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Secondary Filler Behavior on the Chopped Carbon Fiber (CCF) Reinforced Epoxy Composite Bipolar Plate for Proton Exchange Membrane Fuel Cell (PEMFC)

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ABSTRACT

Bipolar plates constitute a critical component of fuel cells, accounting for a substantial portion of the stack's volume and significantly influencing overall system efficiency. This study investigates the fabrication of bipolar plate using epoxy/graphite (EP/G) composites reinforced with chopped carbon fiber (CCF) through a one-step compression molding technique. By comparing electrical conductivity and structural compactness using high-aspect-ratio graphite materials expanded graphite (EG) and carbon black (CB) the results reveal that EG provided superior conductivity and compactness due to its higher density, lower surface area, and minimized void formation. The CCF-reinforced EP/G/EG composite achieved the highest conductivity of 11.2 S cm⁻¹ at 7.5 wt% EG, while CB-filled composites recorded 8.5 S cm⁻¹ at 2.5 wt% CB. The CCF-reinforced EP/G/EG composite exhibited a significantly lower corrosion rate compared to the CB-filled counterpart, a performance attributed to its superior compactness, which effectively minimizes water absorption through the bipolar plate. The optimized CCF-reinforced EP/G/EG composite demonstrates excellent potential for energy conversion in fuel cell applications, contributing directly to Sustainable Development Goal (SDG) 7: Affordable and Clean Energy through improved material efficiency and system performance. Moreover, by promoting the use of sustainable materials and scalable fabrication techniques, this work also supports SDG 13: Climate Action, paving the way for greener, more efficient energy technologies that reduce reliance on fossil fuels and minimize carbon footprints.

Keywords: Composite bipolar plate; electrical conductivity; fuel cell; lightweight bipolar plate; proton exchange membrane fuel cell (PEMFC)

INTRODUCTION

Fuel cells, a burgeoning renewable energy technology, offer a promising solution to mitigate environmental pollution and address the escalating energy crisis. For transportation field, proton exchange membrane fuel cells (PEMFC) have gained prominence owing to their superior efficiency and zero-emission operation (Z. Hu et al. 2018). PEMFC, a frontrunner among alternative power sources, has attracted considerable attention for their potential in the automotive sector. Their exceptional efficiency, power density, rapid startup, low operating temperatures, and zero-emission operation make them a compelling choice (Gao et al. 2021). For transportation applications, PEMFC have emerged as the preferred fuel cell technology due to their superior efficiency and zero-emission profile. The fuel cell hybrid city bus (Samsun et al. 2016), renowned for its extended range, minimal environmental impact, and durability, has garnered significant attention from governments and research institutions worldwide, with numerous operational demonstrations validating its feasibility (Pany et al. 2016). While city buses powered by

PEMFC meet commercial demands (Bartolozzi et al. 2013), the longevity of their fuel cell stacks remains a critical challenge (Pei & Chen 2014).

Despite their promising potential, the widespread commercialization of PEMFC remains hindered by factors such as higher costs, lower performance, and limited durability, and weight and space limitation in application (Shen et al. 2020). A critical component that significantly influences these aspects is the bipolar plate component. Bipolar plates fabricated from graphite, metal, or carbon polymer composites constitute a significant component of fuel cell stacks, accounting for 60% to 80% of the total weight and 30% to 40% of the overall stack cost (Kim et al. 2015). The constraints of limited space and weight, as illustrated in Figure 1, have drawn significant attention from researchers, driving efforts to enhance the bipolar plate component to meet these demands without compromising its high performance.

Bipolar plate serves critical functions within fuel cell stacks, including interconnecting adjacent cells, distributing fuel gas, facilitating heat and water removal, and ensuring mechanical support for the membrane electrode assembly (MEA) while sustaining the required clamping pressure (Arvay et al. 2013). While all these three types of bipolar plate continue to be explored, recent publications indicate a growing attention on metallic and composite-based options for fuel cell applications. Each type presents unique advantages and limitations, prompting researchers to dedicate extensive efforts over the years to develop innovative materials and solutions to overcome the challenges associated with bipolar plate.

