



An experimental and theoretical study on the electrical conductivity of polymer composites

Szabolcs Hajagos^{a,b} , József Gábor Kovács^{a,b}, András Suplicz^{a,b}, Péter Széplaki^a , Béla Zink^{a,b,*}

^a Department of Polymer Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3, Budapest, 1111, Hungary

^b MTA-BME Lendület Lightweight Polymer Composites Research Group, Budapest University of Technology and Economics, Műegyetem rkp. 3, Budapest, 1111, Hungary

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ABSTRACT

In recent years, hydrogen fuel cells have emerged as one of the most promising green energy sources. Although fuel cells and their manufacturing technologies are still under development, recent research has shown encouraging progress. While polymers are typically known for their excellent electrical insulating properties, incorporating appropriate conductive fillers can transform them into electrically conductive composites. Potential fillers include graphite, graphene, carbon black, and carbon fibers. In this study, we evaluate the effect of filler properties on mechanical properties, and thermal and electrical conductivity in conductive mono-composites. Our results and conclusions can contribute to the development of conductive hybrid polymer composites suitable for fuel cell applications. We prepared composites using carbon black, carbon fiber, and graphite in a polypropylene matrix. We investigated the effects of processing parameters and evaluated the resulting materials' mechanical, thermal, and electrical properties. Among the tested fillers, one type of graphite exhibited superior electrical and thermal conductivity without compromising mechanical performance. Furthermore, we adapted a semi-empirical thermal conductivity model to describe the electrical conductivity of composites above the percolation threshold. The modified model showed high accuracy, offering a practical tool for material design and engineering applications.

1. Introduction

Due to the energy crisis of recent years, interest in alternative energy sources has increased. Fuel cells, which convert chemical energy into electrical energy, stand out for their high energy yield and lack of moving parts. They are also suitable for both stationary and mobile applications. The proton exchange membrane fuel cell (PEMFC) is the most widely used type, consisting of two central units, the Bipolar Plate (BP) and the Membrane Electrode Assembly (MEA) [1,2].

The functions of the bipolar plate include distributing the fuel, conducting the generated electric current, dissipating heat, removing the generated water, and supporting the MEA and the entire stack. This component accounts for 50–80 % of the weight of the stack and 40–60 % of its cost [3,4]. Based on the requirements, the BP must be light and cheap, an excellent thermal and electrical conductor, and have good mechanical properties. It must also meet other requirements, such as

resistance to electrical corrosion, low hydrogen permeability, and a low coefficient of thermal expansion. The BP can be made from metal, graphite, or a polymer composite. Metal BPs offer good mechanical properties and excellent conductivity, but they have a high density, price, and low corrosion resistance. Graphite plates have excellent conductivity and lower density, but they have high manufacturing cost and are brittle, which can easily lead to failure. On the other hand, polymer composite bipolar plates have low density and high corrosion resistance, and are also easier to manufacture, though they typically have worse mechanical properties and lower conductivity. To increase their conductivity, fillers such as graphite (G), graphene (GE), carbon black (CB), carbon nanotubes (CNT), and metal powders (MP) are commonly used [4–6].

Electrical conduction in CPCs primarily arises from a percolated network of filler–filler contacts, where electron transport is governed by contact resistance and quantum tunneling across sub-micrometer gaps

* Corresponding author. Department of Polymer Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3, Budapest, 1111, Hungary

E-mail address: zink@pt.bme.hu (B. Zink).

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within the polymer interphase. Polymer chains act as an insulating matrix; anisotropic fillers (flakes, fibers) introduce direction-dependent pathways once an interconnected network forms [4,7,8].

