advantageous in various applications. The substantial contact angle signifies strong surface tension and minimal interaction between the material and water molecules. In industrial contexts, materials with high water contact angles can be employed for coatings or surface treatments to enhance waterproofing and corrosion resistance. Overall, the measured water contact angle of samples underscores their pronounced hydrophobic nature, highlighting their potential utility on bipolar plates.

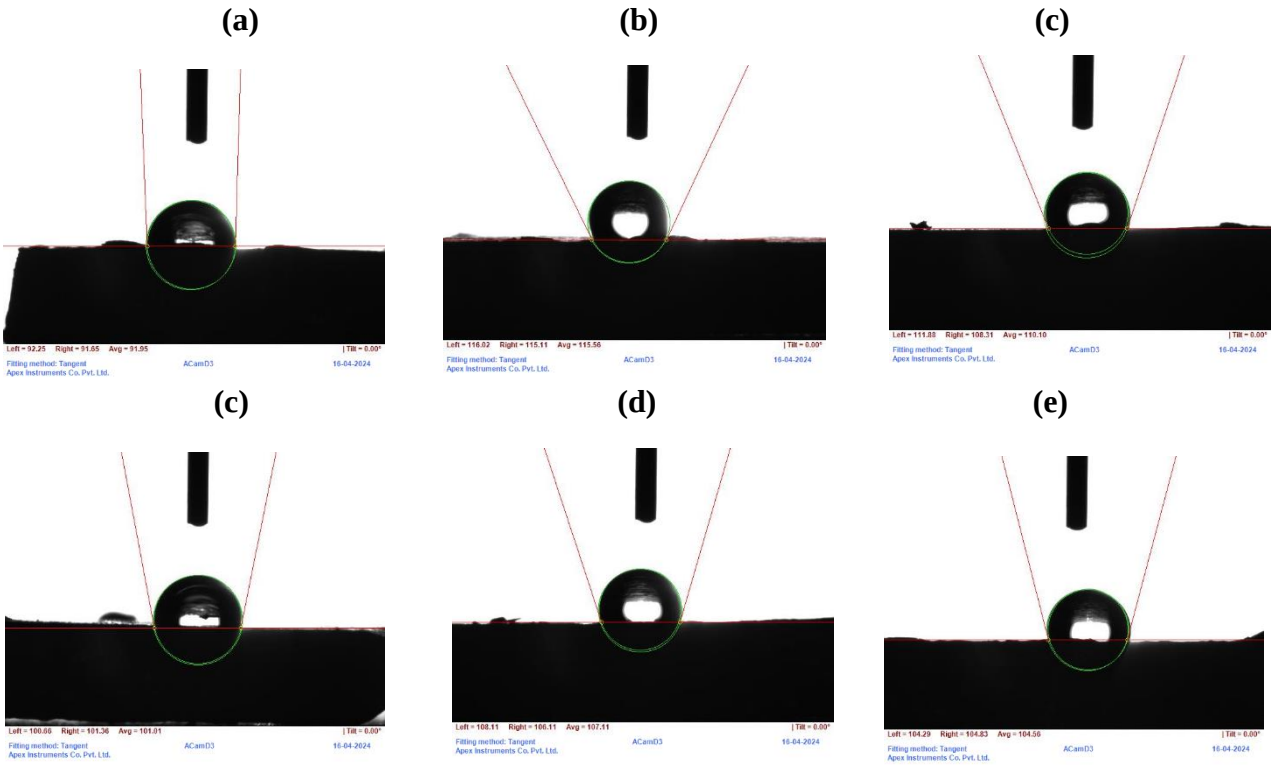


**Fig 5.5:** Water contact angle of ER/NFG/CB/Cu samples of different fiber lengths (a) 1mm, (b) 2mm, (c) 3mm, (d) 4mm, (e) 5mm, (f) 6mm.

## 5.5 WATER ABSORPTION

When particle agglomerate within a composite material, they create voids or empty spaces within the structure. These voids can lead to an increase in the material's water absorption capacity. Despite the overall volume of the composite remaining relatively constant, the presence of these voids allows for greater penetration of water molecules into the material. This phenomenon occurs because of the voids provide pathways for water to infiltrate and permeate through the composite. As a result, the composite absorbs more water, which can

have implications for its mechanical properties. Understanding the relationship between particle agglomeration and water absorption is crucial for designing composite materials with desirable properties for various applications. By mitigating agglomeration and controlling the distribution of particles within the composite, engineers and material scientists can optimize the material's resistance to water absorption and enhance its overall performance and durability.