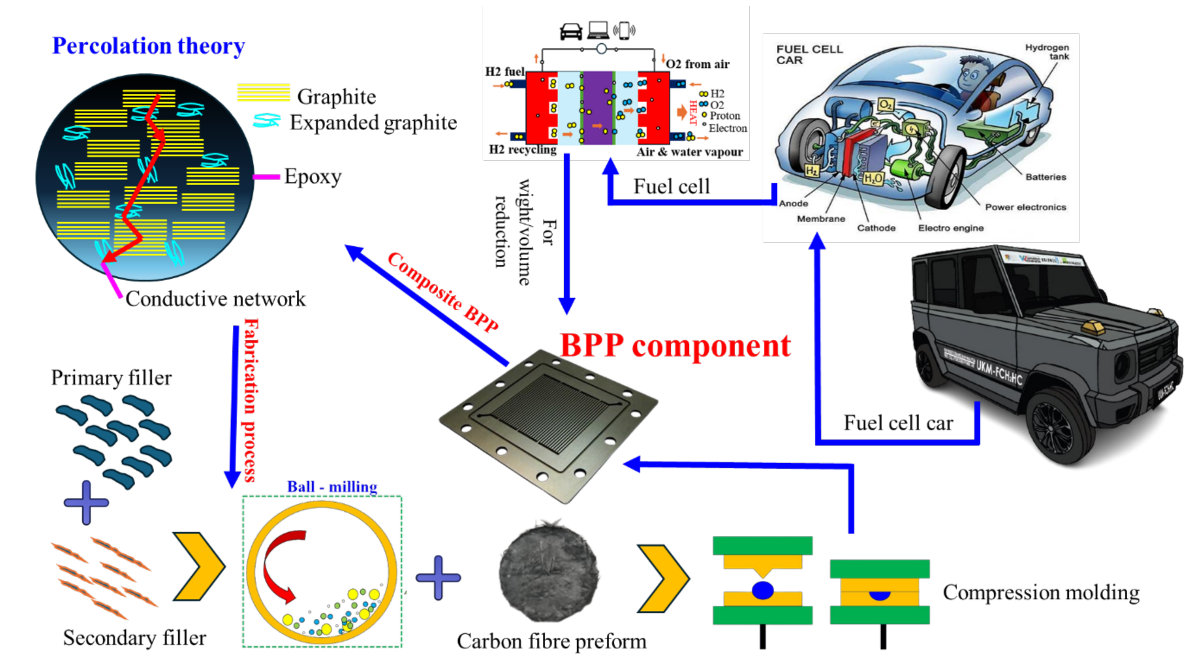

FIGURE 1. Lightweight composite bipolar plate development for PEMFC system that integrated in limited space of transportation application

Graphite, once the predominant for bipolar plate technology, has faced challenges due to its substantial weight, brittleness, and costly machining process, leading to a shift towards composite and metal-based alternatives. Although graphite offers unique benefits including low contact resistance, exceptional corrosion resistance, and high electrical conductivity, its inherent particle properties result in limited mechanical properties and a highly porous structure cause in increasing hydrogen permeability. Moreover, the fabrication of flow channels in graphite bipolar plate is a complex process, time-consuming, and hinders mass production due to the reliance on computer numerical control machinery (Cunningham & Baird 2007). Metal bipolar plate offers potential advantages owing to their excellent electrical and thermal conductivity, along with superior mechanical strength. However, their corrosion issue and degradation in the harsh operating environment of fuel cells, characterized by a pH of 2-4 and humid conditions at 80°C, presents significant challenges (Alaswad et al. 2016). The primary limitations of metal bipolar plate include their susceptibility to corrosion, hydrophilic nature, and high interfacial contact resistance (ICR). These factors can lead to reduced power output performance, decreased cell efficiency, and potential damage to the MEA and the expensive platinum catalyst. The formation of a corrosion layer can progressively elevate the overall electrical resistance of the cell, thereby diminishing the theoretical performance advantages of metal BPP over time. Composite bipolar plate offers a potential solution to the challenges demonstrating advantages such as enhanced mechanical strength, reduced contact resistance, elimination of complex and high-cost machining processes, and superior corrosion resistance.