Extensive studies have been conducted on producing and testing conductive polymer composites (CPC) with thermoplastic and thermoset materials. Zheng et al. [9] created CPC using a poly(methyl methacrylate) (PMMA) matrix and graphite as filler. They used two types of graphite, a natural and an expanded graphite, and determined the percolation threshold and conductivity of each sample. Their results showed that expanded graphite is more suitable for producing CPC as it exhibited an approximately 70 % lower percolation threshold and an electrical conductivity an order of magnitude higher than natural graphite. Hu et al. [10–12] conducted several experiments on electrically conductive composites. In one of their studies, graphite and multi-walled carbon nanotubes (MWCNT) were mixed in a polyvinylidene fluoride (PVDF) matrix. The highest in-plane conductivity, 161.57 S cm^{-1} , was produced with 5 wt% MWCNT and 35 wt% graphite content. In one of their other studies, they also used a PVDF matrix but added graphite and carbon black, creating a synergistic conductor network. With 6 wt% CB and 34 wt% graphite, they achieved an in-plane conductivity of 177.87 S cm^{-1} . In their subsequent study, they created a 3-dimensional conductor network and associated it with an epoxy matrix, thus creating a sample with an in-plane conductivity of 212.64 S cm^{-1} . Beyond carbon-based fillers, recent studies have explored inorganic nanoparticles such as Sm_2O_3 , CeO_2 , and Nd_2O_3 in epoxy matrices [13,14], surface-engineered systems like graphene- and resin-coated nickel foams [15], carbon fiber surface treatments to enhance damping in CFRPs [16], and even vibration-based piezoelectric energy harvesting on lightweight metallic substrates [17], all highlighting how filler type, morphology, and interfacial design govern the multifunctional performance of composites.

Santiago et al. [18] investigated the suitability of different thermoplastic polymer matrix materials for use as bipolar plates. Polylactic acid (PLA) was ruled out because it degrades at the working temperature of the fuel cell. Their results indicated that the hardness of polyamide 6 (PA6) and thermoplastic polyurethane (TPU) would decrease during extended use. They found polycarbonate (PC), acrylonitrile butadiene styrene (ABS), and chlorinated polyethylene (CPE) matrix materials the most suitable. More research has been conducted focusing on polypropylene (PP) [19–22] as it is cost-effective, has good resistance to most inorganic acids and environmental stress, and has excellent fatigue resistance. It is more rigid than polyethylene (PE) and is unaffected by submersion in water; it retains its mechanical properties at elevated temperatures and has low density and excellent processing characteristics [3].

Several models have been developed to predict the electrical conductivity of CPC. Predicting the electrical conductivity of these composites is essential for efficient material design. While classical percolation theory provides an easy solution, it is often too simple for complex systems [23]. The General Effective Medium (GEM) model is a widely used advanced model [24]. It works well for composites with one or more types of fillers and at higher filler loadings. However, GEM does not fully consider the effect of filler orientation or shape. Modified models like the Mamunya model [25], additive models [26], and the McLachlan model [27] include parameters such as filler packing, surface energy, and structure to improve accuracy. Some models, like the Scarisbrick model, focus on how the contact between filler particles affects conductivity. Others, such as the Fiber Contact Model (FCM) [28], include filler orientation as a key factor. This is important because the alignment of conductive fillers, especially in the extrusion direction, significantly improves conductivity [29]. More recent advancements have focused on the critical role of the polymer–filler interphase region and quantum tunneling in governing conductivity [30,31]. These models provide high accuracy by including interphase thickness and tunneling distance. Similarly, sophisticated models have been developed for hybrid systems with multiple filler types and composites where filler

orientation is a dominant factor [32].

However, while these advanced models are physically comprehensive, their reliance on parameters difficult to measure limits their practical use in material design. That is why there remains a need for simple, robust, semi-empirical models that can reliably predict electrical conductivity using easily obtainable inputs. Our goal, therefore, is to develop and validate such a model, adapted from established thermal conductivity principles, which uses basic material properties to provide a valuable predictive tool for engineering applications in the design of fuel cell components.

