

Research Paper

Activated Carbon as a Functional and Sustainable Filler in Composite Bipolar Plates For Fuel Cell Applications

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🔗 <https://doi.org/10.31603/ae.16009>

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang

Article Info

Submitted:

18/01/2026

Revised:

12/04/2026

Accepted:

14/05/2026

Online first:

14/05/2026

Abstract

Bipolar plate is a key component that determines a fuel cell's performance and service life. Carbon-based polymer composite materials were developed as lightweight, easy-to-process alternatives to metal. The use of carbon-based fillers in polymer composites has grown rapidly as an alternative to bipolar plate materials in fuel cell applications, especially to meet performance targets set by the U.S. Department of Energy (DOE). DOE requires high electrical conductivity (≥ 100 S/cm in the in-plane direction and ≥ 10 S/cm in the through-plane direction), low density, adequate mechanical strength, and good corrosion resistance and chemical stability. Recent studies have shown that the addition of carbon fillers, such as graphite, carbon black, graphene, and activated carbon (AC), can increase electrical conductivity by forming conductive percolation networks in polymer matrices. This study evaluates the potential of AC from household waste in the form of coconut shells as fillers in polypropylene (PP) composites for bipolar plate applications. AC is synthesized through carbonization and activation processes, then mixed into a PP matrix with PP/AC compositions of 100/0, 90/10, 80/20, and 70/30 percent by weight. The focus of the study is the effect of composition variation on density and bending strength. The test results show that increasing the AC fraction tends to decrease the composite density. The maximum density was obtained at a 90/10 (by weight) PP/AC composition of 0.9 g/cm³, indicating more effective filling of the pore matrix by AC particles. On the other hand, bending strength shows a downward trend. The maximum flexural strength is achieved at an AC composition of 34.58 MPa at 10% weight, indicating optimal dispersion and stress transfer between the matrix and the filler. The addition of AC above the composition causes a decrease in bending strength due to potential particle agglomeration, cavities, and the limited mobility of polymer chains. Electrical conductivity tends to increase with the addition of AC due to the formation of a network of electrical currents between carbon particles within cavities, reaching a maximum of 5 S/cm at 30% by weight of AC. The electrical conductivity obtained showed better improvement than several research results on polymeric materials using the hot-press method, with a value of 1.7 S/cm, using graphite filler materials up to 60% by weight. These findings confirm that AC from coconut shells has the potential to serve as a sustainable filler for fuel cell bipolar plates, with an optimal composition that balances density and mechanical properties.

Keywords: Polypropylene; Activated carbon; Density; Flexural strength; Electrical conductivity

1. Introduction

Coconut shell waste is considered a valuable feedstock for activated carbon (AC) synthesis, attributed to its high fixed-carbon content and inherent structural hardness [1]. AC from coconut shells is typically produced by pyrolysing coconut shells at 500–800 °C, followed by physical or chemical activation, yielding a large surface area and micropores [2]. Various studies report that coconut shell-activated carbon has high adsorption capacity for water treatment, heavy metal adsorption, and the purification of industrial liquid waste [3]. Recent developments have also utilised coconut-shell AC as a supercapacitor electrode material, battery anode material, and greenhouse gas adsorbents, thereby adding economic value to this waste stream for the future sustainable energy sector in various developing countries [4], [5].

Carbon-filled composite polymers are widely developed as PEM fuel cell bipolar plate materials because they combine corrosion resistance, low-density, and good processability [6]. Various carbon-based fillers, such as graphite, carbon black, graphene nanoplatelets, nanotubes, and AC, are used to form conductive networks within thermoplastic polymer matrices or thermosets [7], [8]. Alejandro Gomez *et al.* [7] summarise the latest trends in polymer-carbon composites for bipolar plates, including their mechanical and electrical performance. Tariq *et al.* [9] optimised PP composites containing graphite and carbon black so that conductivity was achieved without sacrificing significant flexural strength. Cost

studies show graphite-based composite bipolar plates are more economical than coated metal designs in mass production [10].

Activated carbon-filled composite polymers are emerging as promising candidates for bipolar plate PEM fuel cells because they are lightweight, corrosion-resistant, and low-cost [7]. Various studies confirm that polymer-carbon composites can meet DOE's technical targets for flexural strength and conductivity when formulations and filler fractions are optimised [7]. Polymer/AC composites fabricated using the hot-press method is capable of meeting the flexural strength requirements for bipolar plate applications. This indicates that the combination of materials and processes provides a robust structure, thereby supporting its mechanical integrity and potential applications in fuel cell systems [11]. Furthermore, the use of activated carbon-filled epoxy showed an increase in flexural strength compared to pure epoxy [12]. A study of UHMWPE/AC composites confirms the porosity and thermal stability advantages of AC for energy and fuel cell applications [13]. The use of AC as an alternative to other carbon-based fillers, such as graphite, carbon black, and carbon nanotubes, is illustrated in Figure 1.