However, their non-conductive matrix can limit electrical conductivity. Increasing the filler content to enhance conductivity may inadvertently compromise mechanical strength due to the brittle nature of fillers (Boyacı San & Okur 2017). Graphite is commonly employed as the primary conductive filler in polymer composite bipolar plate due to its conductive properties and cost-effectiveness. To further enhance conductivity, researchers often incorporate minor amounts of secondary conductive fillers, such as carbon black (CB), to bridge the gaps between the primary graphite particles, creating additional conductive pathways (Alo et al. 2021; Bairan et al. 2016; B. Hu et al. 2022; Rigail-Cedeño et al. 2020; H Suherman et al. 2014; Zaccone et al. 2021). Recent studies have investigated the utilization of CB as a secondary filler to enhance the electrical conductivity of composite bipolar plate. Hu et al. (2022) successfully achieved an in-plane conductivity of 177.87 S cm^{-1} using a low filler loading of 6 wt% CB and 34 wt% graphite combined with polyvinylidene fluoride (PVDF). Similarly, Andre et al. (2020) employed EG as the primary filler and incorporated 1 wt% CB to achieve an in-plane conductivity of 50 S cm^{-1}. While EG is commonly used as a primary filler in composite bipolar plate, a comprehensive evaluation of its effects as a secondary filler remains unexplored. From a fundamental materials science perspective, the dispersion behavior and interfacial interaction between polymer matrix and conductive fillers play a decisive role in determining the final performance of composite bipolar plates. Beyond geometric factors such as particle size and aspect ratio, the thermodynamic compatibility between the polymer matrix and fillers governs phase morphology and filler distribution. This compatibility can be described using the Flory–Huggins interaction parameter (χ), which quantifies the energetic favorability of mixing between two components. A lower χ value indicates stronger intermolecular affinity and improved interfacial adhesion, leading to uniform filler dispersion and the formation of an effective conductive network. Conversely, a higher χ value suggests poor thermodynamic interaction, potentially resulting in filler agglomeration, heterogeneous morphology, and increased porosity. In polymer–carbon systems, interfacial interactions may arise from van der Waals forces and π–π interactions between the aromatic structures of polymer and graphitic materials. However, differences in surface structure, specific surface area, and defect density between the conductive fillers can influence their effective interaction with polymer, thereby affecting dispersion quality, thermal stability, and electrical transport properties. Previous polymer thermodynamic studies have demonstrated that filler–matrix compatibility significantly influences composite morphology and transport behavior (Rana et al. 1993, 1996a, 1996b, 2000). Therefore, understanding the thermodynamic interaction between EP and different secondary conductive fillers provides an important theoretical basis for rational composite design. The main objective of this study is to investigate the impact of different secondary fillers of CB and EG on the electrical conductivity of composite bipolar plates. A further issue for composite bipolar plate is preserving mechanical strength while attaining enhanced electrical conductivity. Thick composite bipolar plates are typically employed to address this issue; however, this approach imposes constraints on weight and space in applications.

TABLE 1. Comparative study for composite bipolar plate

Ref.	Matrix	Primary fillers	Secondary fillers	Others	Fabrication process	Results
(Kang et al. 2016)	EP	G		Graphite prepregs	Graphite slurry coated on the prepreg drying wet mixing of EP & G dry stacked together and undergo compression moulding process	0.6 mm of thickness bipolar plate with superior conductivity.
(Maheshwari et al. 2007)	Phenolic resin	G	CB	CCF	Wet mixing of the fillers CCF preform hand-layup of the filler slurry to the preform compression moulding	CB as one of the reinforcements to improve the electrical conductivity for 2.4 mm of bipolar plate.

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(Onyu & Yeetsorn 2022)	TPV	G		Pyrolytic graphite sheet CF sheet	Dry mix of TPV + G melt mixed compression moulding process stacked to CF sheet stacked to pyrolytic graphite sheet compression moulding process	The layered composite bipolar plate of 3 mm thickness has high electrical conductivity.
(Choi et al. 2021)	Phenolic resin	G	CB	CCF	Wet mixing of the fillers CCF preform hand-layup of the filler slurry to the preform compression moulding grinded	Great electrical conductivity, mechanical strength and gas permeability for thickness plate of 200 m.
This study	EP	G	EG CB	CCF	Dry mix of the fillers CCF preform sandwiched the CCF preform with fillers & compression moulding	The EG show a higher electrical conductivity compared to the CB bipolar plate.