**Fig 5.7:** Water Absorption (%) of composite with Cu fiber length.

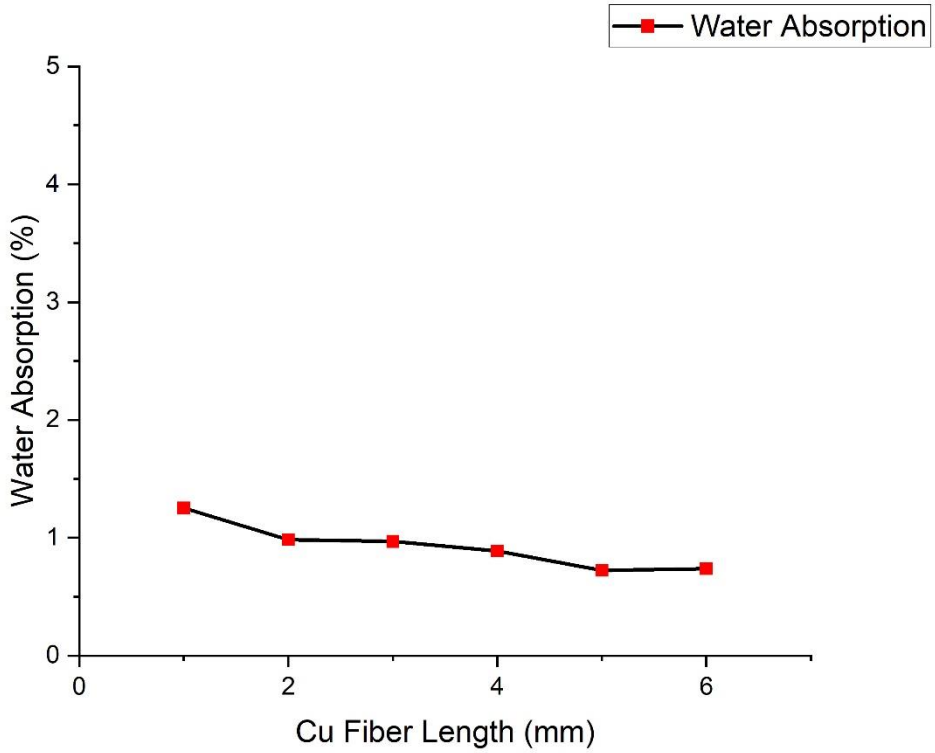


**Table 5.4:** Variation of water absorption (%) of composite with Cu fiber length.

| Fiber length (mm) | Water absorption (%) |
|---|---|
| 1 | 1.252 |
| 2 | 0.985 |
| 3 | 0.969 |
| 4 | 0.889 |
| 5 | 0.725 |
| 6 | 0.739 |

## 5.6 BULK DENSITY

When micro voids are present within a material, the bulk density tends to decrease. These tiny voids or spaces within the material reduce the overall density by displacing some of the solid material. However, it is observed that despite the presence of micro voids, the density remains constant. This phenomenon suggests that there might be other factors compensating for the decrease in density caused by the micro voids. One possible explanation could be the arrangement or packing of the solid particles within the material, which might undergo rearrangement to counteract the effects of the micro voids. Understanding these mechanisms is crucial for ensuring the consistency and predictability of material properties, especially in industries where bulk density plays a critical role in product performance and quality control. Samples show an average density of 2.44 g/cm$^3$.