The United States Department of Energy (US DOE) has set a bending strength target of at least 25 MPa for polymer electrolyte membrane fuel cell bipolar plates to ensure mechanical reliability in transportation and automotive applications. This target serves as a reference for the design of efficient next-generation polymer-carbon composites [14]. The relationship between density

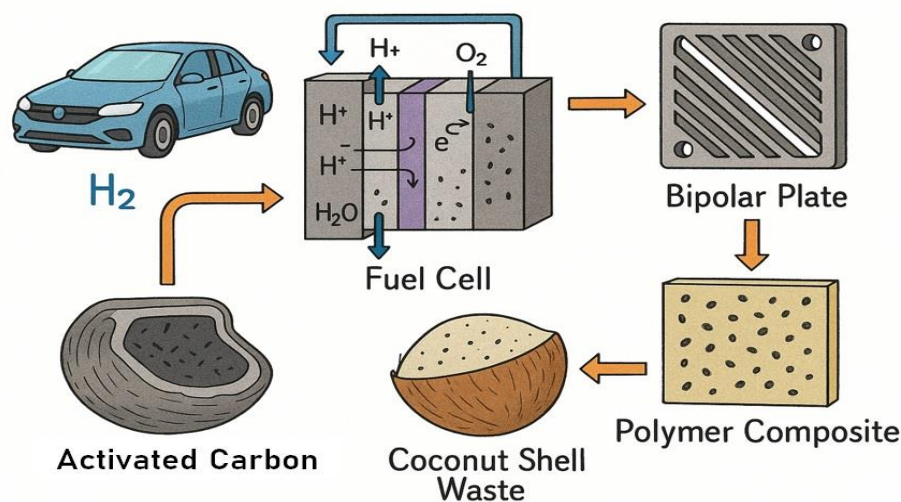


Figure 1. Activated carbon filler scheme as an alternative to bipolar plate filler material

and bending strength in bipolar plate composite polymers is greatly influenced by the level and type of carbon filler. Density generally increases when graphite or other carbon fractions are raised, while porosity decreases and stiffness increases, but the risk of brittleness also increases [15]. Various studies have shown that density is not always directly proportional to the flexural strength of conductive composites for bipolar plates. Materials with lower density can still have adequate bending strength through the design of layered structures, and the increase in strength is also greatly influenced by the optimization of microstructures and filler types. This confirms that the distribution of fillers, matrix–filler interactions, and the formation of internal networks are more decisive than simply increasing material density [16]. Recent research shows that AC-filled PP composites can increase electrical conductivity via a percolation mechanism, but require a high filler fraction due to irregular particle morphology and low aspect ratios [17]. Carbon black is reported to be more effective in forming a continuous conductive network at intermediate filler fractions due to its high specific surface area and more homogeneous dispersion in the PP matrix [18]. Graphite exhibits a gradual increase in conductivity; however, limitations related to particle orientation and interlayer contact restrict further conductivity enhancement [19], [20]. Carbon nanotubes provide the greatest conductivity enhancement at low fractions, owing to their high aspect ratio and three-dimensional percolation network [21]. Electrical conductivity is a critical requirement for bipolar plate materials in high-performance fuel cells. Conductive polymer composites filled with carbon materials offer advantages such as low density, corrosion resistance, and manufacturing flexibility, provided that their conductivity satisfies DOE targets of ≥ 100 S/cm in-plane and ≥ 10 S/cm through-plane [22].

This study introduces a comprehensive approach by integrating thermal analysis (TGA), density, bending strength, porosity, and AC particle distribution to evaluate the structure–property relationships of bipolar plate composites. This approach reveals the relationship between microstructures and properties in bipolar plate composite polymers, particularly the formation of conductive networks

that improve electrical conductivity, as supported by recent research on sustainable composite materials for fuel cell applications. Although various studies have reported improvements in mechanical, thermal, and electrical properties in carbon-based composites, most studies still examine these parameters separately, without comprehensively integrating their relationships. In addition, the role of AC as a filler in composites is expected to form an effective conductive network, and its relationship to porosity and thermal stability has not been systematically explored. This gap limits the understanding of the structural mechanisms governing composite performance. This study overcomes this by combining analyses of TGA, density, bending strength, porosity, and particle distribution into a unified framework, thereby enabling a clearer explanation of how microstructures affect electrical conductivity and composite performance in fuel cell bipolar plate applications.

2. Experimental Methods

The study began with the preparation of materials consisting of a PP matrix and AC filler. Impact-grade copolymer Titan PM 655 was used as the PP matrix material for the hot-press molding process. The material has a melting point of 160–170 °C, a density of 0.9 g/cm³, and a flow rate (MFI) of 1.7 (g/10 min) and was supplied in granular form as shown in Figure 3. The maximum processing temperature is 230 °C. The PP material was purchased from Polypropylene Malaysia Sdn. Bhd.

Borneo-brand AC is a composite filler produced from coconut shell charcoal via a controlled activation process. Coconut shells were chosen as the raw material because they have a hard carbon structure and a high carbon yield. The AC produced exhibits a high fixed carbon content of 85% to 95%, reflecting the material's good purity and stability. Borneo AC has a well-developed pore structure, with a specific surface area of 300–2000 m²/g. This large surface area indicates high adsorption ability. The high iodine number, which can exceed 1000 mg/g, confirms the dominance of the micropore structure, which is effective for the adsorption of small molecules and dissolved ions. The powdered AC is 325 mesh, with a water content of about 5–15%, an ash

content of 2-3%, and the with the remaining carbon present in layered amorphous structures.

Furthermore, Thermogravimetric Analysis (TGA) is widely used to determine the upper limit of process temperature during the manufacture of PP-based conductive polymer composites and carbon fillers, especially in the hot-press method [17]. TGA provides important information on the thermal stability of materials by evaluating mass changes during a controlled temperature rise, thereby enabling the identification of the degradation onset temperature of the polymer matrix [23]. Another study reported that TGA data are crucial in determining the safe temperature range of the manufacturing process to prevent degradation of PP polymer chains during thermal processing [24]. The interaction between the PP matrix and the AC filler has been shown to affect the thermal degradation mechanism and the final residue of the material. Therefore, TGA analysis is considered a fundamental step in designing safe, optimal hot-press parameters for carbon-based polymer composite systems.