Extensive literature highlights the significant role of carbon fibers in enhancing the mechanical strength of composite bipolar plates. These fibers are typically utilized in two forms—chopped and sheet. Both configurations, particularly chopped carbon fibers (CCF), demonstrate substantial potential in reinforcing the mechanical integrity of bipolar plate. Kakati et al. (2010) investigated the influence of carbon fiber content on the flexural strength and electrical conductivity of composite bipolar plate. Their findings revealed a moderate improvement in both properties with the addition of carbon fibers; however, electrical conductivity sharply declined when the fiber content exceeded 5%. In a related study, Maheshwari et al. (2007), developed composite bipolar plate by incorporating CCF into a carbon filler–polymer matrix. Their results demonstrated a remarkable increase in flexural strength—from 34 MPa to 82 MPa—as the carbon fiber volume fraction rose from 2.5% to 7.5%. This enhancement was attributed to the strong interfacial bonding between the carbon fibers and the polymer matrix. However, the in-plane conductivity of electrical performance declined as CCF content increased.

Besides, various fabrication methods have been employed for CCF-based composite bipolar plate, including slurry moulding followed by compression moulding (Maheshwari et al. 2007), hand lay-up on carbon sheets (Budsaba Karoonsit 1 & Maiket 2022; Kuan et al. 2021) and multi-step compression moulding processes (Onyu & Yeetsorn 2022). Despite their effectiveness, these techniques are often time-consuming and costly as presented in Table 1. These conventional approaches typically require multiple intermediate steps such as slurry preparation, wet impregnation, drying, prepreg handling, stacking of several layers, and post-grinding. Such sequential processing increases fabrication time, labor intensity, material handling complexity, and energy consumption, thereby contributing to higher production costs and limiting scalability for mass production. In contrast, the present study introduces a simplified one-step compression moulding process. In this approach, CCF is first prepared as a dry preform, which is then directly sandwiched with a homogeneous mixture of EP/G and the selected secondary conductive filler (CB or EG), followed by a single compression moulding cycle. Unlike previously reported methods, no slurry coating, intermediate drying, prepreg preparation, or multi-stage stacking procedures are required. By eliminating these additional processing stages, the proposed method reduces fabrication time, minimizes material waste and energy usage, and lowers overall manufacturing cost while maintaining structural integrity and electrical performance. This streamlined process offers improved practicality and industrial feasibility for large-scale composite bipolar plate production.

METHODOLOGY

BASE MATERIALS AND FABRICATION OF BIPOLAR PLATE

Epoxy (ASASIN 3515 A/B) was of the bisphenol-A type and procured from Asachem (M) Sdn. Bhd., Malaysia was chosen as the polymer matrix. Synthetic graphite (Timrex® KS5-75TT) from Imerys Graphite and Carbon Switzerland Ltd. was used as primary conductive fillers. The secondary conductive fillers of high-aspect-ratio expanded graphite (EG) C-ThermTM 002 supplied from Imerys Graphite and Carbon Switzerland Ltd while CB Vulcan XC-72R from Cabot Corporation, USA. The conductive fillers were mixed with ball milling process, and the mixture was added to the epoxy using the mechanical mixer (RM20-KIKA-WERK). Meanwhile, the chopped carbon fiber (CCF) immersed in the surfactant (Triton X-100) followed by the filtration process forming carbon fiber preform. The preform was sandwiched with the conductive fillers powder, then hot-pressed and cured at a certain pressure and temperature.

CHARACTERIZATION

The specific surface area, pore size distribution, and pore volume were characterized using a Micromeritics ASAP 2020 analyzer equipped with nitrogen adsorption-desorption capabilities. The Brunauer-Emmett-Teller (BET) and Barrett-Joyner-Halenda (BJH) methods were employed to analyze the obtained data. The morphological characteristics of the fabricated composite bipolar plate were examined using scanning electron microscopy (SEM) with a Gemini 500 instrument (Zeiss, Germany). Through-plane electrical conductivity was evaluated using a tester manufactured by ZBT (Duisburg, Germany) (Hendra Suherman et al. 2013). The porosity analysis for each sample was conducted following ASTM C20, whereas the water absorption data was determined by using D 570. The optimal composition of CB and EG as secondary fillers was selected for further corrosion resistance evaluation. Corrosion behavior was assessed using potentiodynamic polarization measurements conducted on a GAMRY electrochemical workstation. The experimental setup comprised a conventional three-electrode electrochemical cell with an electrolyte of 0.5 M H_2SO_4 solution conducted at 70 °C. The composite sample, with an effective surface area of 0.785 cm², functioned as the working electrode, while an Ag/AgCl electrode and a platinum sheet were used as the reference and counter electrodes, respectively. Prior to polarization testing, the sample was stabilized at open circuit potential (OCP) for one hour. Potentiodynamic polarization was then carried out over a potential range of –0.6 V to 1 V, at a scan rate of 1 mV s^{-1}.