Nomenclature

A	electrode contact area [m^2]	CPE	Chlorinated Polyethylene
c	apparent heat capacity of thick sample [J/K]	GE	Graphene
C	fitting parameter [–]	MEA	Membrane Electrode Assembly
C_p	specific heat capacity of thin sample [$\text{J/(kg}\cdot\text{K)}$]	MP	Metal Powder
D	diameter of thick sample [m]	MWCNT	Multi-Walled Carbon Nanotube
F	geometric factor [–]	PA6	Polyamide 6
I	current [A]	PC	Polycarbonate
K	number of fitted parameters [–]	PE	Polyethylene
L	sample height [m]	PEMFC	Proton Exchange Membrane Fuel Cell
M	mass of thick sample [kg]	PLA	Polylactic Acid
MSWD	Mean Square Weighted Deviation [–]	PMMA	Poly(methyl methacrylate)
n	number of data points [–]	PP	Polypropylene
P	modulation period [s]	PVDF	Polyvinylidene Fluoride
R^2	Adjusted coefficient of determination [–]	TPU	Thermoplastic Polyurethane
RSS	residual sum of squares [–]	<i>Greek letters</i>	
TSS	total sum of squares [–]	λ	thermal conductivity [$\text{W/(m}\cdot\text{K)}$]
U	voltage [V]	ρ	specific resistivity [$\Omega\cdot\text{m}$]
w	sample thickness [m]	σ	electrical conductivity [S/m]
<i>Superscripts and subscripts</i>		σ_c	specific conductivity of composite [S/m]
ABS	Acrylonitrile Butadiene Styrene	σ_f	conductivity of filler [S/m]
BP	Bipolar Plate	σ_p	conductivity at percolation threshold [S/m]
CB	Carbon Black	φ	filler content [wt%]
CNT	Carbon Nanotube	φ_{max}	maximum filler content [wt %]
CPC	Conductive Polymer Composite	φ_p	percolation threshold filler content [wt%]

2. Experiment

2.1. Materials

The Tipplon H145F polypropylene homopolymer (MOL Petrochemicals Co. Ltd., Tiszaújváros, Hungary) was used as the matrix material. According to the technical datasheet [33], this grade is recommended for injection molding, with a processing temperature range of 190–235 °C. Its melt flow index is 29 g/10 min, measured at 230 °C under a 2.16 kg load. Polypropylene was chosen due to its low density, sufficient mechanical properties, chemical resistance, water stability, and adequate heat resistance within the bipolar plate’s operating window, as well as its availability as one of the cheapest polymers on the market.

Synthetic graphite, carbon black, and carbon fiber were used to develop CPC. For each filler type, two different grades were used. The grades differed by particle size for graphite and carbon fibers, and by BET specific surface area for carbon blacks. The properties of the fillers

Table 1
Properties of the fillers used [34–38].

Properties	KS5-75 TT	SFG150	BNB90	ENSACO 250G	ENSACO 260G	PX35	
						chopped	milled
Short name	KS5-75 TT	SFG150	BNB90	ENS250G	ENS260G	PX35-C	PX35-M
Type	graphite			carbon black		carbon fiber	
Particle size [μm]	88	150	85	35	n.a.	8000	150
Aspect ratio [–]	5	5	n.a.	1	1	1000	20
BET specific surface [m ² /g]	4.4	2.3	28	65	70	n.a.	n.a.
Apparent bulk density [g/cm ³]	0.44	0.26	0.03	0.17	0.17	0.2	0.49

Table 2
Filler content for each mono-composite compound.

	KS5-75 TT	SFG150	ENS250G	ENS260G	PX35-C	PX35-M
Filler content [wt%]	10, 20, 40, 60, and 80	10, 20, 40, 60, and 80	10, 20, 40, and 50	10, 20, 40, and 50	10, 20, 40, and 60	10, 20, 40, 60, 80

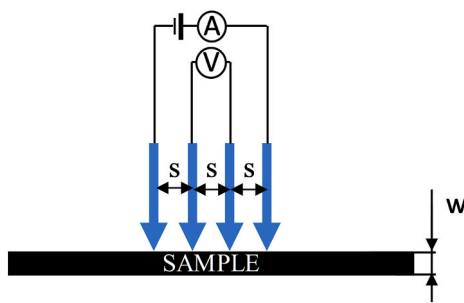


Fig. 1. Schematic illustration of the four-point probe method used for in-plane electrical conductivity measurements [39].

used are summarized in Table 1.

2.2. Sample preparation

Mono-composite compounds with different filler contents were prepared to determine the percolation threshold (Table 2). The upper filler content limit for each composite was determined by its processability.

The components were melt-mixed with a Brabender PlastiCorder internal mixer equipped with W50 roller blades, at 195 °C and 50 rpm for 10 min, while the torque was monitored and recorded. From the melt-mixed materials, plates with dimensions of 80 x 80 x 2 mm were compression-molded at 200 °C and 85 kN using a Teach-Line Platen Press 200E. Two plates were prepared from each composition. Electrical conductivity was measured on both plates, after which one was used for thermal conductivity and flexural tests.