The composite preparation process was carried out by varying the composition of PP and AC at 100/0, 90/10, 80/20, and 70/30 wt.%, with five specimens prepared for each composition. Melt mixing was performed using an internal mixer equipped with a roller-blade system at a temperature of 200 °C, rotation speed of 50 rpm,

and mixing time of 30 min. During the process, PP was first melted in a 100 g-capacity chamber, followed by the gradual addition of AC filler to ensure homogeneous dispersion. The blended material was then shredded into fine granules prior to specimen fabrication.

Composite specimens were fabricated using the hot-press compression molding method at a temperature of 220 °C, pressure of 49.8 kN, and holding time of 20 min. The molded plates had dimensions of 140 mm × 65 mm × 2.5 mm and were subsequently cut according to ASTM D790-03 standard dimensions (100 mm × 12.7 mm × 2.5 mm) for flexural testing. The overall research procedure is illustrated in Figure 2, while the composition details are presented in Table 1.

Density is a fundamental physical parameter in carbon-filled polymer composites because it influences the mass, thickness, structural rigidity, and indirectly the thermal and electrical performance of bipolar plates. Compared with conventional metal or graphite plates, polymer-carbon composite bipolar plates are generally lighter. However, their relatively lower mechani-

Table 1. Composition of PP/AC composite

Polypropylene (wt%)	Active carbon (wt%)
100	0
90	10
80	20
70	30

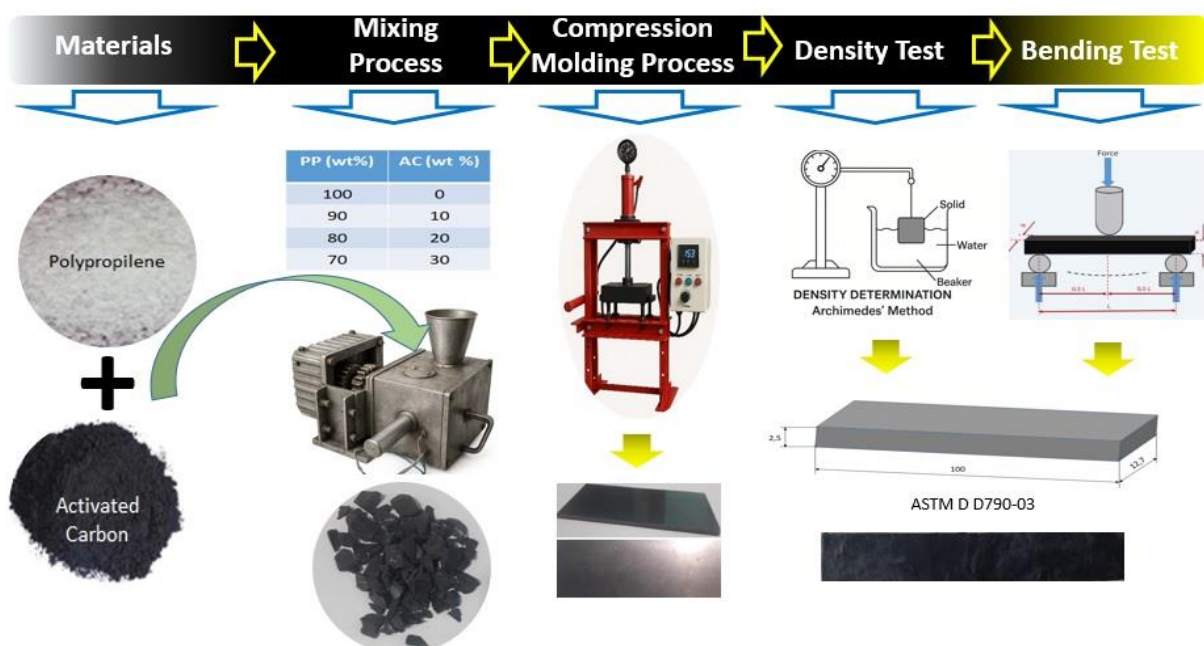


Figure 2. Schematic of the polymer composite research process

cal strength and electrical conductivity often require thicker plates or higher filler contents to achieve adequate structural and functional performance. This requirement can increase the effective density and overall stack volume. Therefore, optimizing the density of polymer-carbon composite bipolar plates is essential to achieving an appropriate balance between lightweight design, plate thickness, mechanical stability, and fuel cell stack performance [14]. In this study, density was measured according to the procedures established in ASTM standard D792 [25], [26]. Archimedes' principle states that an object immersed in a fluid experiences a buoyant force equal to the weight of the displaced fluid. Density measurements were performed by recording the specimen mass in air and its apparent mass in water at ambient temperature. The density is calculated by Eq. (1).

$$\rho m = \frac{ms}{(ms - mg)} \rho w \quad (1)$$

In Eq. (1), ρm represents the actual density of the specimen (g/cm^3), ms represents the mass of the dry sample (g), mg represents the pseudo-mass of the sample measured in water (g), and ρw represents the density of water, assumed to be 1 g/cm^3 [26].