RESULTS AND DISCUSSION

In this study, the primary conductive filler, graphite, was combined with secondary fillers, that are EG or CB, using a ball milling process. The interaction between graphite and the secondary fillers during mixing has significantly influenced the properties and performance of the resulting bipolar plate. This study aimed to assess the differential impact of employing distinct secondary fillers within a composite bipolar plate. The textural properties of the resultant composite bipolar plate, encompassing surface area, pore volume, and pore diameter, were meticulously characterized via nitrogen (N_2) adsorption-desorption isotherm analysis. Table 2 presents a comparative overview of the BET analysis of CB and EG incorporated with graphite by ball milling process. The results revealed that the utilization of CB as the secondary filler within the composite bipolar plate yielded a significantly higher specific surface area (8.6053 m² g^{-1}) compared to that observed with EG (5.9717 m² g^{-1}). The pore volume data of CB exhibiting a larger total pore volume than EG. Furthermore, the composite materials demonstrated discernible variations in their mean pore diameters, with CB displaying the most pronounced diameter at 41.5110 nm. The BET analysis unequivocally underscored the substantial influence exerted by the selection of the secondary filler on both the surface area and porosity characteristics of the resultant composite bipolar plate.

To further characterize the bipolar plate materials, their porosity and water absorption profile were determined using D570 standard. Figure 2 illustrates the porosity profiles of composite bipolar plate incorporating EG and CB as secondary fillers. A comparative analysis revealed that the porosity profile of composites incorporating EG as the secondary filler was significantly lower than that of composites utilizing CB. Figures 2(a) reveal a consistent decrease in porosity within the rise in EG loading from 2.5 wt% to 7.5 wt%. However, a notable increase in porosity is observed at the 10 wt% EG loading. This phenomenon can be ascribed to the formation of micro-voids within the composite at elevated filler concentrations, a consequence of reduced resin content. The reduced resin availability likely hinders effective wetting of the filler particles, thereby promoting the development of porosity within the composite matrix. In contrast, the incorporation of CB as the secondary filler resulted in a detrimental increase in porosity beyond a 2 wt% composition. This observation can be ascribed to the spherical morphology of CB particles, which inherently possess a low aspect ratio (Afiqah et al. 2016). Fillers with low aspect ratios exhibit a reduced efficiency for efficient electrical conduction (Antunes et al. 2011). The porosity of the bipolar plate plays a crucial role in determining its structural compactness and overall integrity.

Subsequently, the density profile exhibited a trend consistent with the porosity and water absorption data. The bipolar plate incorporating EG as the secondary filler demonstrated a significantly higher density compared to those containing CB, with an approximate 16% increase. It is crucial to acknowledge that attaining a compact and dense structure is paramount for ensuring optimal filler-filler contact and enhancing overall material performance (Taherian 2014). The observed low density in the CCF reinforced EP/G/CB composites indicates a less compact plate structure. This phenomenon is likely attributed to the presence of voids and a less cohesive matrix, consequently leading to increased susceptibility to surface penetration (Husin et al. 2015). This observation is supported by the micrograph images presented in Figure 3 that revealed a substantial reduction in void formation within the EG compared to those incorporating CB as the secondary filler.

TABLE 2. The specific surface area, pore volume, and average pore diameter of bipolar plate

Secondary fillers	Surface area (m^2 g^{-2})	Total pore volume (g cm^{-3})	Pore diameter (nm)
CB	8.6053	0.067805	41.5110
EG	5.9717	0.029979	20.5501