2.3. Characterization

2.3.1. Electrical conductivity measurements

In-plane electrical conductivity was measured using a four-point probe resistivity method on compression-molded plates with dimensions of 80 x 80 x 2 mm. In this method, four needles are placed in contact with the surface of the sample at equal spacing of 20 mm. Current was applied through the outer probes, and the voltage was measured across the inner probes which eliminates the effect of contact resistance and ensures that only the material's resistance is measured. Conductivity was recorded continuously for 1 min with a sampling rate of 1 Hz (Fig. 1).

The electrical resistance of the sample was then calculated using Ohm's law. Since the thickness of the samples (2 mm) was significantly smaller than the spacing of the needles (20 mm), the formula Eq. (1) was

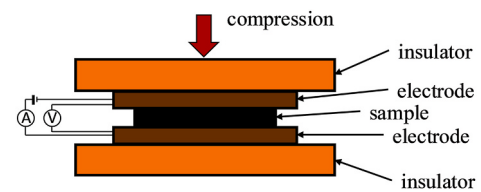


Fig. 2. Schematic illustration of the two-probe method used for through-plane electrical conductivity measurements [42].

applied to calculate the specific resistance [40]:

$$\rho = F \cdot \frac{\pi \cdot w}{\ln 2} \cdot \frac{U}{I} \quad (1)$$

where ρ is specific resistance [$\Omega \cdot m$], w is sample thickness [m], U is the voltage [V], I is the current [A], and F is the geometric factor [–], in this case, F is equal to 0.781, according to Topsoe [41].

The specific conductivity of the sample was obtained by taking the reciprocal of the specific resistivity, as shown in Eq. (2) [40]:

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

where σ is the electrical conductivity [S/m].

Through-plane electrical conductivity was measured using a two-probe resistivity method on compression-molded plates with dimensions of 80 x 80 x 2 mm. In this method, the sample was placed between two parallel electrodes that ensured uniform current distribution across the contact area. The tests were performed under a compressive stress of 0.2 MPa to guarantee stable contact between the electrodes and the sample surface. A constant current was applied through the electrodes, and the voltage drop across the sample thickness was measured (Fig. 2). As in the in-plane conductivity measurements, the conductivity was recorded continuously for 1 min with a sampling rate of 1 Hz.

The electrical resistance of the sample was then calculated using Ohm's law. Considering the electrode geometry, Eq. (3) was used to calculate the specific resistance [42]:

$$\rho = \frac{U \cdot A}{I \cdot w} \quad (3)$$

where ρ is specific resistance [$\Omega \cdot m$], w is sample thickness [m], U is the voltage [V], I is the current [A], A is the contact area of the electrode [m²].

The electrical conductivity of the sample was obtained as the reciprocal of the specific resistivity, according to Eq. (2).



Fig. 3. Three-point bending test rig.

2.3.2. Morphology

Filler dispersion was examined by scanning electron microscopy (JEOL JSM 6380LA, Jeol Ltd., Tokyo, Japan) operated at 10 kV. The surfaces of the samples were coated with gold to enhance conductivity.

2.3.3. Bending test

A three-point bending test was carried out using a Zwick Z005 (Ulm, Germany) universal testing machine equipped with a 5 kN load cell, at a crosshead speed of 2 mm/min. The support span was set to 64 mm, and the specimens had dimensions of 80 x 25 x 2 mm, in accordance with ISO 178:2019. For each compound, three specimens were tested, and the flexural strength was calculated following the standard procedure. Fig. 3 presents the test rig.

2.3.4. Thermal conductivity

The measurement was performed according to the method described by Marcus and Blaine [43], which involves two measurements on each compound. First, a thin sample with a thickness of 0.5 mm was used to determine the specific heat capacity, and second, a thick sample with a thickness of 2 mm was used to determine the apparent heat capacity. The diameter of the thick sample was 3.7 ± 0.3 mm. Thermal conductivity was calculated with Eq. (4):

$$\lambda = \frac{8 \cdot L \cdot C^2}{C_p \cdot M \cdot D^2 \cdot P} \quad (4)$$

where λ is thermal conductivity [W/(m·K)], L is the height of the thick

sample [m], C is the apparent heat capacity of the thick sample [J/K], C_p is the specific heat capacity of the thin sample [J/(kg·K)], M is the mass of the thick sample [kg], D is the diameter of the thick sample [m], and P is the modulation period [s].