Conductive polymer composite materials used as PEM fuel cell bipolar plates must exhibit a flexural strength greater than 25 MPa. Qualified flexural strength is required to support membrane electrode assembly (MEA) structures and withstand compressive loads in bipolar plate assemblies. ASTM standard D790-03 is used for bending testing [27]. Flexural testing was performed using the Universal Testing Machine (UTM) Model Instron 5567. The specimen

dimensions were $100 \text{ mm} \times 12.7 \text{ mm} \times 2.5 \text{ mm}$, following the three-point bending test standard ASTM D790-03. Then, Eq. (2) is used to calculate bending strength based on measurement data [28].

$$\sigma_{UF} = \frac{3P_{max}L}{2bh^2} \quad (2)$$

In Eq. (2), P_{max} represents the ultimate applied load (kN), b denotes the specimen width (mm), h is the specimen thickness (mm), and L corresponds to the span length between the two supporting points (mm). These parameters are used to determine the flexural strength under three-point bending conditions.

Electrical conductivity testing was performed on PP-based composite specimens reinforced with AC filler. Each specimen was fabricated in a rectangular shape with dimensions of $100 \text{ mm} \times 12.7 \text{ mm} \times 2.5 \text{ mm}$ as shown in Figure 3. Electrical conductivity measurements were carried out along the longitudinal direction of the specimen to obtain representative characteristics. A total of ten test points were evenly distributed in the predetermined test area, as marked in Figure 3. Measurements were carried out sequentially at each point using an electrical conductivity test device. The electrical conductivity of the specimen was determined as the average of 10 measurement points to minimise the influence of local material heterogeneity.

3. Results and Discussion

The TGA results are presented in Figure 4. The AC-filled PP composite exhibited a relatively stable mass reduction up to approximately 350°C , indicating minimal moisture and volatile content in the material. The main thermal degradation

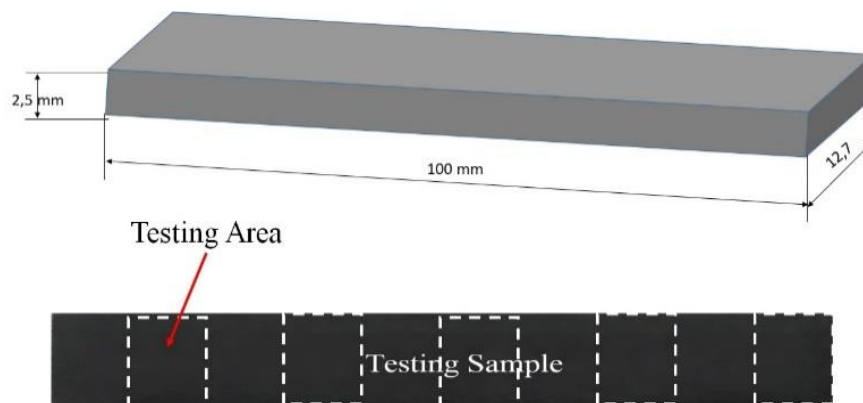


Figure 3. Schematic of the electrical conductivity test setup for PP/AC composites

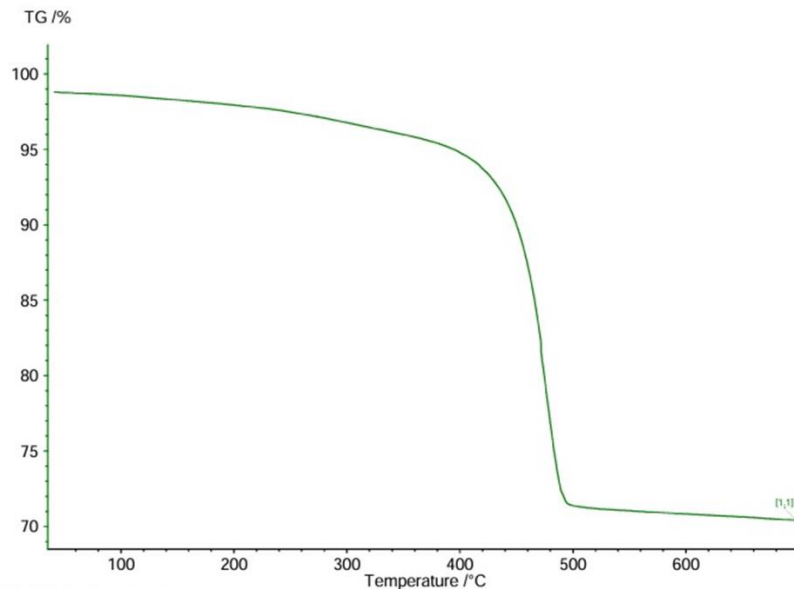


Figure 4. Thermogravimetric analysis test of PP/AC composites

occurred in the 400–500 °C range, characterized by a significant mass loss due to the decomposition of PP polymer chains. Beyond 500 °C, the residual mass remained relatively stable up to 700 °C, indicating the presence of thermally stable AC filler. These results confirm that the composite possesses adequate thermal stability for hot-press processing below its main degradation temperature.

The density test results are shown in Figure 5. The density of the PP/AC composites decreased with increasing AC fraction, from approximately 1.00 g/cm³ for pure PP to about 0.80 g/cm³ at 30 wt% AC. This behavior can be attributed to the highly porous structure and low intrinsic density of coconut shell-derived AC, which promotes microvoid formation within the composite matrix.

The decrease in density is also associated with imperfect interfacial packing between the PP matrix and AC particles. At higher filler loadings, particle agglomeration may occur, leading to the formation of gaps and residual voids that reduce the effective mass per unit volume of the composite. Yasdi et al. [3] reported that coconut shell-derived AC possesses a high surface area and porous structure, which are commonly associated with low bulk density. Similarly, Akram Alabadi et al. [29] observed that the activation process reduced AC density due to increased porosity. Uchechi C. Mark et al. [30] also demonstrated that carbon fillers derived from coconut shells significantly influence void

formation and composite porosity in PP-based materials.