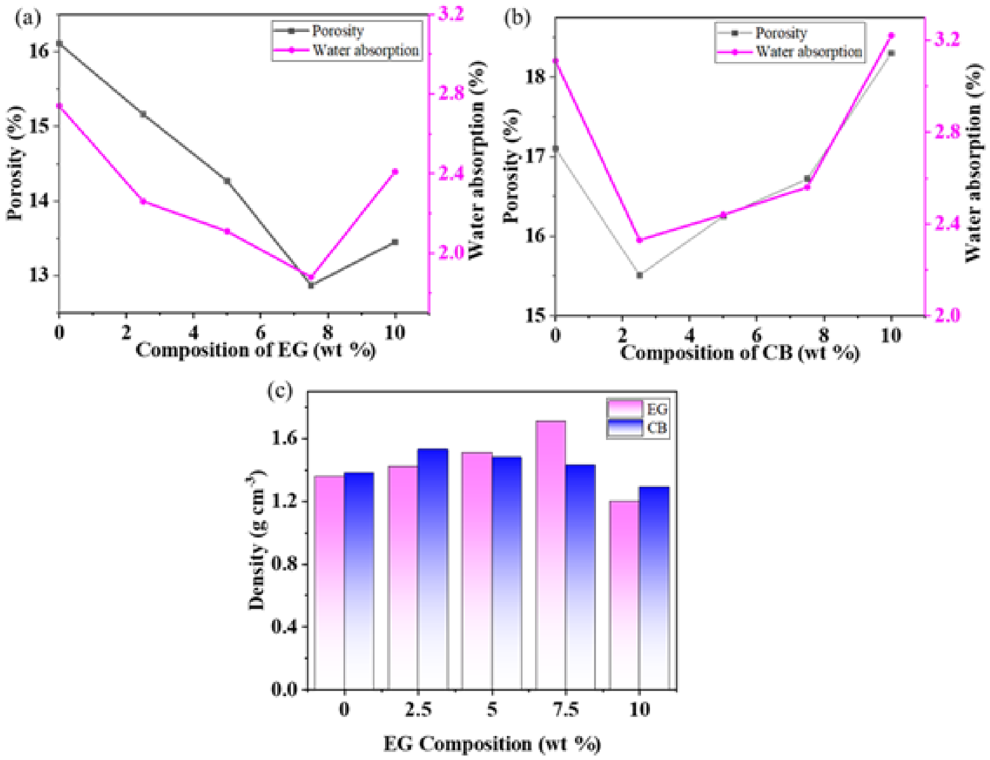

FIGURE 2. Variation in porosity and water absorption of CCF-reinforced EP/G composite with increasing (a) EG and (b) CB composition. (c) The density profile of the CCF-reinforced EP/G composite incorporated of EG and CB as secondary conductive filler

Figure 4 illustrated the through-plane conductivity of the composite bipolar plate. This study has demonstrated that EG-based composites exhibited the highest electrical conductivity (11.2 S cm^{-1}) compared to those incorporating CB, which recorded achieved 8.5 S cm^{-1}. This observation aligns with the established understanding that a compact and dense structure facilitates the electron movement by formation of an effective conductive network within the composite, thereby enhancing its overall electrical conductivity (Akhtar et al. 2018). The micrograph images presented in Figures 3a and b provide compelling evidence to support the observed lower electrical conductivity in CB-based composites. These images reveal a less compact structure characterized by the presence of voids within the CB-filled composites bipolar plate. In summary, the incorporation of CCF into the EP/G matrix, in conjunction with EG as the secondary filler, resulted in the most favorable performance. This superior performance can be attributed to the synergistic effect of low surface area leading to high compactness within the resulting composite, thus significantly enhanced electrical conductivity.