3. Results and discussion

3.1. Processability

The torque generated during melt mixing was recorded and evaluated. Fig. 4/a shows a typical torque curve, where the initial peak corresponds to the loading of the matrix into the mixer and the second, larger peak indicates the addition of the filler, followed by an equilibrium torque during homogenization. Similar behavior was observed for the other fillers and contents.

An increase in torque demand with increasing filler content was observed only for the ENSACO-type carbon blacks (Fig. 4/b). This behavior can be attributed to the increased viscosity of the composite, which results in reduced processability. In contrast, the equilibrium torque was found to remain low and nearly independent of filler content for all other tested fillers (SFG150, PX35-C, PX35-M, and KS5-75 TT), indicating that good processability was maintained even at high filler content. This effect is particularly significant for graphite fillers, whose plate-like particles can become aligned and slide past one another in the shear field, acting as a solid lubricant and thereby minimizing the increase in melt viscosity even at a filler content as high as 80 wt%.

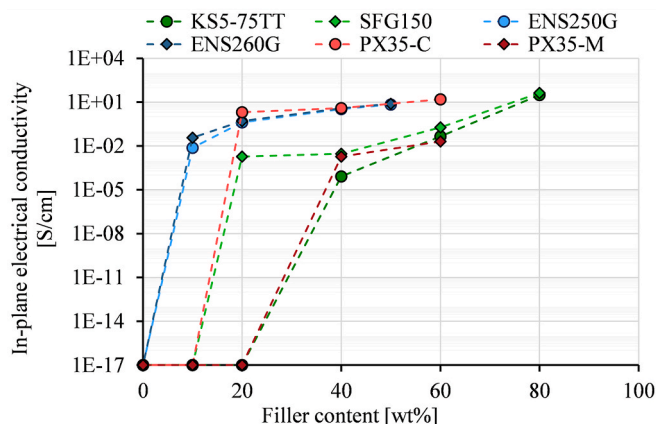


Fig. 5. In-plane conductivity of the investigated compounds.

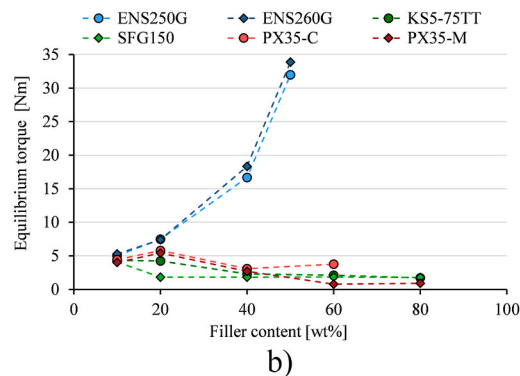
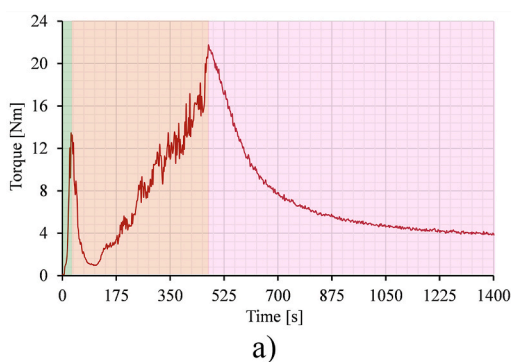


Fig. 4. Torque curves for PX35-C at 60 wt% (green – loading the matrix, orange – addition of filler(s), pink – mixing and homogenization) (a), equilibrium torque of different fillers for each weight percentage (b).