At low to moderate filler contents, AC particles can still be relatively well dispersed within the matrix. However, excessive filler addition tends to increase particle agglomeration and interfacial defects, thereby reducing composite compactness and flexibility. Overall, these findings confirm that filler-induced porosity plays a dominant role in controlling the density evolution and structural characteristics of PP/AC composites.

This decreasing density trend is advantageous for lightweight bipolar plate applications, confirming that carbon-reinforced polymer composites provide low density, which is critical for efficient bipolar plate design [7]. Therefore, a density reduction of up to 20% is expected to improve the cell's power density. However, composition optimisation must balance low den-

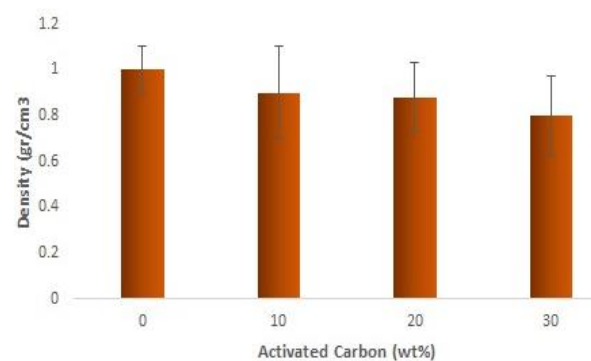


Figure 5. Density of PP/AC composites with different filler compositions

sity with mechanical integrity. This result is the basis for selecting the optimal AC fraction.

The results of the bending test in Figure 6 show that the bending strength of the composites decreases sharply with increasing mass fraction of AC. Samples without AC fillers exhibit a flexural strength of approximately 36 MPa. In contrast, a composition containing 10 wt% AC exhibits a marginally lower strength of approximately 34 MPa. Compositions containing 20 wt% and 30 wt% of AC exhibit a significant decline in bending strength, to approximately 12 MPa and 10 MPa, respectively. This trend indicates that exceeding a threshold of AC incorporation compromises the matrix's structural integrity. At lower concentrations, AC particles function as rigid fillers and local voltage dispersers. Adequate dispersion still allows PP to form a continuous path. AC can trigger PP crystal nucleation, thereby maintaining initial stiffness. However, AC is polar and porous, whereas PP is nonpolar. This mismatch reduces interfacial adhesion and weakens load transfer. As the filler fraction increases, the melt viscosity increases, and particle wetting decreases. These conditions promote agglomeration, forming a heterogeneous, filler-rich zone. This zone concentrates tension and accelerates the initiation of cracks on the tensile side. The porosity of AC, as well as trapped air during mixing, forms microscopic voids as shown in Figure 5. With the phenomenon of observation from fractured surfaces in various variations of PP/AC composition. The void and debonding interfaces act as notch-like defects, thereby reducing the fracture strain. At 20–30 wt%,

particle–particle contact increases, but the bond with the matrix remains weak as shown in Figure 7. The load becomes unevenly distributed, PP plastic deformation is reduced, and cracks propagate quickly. These results confirm that increasing filler content does not necessarily strengthen the composite. Optimization requires control of particle size, dispersion, and compatibility agents. Without it, AC serves more as a major initiator of damage. This phenomenon shows the same tendency as the results of other studies carried out by Kawalerczyk *et al.* reported that the addition of 0.75–1 wt% AC coconut shells in UF adhesives increases the bending strength and modulus of elasticity of the particle board, while 1.5 wt% again decreases its strength due to the tendency of agglomeration [31]. The use of AC as a filler influences mechanical properties, as reported in studies on coconut shell-reinforced PP composites, which showed that controlling filler and resin content has a strong effect on bending strength and other mechanical properties [32].