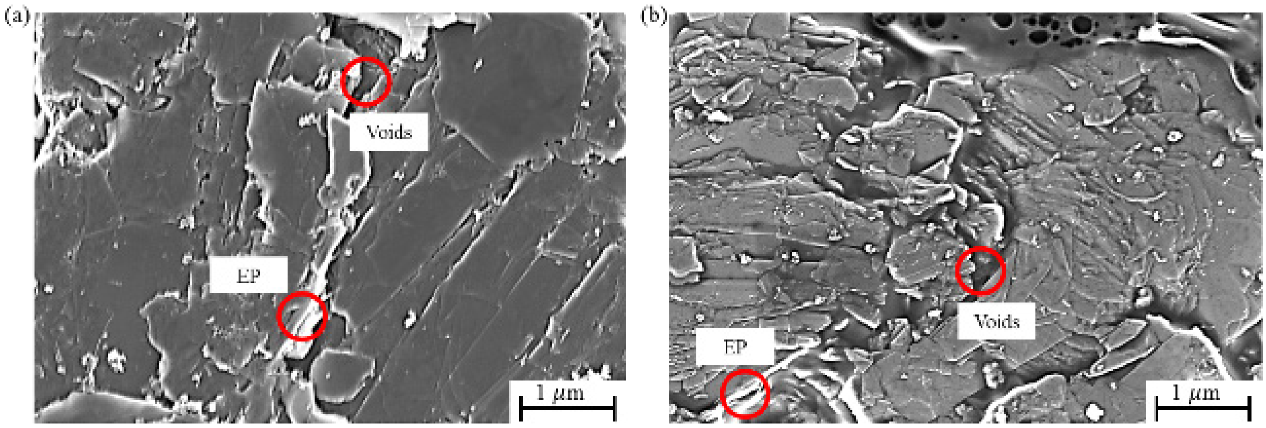

FIGURE 3. Micrograph image of the CCF-reinforced EP/G composite incorporated of (a) EG and (b) CB as secondary conductive filler

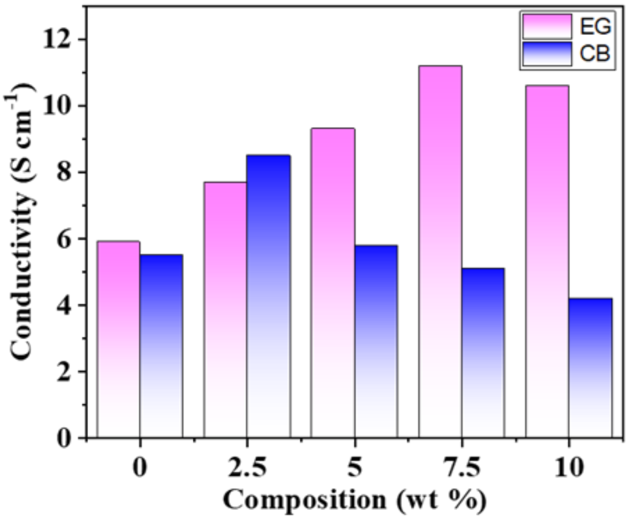

FIGURE 4. Through-plane conductivity of the CCF reinforce EP/G with the incorporation of EG and CB as secondary conductive fillers

In addition, corrosion behaviour is a critical factor in bipolar plate technology, as it directly impacts the long-term durability and reliability of PEMFC systems. To assess this, the optimal composite samples using CB and EG as secondary fillers were selected for corrosion analysis. Figure 5 presents the polarization curves of the composite bipolar plate at open circuit potential (OCP). The curve for the EG-filled composite exhibits a more positive shift compared to the CB-filled counterpart, indicating superior corrosion resistance. Specifically, the corrosion potential (E_{corr}) of the EG-based plate reached 0.48 V, significantly higher than the 0.35 V recorded for the CB-based plate. Furthermore, the corrosion current density (I_{corr})—a key indicator of corrosion rate—was substantially lower for EG at 1.80 μA cm^{-2} compared to 4.83 μA cm^{-2} for CB (Natarajan & Zahir Said Al Shibli 2021; Zhou et al. 2022). This disparity is attributed to the structural compactness of the composites: the CB-filled bipolar plate exhibits higher porosity, resulting in increased water absorption and, consequently, a higher corrosion rate. In contrast, the EG-filled bipolar plate forms a more compact structure that not only enhances corrosion resistance but also maintains higher electrical conductivity.

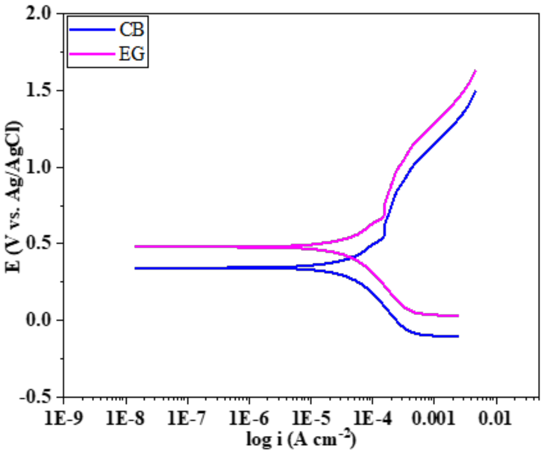

FIGURE 5. Polarization curve of the EG and CB as the secondary fillers in the composite bipolar plate.