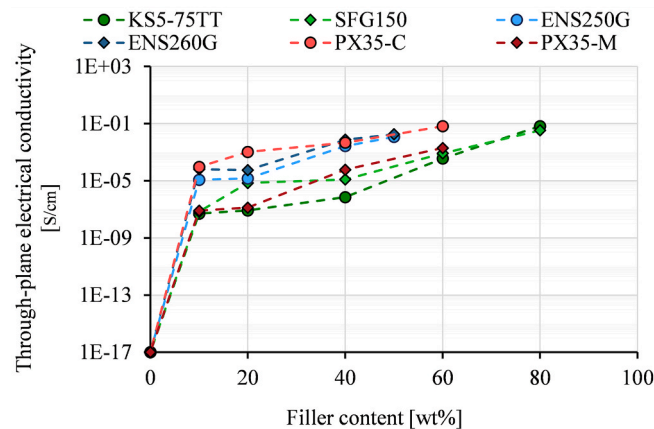


Fig. 6. Through-plane conductivity of the investigated compounds.

3.2. Electrical conductivity

3.2.1. In-plane conductivity

The in-plane electrical conductivity results (Fig. 5) highlight the complex relationship between filler characteristics and composite performance. The highest conductivity was obtained with SFG150 graphite (27.84 S/cm at 80 wt%), while the lowest was with PX35-M carbon fiber (0.02 S/cm at 60 wt%). The ENSACO carbon blacks exhibited the lowest percolation threshold, forming a conductive network at approximately 10 wt%. For all measurements, the relative standard deviation was below 1 %.

It was revealed that simple parameters like specific surface area have opposing effects depending on filler type. For carbon blacks, the ENSACO 260G grade with a higher BET surface area yielded higher conductivity than the ENSACO 250G with a lower BET surface area. This aligns with the concept that a higher surface area in conductive grades correlates with a more complex, branched aggregate structure, which is more efficient at forming a long-range conductive network. On the other hand, for graphites, the SFG150 grade with higher conductivity has a lower BET surface area than the KS5-75 TT grade with lower conductivity. This suggests that for graphite, where conduction relies on contact between individual flakes, the larger and smoother flakes of SFG150 form more extensive, lower-resistance contacts. The higher surface area of KS5-75 TT may indicate greater surface roughness or porosity, which increases contact resistance, and delays efficient electron transport between flakes.

3.2.2. Through-plane conductivity

The through-plane electrical conductivity results (Fig. 6) show a universal percolation threshold at ≈ 10 wt% for all fillers, after which conductivity increases more gradually. Similar to the in-plane measurements, the relative standard deviation was below 1 % in all through-plane tests. At high loadings, KS5-75 TT graphite achieved the highest through-plane conductivity (≈ 1 S/cm at 80 wt%), outperforming SFG150, which reflects KS5-75 TT's ability to form effective vertical contacts across the sample thickness.

Among fibers, PX35-C (chopped carbon fiber) displayed relatively high through-plane conductivity, significantly higher than PX35-M (milled fiber), indicating that the longer fiber fragments are more

effective at bridging the thickness of the plate. By contrast, carbon blacks (ENS250G, ENS260G), which possess an essentially spherical morphology and thus a low aspect ratio, showed lower ultimate conductivity. Their compact, isotropic aggregates allow network formation at ≈ 10 wt% but do not efficiently span the sample thickness, leading to moderate conductivity plateaus compared with the high-aspect-ratio fillers.

Overall, the comparison highlights how filler morphology and aspect ratio dictate post-percolation behavior: lamellar graphites and elongated fibers promote superior through-thickness conduction, while spherical carbon black particles are disadvantaged in this configuration.

3.3. Modeling electrical conductivity

A model was established to describe the in-plane electrical conductivity of the mono-composites above their percolation threshold. For this purpose, a model previously developed by Suplicz et al. [44] to describe the thermal conductivity of composites was adapted due to the similar saturation process. The relationship was modified to describe the change in specific in-plane electrical conductivity above the percolation threshold. The revised model is shown in Eq. (5) [44]:

$$\sigma_c = \sigma_p \left[1 - \left(\frac{\varphi - \varphi_p}{\varphi_{max} - \varphi_p} \right)^C \right] + \sigma_f \left(\frac{\varphi - \varphi_p}{\varphi_{max} - \varphi_p} \right)^C ; (\varphi_p \leq \varphi \leq \varphi_{max}) \quad (5)$$

where σ_c is the specific conductivity of the composite [S/m], σ_p is the specific conductivity of the polymer composite at the beginning of percolation [S/m], σ_f is the specific conductivity of the filler [S/m], φ is specific filler content [wt%], φ_{max} is maximum filler content [wt%], φ_p is filler content at the beginning of percolation [wt%], C is a fitting parameter [–].