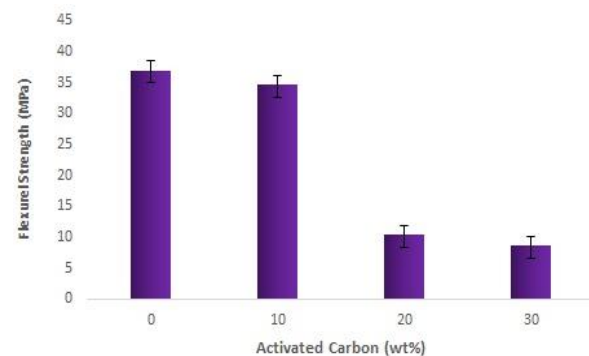


Figure 6. Flexural test results of PP/AC composites with varying composition

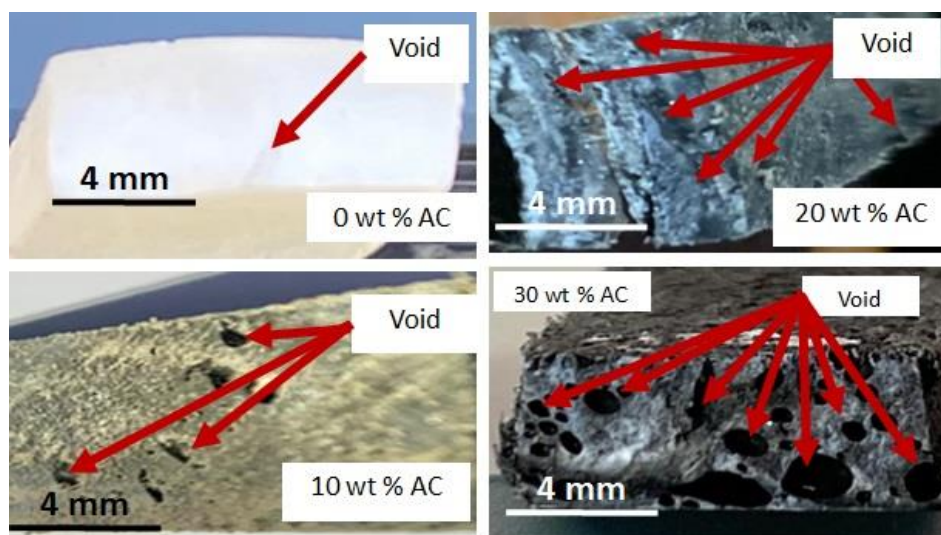


Figure 7. Phenomenon of PP/AC composite polymer cavity composition variation

Based on macro-observations in [Figure 7](#). A cross-section of the specimen shows that the cavity (void) phenomenon is influenced by the AC fraction. At a composition of 0 wt% AC, the PP structure appears relatively homogeneous. The cavities that appear are small and few in number. This condition indicates that the polymer matrix can flow and fill the mold well. At the addition of 10 wt% of AC, an increase in the number of voids begins to be seen. Cavities arise due to differences in flow properties between the matrix and the filler particles. The dispersion of AC that is not evenly distributed leads to the formation of microfissures. At a 20 wt% composition of AC, the void phenomenon is more pronounced and diffuse. Increasing the filler fraction increases the likelihood of particle contact. This condition inhibits the flow of PP during the fabrication process. The matrix is difficult to close the empty space around the AC agglomerate. As a result, larger, irregular cavities form.

At the highest composition, which is 30 wt% of AC, the number and size of the voids increase significantly. Particle agglomeration becomes dominant, reducing the matrix's impregnation ability. In addition, the viscosity of the mixture increases, allowing air to be easily trapped. This phenomenon suggests that an increase in the fraction of AC tends to increase cavity formation. The high void content has the potential to decrease mechanical performance and reduce the structural integrity of PP composites with AC fillers. The phenomenon of increased cavities (voids) in PP composites AC fillers directly affects density and bending strength. Increasing the fraction of AC increases the amount of internal free space. The presence of voids decreases the material's effective density as the air volume

increases. As a result, the composite density tends to decrease as the filler level increases. In addition, a void acts as a point of concentration of bending tension. The voltage is not evenly distributed within the matrix. This condition initiates early cracks. The increase in void content reduces the composite's bending strength.

Based on SEM observations in [Figure 8](#), the phase distribution in the PP/AC composite showed a clear morphological change as the filler fraction increased. At a composition of 10 wt% AC (a), the PP matrix still dominates the structure. AC particles are dispersed relatively separately and embedded within the matrix. The voids formed are small and few in number. This condition indicates that the flowability of PP is still sufficient to encapsulate the filler particles. The interface bond between PP and AC is still relatively effective in this composition. The phenomenon at a composition of 20 wt% AC (b) indicates that the particle distribution begins to show a tendency toward local agglomeration. AC appears denser and forms partial clusters. The PP matrix does not completely fill the gaps between the particles. As a result, the number and size of voids increased. Cavities are abundant around the boundary of the PP/AC interface. This phenomenon indicates a decrease in the quality of matrix impregnation with increasing filler fraction. At the highest composition 30 wt% AC (c), particle agglomeration becomes very dominant. AC forms large clumps that are difficult to disperse. The PP matrix appears fragmented and discontinuous. Large and irregular cavities are widespread. This condition reflects the high viscosity of the mixture and weak interfacial bonding, which can degrade the mechanical performance of composites.

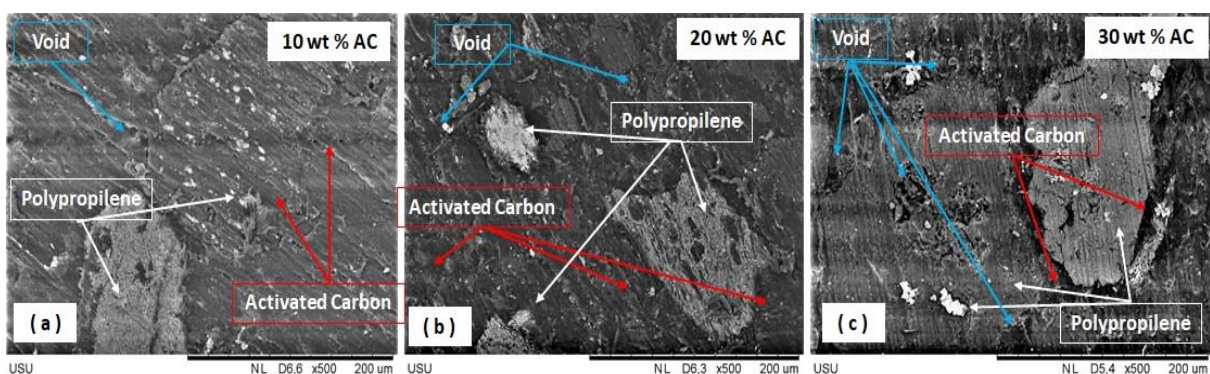


Figure 8. Morphological distribution of PP, AC, and cavity formation in PP/AC composites at different AC contents: (a) 10 wt%, (b) 20 wt%, and (c) 30 wt%

Results of the PP composite electrical conductivity test in **Figure 9**. Charged with AC at weight fraction variations of 10, 20, and 30 %wt, suggesting that increased AC content consistently increases the electrical conductivity value of composites. At a composition of 10 %wt, the conductivity remains relatively low, indicating that the AC particles have not yet formed a continuous conductive network. An increase in the filler fraction to 20 %wt results in a significant increase in conductivity, along with the increased interaction and connectivity between AC particles. At a composition of 30 %wt, the electrical conductivity reaches its maximum, indicating the formation of a more stable, continuous percolation path. These results confirm that the AC content plays an important role in forming a conductive network in the polymer matrix.