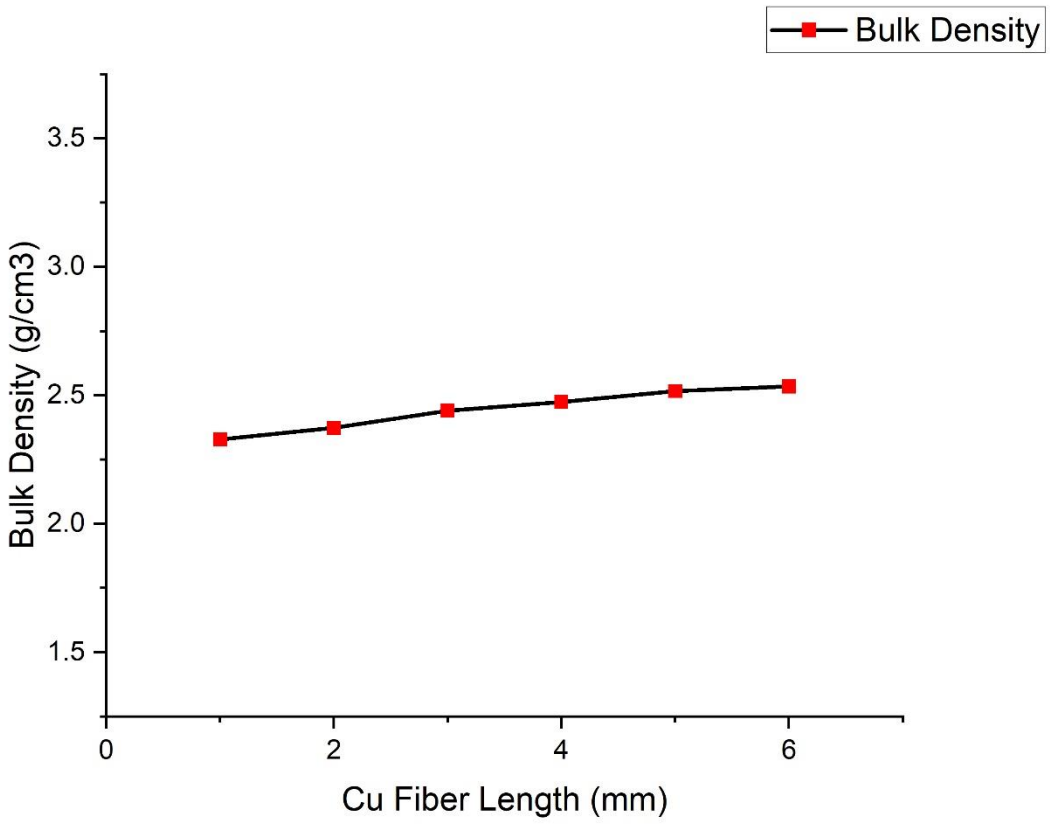


**Fig 5.8:** Bulk Density of composite with Cu fiber length.

**Table 5.5:** Variation of bulk density of composite with Cu fiber length.

| Fiber length (mm) | Bulk density($g/cm^3$) |
|---|---|
| 1 | 2.328 |
| 2 | 2.373 |
| 3 | 2.44 |
| 4 | 2.474 |
| 5 | 2.516 |
| 6 | 2.534 |

# CHAPTER 6

# CONCLUSION

The global climate changes produced by greenhouse gases emissions such as $CO_2$, $NO_x$ and $SO_x$ that are ongoing throughout the world pose a progressively higher demand for replacing today's fossil fuel-based energy production technologies. Among the alternative energies available, PEM fuel cells, are a type of fuel cell being developed mainly for transport applications, as well as for stationary fuel-cell applications and portable fuel-cell applications. They emerged as promising substitutes to fossil fuels. The potential to reduce overall energy consumption, zero carbon emission, and high energy density makes PEM fuel cells suitable for a plethora of applications. In the last few years, research interest in PEM fuel cell technology is considered to be most suitable for the transportation sector and portable energy frameworks.

Through this study it is realised that by using polymer composite bipolar plates we can manufacture PEMFCs with lower cost, weight and size while maintaining appreciably high levels of electrical conductivity and mechanical strength. Out of the composite samples prepared with 44 vol% NFG, 40 vol% ER, 8 vol% CB and 8 vol% Cu fibre, the composite prepared with Cu fibre length of 3mm exhibited the most desirable properties comparatively. The sample showed flexural strength of 43.6 MPa, electrical conductivity of 172 S/cm, shore D hardness of 66.5, bulk density of 2.44 $g/cm^3$ and water contact angle of $110.1^0$ which makes it hydrophobic in nature. This composite was capable of meeting the proposed level of electrical conductivity and flexural strength as per US DoE standards for bipolar plates. Also, copper was much more preferable fibrous filler, compared to other fibers like carbon fibre and MWCNT, as it is much more economical it allows the production process to be commercialized. Further improved result could be achieved in future studies by developing corrosion resistant metal based PCCBP or by use specially made resins such as conductive resins.

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