The superior performance of EG compared to CB in CCF-reinforced EP/G composite bipolar plates can be explained by considering thermodynamic interaction, microstructure, and conductive network formation. According to Flory–Huggins theory, polymer–filler compatibility influences dispersion behavior. Although CB may exhibit relatively good interaction with the epoxy matrix due to its surface functional groups, interfacial affinity alone does not determine overall performance. Experimental results show that EG-filled plates possess lower porosity and higher density than CB-based plates, indicating a more compact structure. SEM observations further confirm that EG composites exhibit fewer surface voids and a more uniform morphology, whereas CB-filled plates display noticeable voids and irregular dispersion. The planar structure of EG promotes better packing during compression molding, reducing void formation and enhancing structural compactness. The denser microstructure of EG plates directly contributes to improved electrical conductivity. The overlapping platelet morphology facilitates continuous conductive pathways and enhances particle–particle contact, thereby reducing electrical resistance. In contrast, the higher porosity and discontinuous distribution of CB limit effective network formation. Although CB contains surface functional groups that may promote interfacial adhesion with epoxy, its high surface energy and tendency to agglomerate can limit effective dispersion and packing. In contrast, the planar morphology of EG facilitates improved structural compactness and conductive network formation.

These findings underscore the promise of EG as a secondary filler in developing high-performance, corrosion-resistant bipolar plate, advancing the commercialization of PEMFC as a clean energy solution. Such innovations align with and contribute to the realization of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) under the United Nations Sustainable Development Goals.

CONCLUSION

This study investigates the fabrication of CCF-reinforced EP/G composite bipolar plate through a streamlined one-step compression moulding process, aiming to optimize fabrication time and enhance the overall performance of PEMFC. The influence of two distinct secondary conductive fillers, EG and CB, on the electrical conductivity of the resulting bipolar plate was systematically evaluated. The experimental findings demonstrated that EG-incorporated bipolar plate exhibited significantly higher electrical conductivity (11.2 S cm^{-1}) compared to their CB-incorporated bipolar plate (8.5 S cm^{-1}). This observed disparity can be attributed to the enhanced compactness of the composites. The selection of the secondary filler exerts a profound influence on the overall performance of the bipolar plate, as it directly impacts their electrical conductivity. Materials characterized by high electrical conductivity and low interfacial resistance are crucial for minimizing ohmic losses and consequently improving the overall efficiency of the PEMFC. This study revealed distinct compositional-dependent behaviours for the two secondary fillers. The incorporation of increasing amounts of EG resulted in a progressive enhancement of electrical conductivity. This can be related to the effective filling of voids and a concomitant reduction in porosity, leading to a more compact and denser bipolar plate structure. Conversely, CB-based composites exhibited a contrasting trend, with increasing CB loadings leading to a decline in electrical conductivity and a concomitant increase in porosity. This behaviour can be ascribed to the spherical morphology of CB particles, which possess a low aspect ratio, thereby hindering the efficient percolation of electrical current within the composite matrix. Additionally, the rate of corrosion of the EG-filled composite bipolar plate is lower compared to CB-filled. In conclusion, the selection and compatibility of secondary conductive fillers play a crucial role in determining the electrical conductivity of the fabricated bipolar plate. The findings indicate that a compact and dense BPP structure, marked by reduced porosity, effectively promotes efficient electron transport, thereby improving the overall electrical conductivity of the composite material. While the present work provides valuable insights into the compositional-dependent behavior of secondary fillers at the material level, future studies should focus on validating these findings under practical operating conditions. Specifically, the fabricated bipolar plates should be evaluated in a single-cell or full PEMFC stack configuration to assess their long-term durability, interfacial contact resistance under compression, and overall system-level performance. Such investigations will provide a more comprehensive understanding of their practical applicability and commercialization potential. The future studies should focus on validating these findings under practical operating conditions. Specifically, the fabricated bipolar plates should be evaluated in a single-cell or full PEMFC stack configuration to assess their long-term durability, interfacial contact resistance under compression, and overall system-level performance. Such investigations will provide a more comprehensive understanding of their practical applicability and commercialization potential. This advancement in bipolar plate technology holds the potential to accelerate the commercialization of PEMFCs, serving as a catalyst for global sustainability efforts, especially in driving progress toward SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) under the United Nations Sustainable Development Goals.

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DECLARATION OF COMPETING INTEREST

None.

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