As the filler content increases, the distance between AC particles decreases, allowing particle contact and electron tunneling to occur more easily. When the filler concentration reaches a critical point known as the percolation threshold, an interconnected conductive network is formed throughout the material, resulting in a sharp increase in electrical conductivity. Beyond the percolation threshold, additional filler further strengthens and expands the conductive pathways, although the rate of conductivity improvement becomes more gradual. However, excessive filler loading may promote particle agglomeration, which can disrupt filler dispersion and reduce the uniformity of the conductive network. As shown in **Figure 8c**, the 30 wt% AC composite exhibited noticeable agglomeration of AC particles. Therefore, the percolation behavior is strongly influenced by factors such as particle size and morphology, filler distribution, matrix-filler interaction, and porosity. In AC-based composite systems, the porous structure of activated carbon may also facilitate the formation of conductive networks at relatively lower filler concentrations.

This behavior is further supported by the increasing distribution and connectivity of AC particles in the PP matrix as the AC weight fraction increases. The SEM-based schematic illustrations in **Figure 10** show the evolution of the conductive network at different filler contents: **Figure 10a** presents the distribution of AC particles

at 10 wt%, **Figure 10b** at 20 wt%, and **Figure 10c** at 30 wt% AC. The maximum electrical conductivity of 5 S/cm was achieved at 30 wt% AC, indicating the formation of an effective and stable conductive network throughout the composite. This result demonstrates better performance than several previously reported hot-pressed polymer composites, such as polyphenylene sulfide/graphite systems, which achieved only approximately 1.7 S/cm despite using graphite filler contents up to 60 wt% [33]. These findings confirm the effectiveness of coconut shell-derived AC as a promising alternative conductive filler for bipolar plate applications.

Figure 10a shows the distribution scheme of AC particles in PP composites with a weight fraction of 10 %wt. In this composition, the AC particles are distributed relatively separately and have not yet formed a continuous conductive network. The path of the electric current, indicated by the white arrow, shows that the relationships between particles remain local and segmented. This condition indicates that the distance between AC particles is still large enough that the formation of electrical conduction links is not optimal. As a result, the electrical conduction mechanism is dominated by limited contact and the possibility of tunneling between fillers. This finding explains the low electrical conductivity at 10 % wt, because the system has not yet reached the percolation threshold. Thus, an increase in the filler fraction is required to form a more stable and continuous conductive network in the polymer matrix.

Furthermore, based on the observations in **Figure 10b** show the distribution scheme of the network of AC particles in PP composites with a

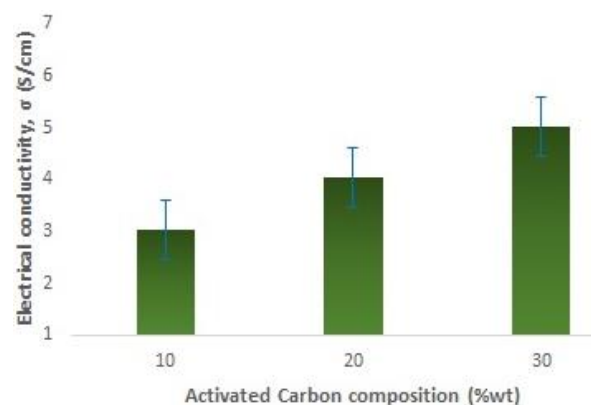


Figure 9. Results of electrical conductivity testing on variations in AC composition of 10% wt, 20% wt, and 20% wt

weight fraction of 20 %wt. In this composition, the AC particles exhibit a reduced distance between the fillers, resulting in a stronger connection between the particles. The path of the electric current, marked by the white arrow, shows the formation of a longer, continuous conductive path from the top to the bottom of the sample. This condition indicates that the system is approaching the percolation threshold, where the electrical conductivity line is no longer isolated. The increased interaction between fillers increases the likelihood of direct contact and tunneling, thereby

significantly improving the electrical conductivity of the composites. These results confirm that the AC fraction of 20 %wt plays an important role in the formation of the initial conductive network in the polymer matrix.

Observations in [Figure 10c](#) show a schematic distribution of the AC particle network in a PP composite with a weight fraction of 30 wt%. In this composition, the AC particles are distributed more densely, forming a dense, interconnected conductive network. An electrical current path is formed between the voids formed in the composite.

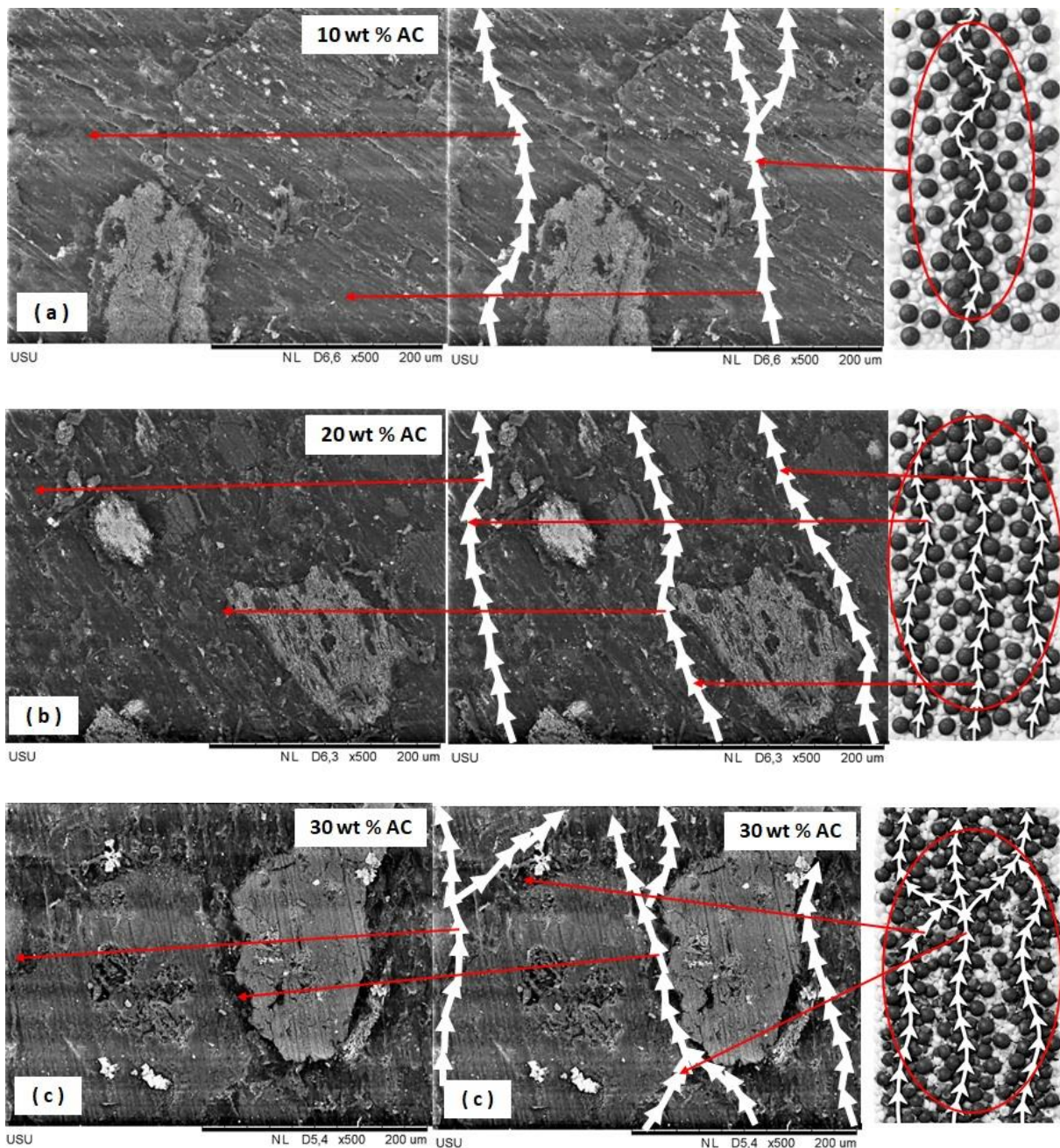


Figure 10. (a). Schematic representation of AC particle network formation in PP/AC composites at different AC loadings: (a) 10 wt%, (b) 20 wt%, and (c) 30 wt%

The electrical path indicated by the white arrow shows the formation of a continuous, branched conduction path from the top to the bottom of the sample. This condition indicates that the system has exceeded the percolation threshold, so that the electrical conduction mechanism is dominated by direct filler-to-filler contact. The increase in the AC network significantly reduces the distance between fillers and strengthens the conduction path. As a result, the composite's electrical conductivity reaches a maximum at 30 wt% filler fraction, indicating the formation of a stable, effective conductive network in the polymer matrix.

4. Conclusion

This study demonstrates that coconut shell-derived activated carbon (AC) is a promising filler material for polypropylene (PP) composites intended for PEM fuel cell bipolar plate applications. Variations in AC content significantly influenced the density, flexural strength, and electrical conductivity of the composites through changes in microstructure and filler distribution.

The decrease in density with increasing AC fraction was mainly associated with increased porosity and void formation within the composite matrix. The optimum flexural strength was obtained at 10 wt% AC, where good particle dispersion and effective stress transfer were achieved. The maximum flexural strength reached 36 MPa, exceeding the DOE minimum requirement of 25 MPa for bipolar plate applications. However, further increases in AC loading reduced the mechanical properties due to particle agglomeration and restricted polymer chain mobility.

In contrast, higher AC content promoted the formation of conductive networks beyond the percolation threshold, resulting in a significant increase in electrical conductivity, reaching 5 S/cm at 30 wt% AC. These findings indicate that the developed PP/AC composite has strong potential as a lightweight and sustainable bipolar plate material, although further optimization is required to achieve a balanced combination of mechanical and electrical performance suitable for industrial applications.

Nevertheless, this study has several limitations, particularly the absence of direct fuel

cell performance evaluation, including electrochemical stability, corrosion resistance, and long-term operational durability testing. Therefore, future research should focus on integrating functional testing in real fuel cell systems and developing more controlled microstructure engineering strategies. Overall, coconut shell-derived AC offers promising prospects for the development of economical, lightweight, and environmentally sustainable bipolar plates for next-generation fuel cell technologies.

Acknowledgements

The authors gratefully acknowledge the financial support given for this work by the Dana Internal Yayasan Universitas Medan Area (DIYA UMA) 221/P3MPI/3.1.1/XI/2025 for supporting this work.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors were responsible for data analysis, interpretation, and discussion of the results. The authors read and approved the final manuscript.

Funding

Dana Internal Yayasan Universitas Medan Area (DIYA UMA) 221/P3MPI/3.1.1/XI/2025.

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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