Analysis was run in OriginPro 8.5 (OriginLab Corp., Northampton, Massachusetts, USA). The Non-Linear Least Squares method was used with Levenberg-Marquardt (L-M) Algorithm. The confidence interval was calculated using the Asymptotic-Symmetry Method. The tolerance limit was set to 1E-9 and the maximum number of iterations was set to 400. Only post-percolation data ($\varphi \geq \varphi_p$) were fitted; sub-threshold points were displayed but excluded from parameter estimation. No bounds were used for fitting.

The conductivity of the filler was taken as 60 S/cm for carbon black [45] and 500 S/cm for graphite [46]. Maximum filler content was $\varphi_{max} = 96.2$ % for both fillers [44]. Parameter C allows control of the variation of the slope of the function. Parameter C shows how quickly conductive networks are built, or how intensively the connections between the particles are formed, which thereby create a conductive network. The fitted values for parameter C and other model parameters are given in Table 3.

For evaluation of the fitting goodness Mean Square Weighted Deviation (MSWD) and Adjusted Coefficient of Determination ($\bar{R}_2$) were used. The MSWD value was calculated as the residual sum of squares (RSS) divided by the degrees of freedom (df) Eq. (6):

$$MSWD = \frac{RSS}{n - K} \quad (6)$$

where n is the number of data points and K is the number of parameters fitted by regression.

Adjusted coefficient of determination is calculated using Eq. (7)

Table 3

Fitting and goodness of fit parameters for different materials (Mean Square Weighted Deviation-MSWD, adjusted coefficient of determination- $\bar{R}_2$).

Materials	Parameter C [–]	σ_p [S/cm]	φ_p [wt%]	φ_{max} [wt%]	σ_f [S/cm]	MSWD [–]	$\bar{R}_2$ [–]
ENS250G	2.508	0.1094	17.5	96.2	60	0.01151	0.998
ENS260G	2.571	0.0370	10	96.2	60	0.03990	0.997
SFG150	10.381	0.0019	20	96.2	500	0.03178	0.999
KS5-75 TT	8.266	0.0990	40	96.2	500	0.00447	0.999

Table 4
Goodness of fit parameters for the power law and the classical percolation theory models applied to SFG150 and ENSACO 250G.

Materials	Model	MSWD [–]	$\bar{R}_2$ [–]
ENS250G	power law	0.15737	0.980
ENS250G	classical percolation theory	0.00947	0.999
SFG150	power law	7.946	0.977
SFG150	classical percolation theory	0.000681	1

$$\bar{R}_2 = 1 - \frac{\frac{RSS}{n-K}}{\frac{TSS}{n-1}} \quad (7)$$

where TSS is the total sum of squares.

A notable finding from the fitting process is the significant difference in parameter C between filler types. The values for graphite composites (10.38 and 8.27) are substantially larger than for carbon black composites (2.51 and 2.57). A larger C value corresponds to a sharper, more pronounced "S-shaped" transition of the conductivity curve. This suggests that the network formation mechanism may differ; the high aspect-ratio graphite flakes may require more cooperative alignment to form an efficient conductive pathway, leading to a sharper transition, whereas the more isotropic carbon black aggregates may form a network more gradually.

To further assess the suitability of the proposed equation, two additional modeling approaches - the power law and the classical percolation theory - were applied for comparison. These models were evaluated for two selected materials: SFG150 and ENSACO 250G (Table 4). The results of modeling are shown in Fig. 7.

Validation was carried out using a third type of graphite (Fig. 8), expanded natural graphite. Because of the limited fitting data available, no correlation can be evaluated on how the filler parameters (shape, specific surface, etc.) affect the fitting parameters, for example, percolation threshold and conductivity. σ_p and φ_p were estimated using measurement data; σ_f and φ_{max} are the same as those used previously.

Furthermore, at least two points are needed to fit the power law, and three points to fit the classical percolation theory model. Therefore, two measurement points were used to fit our proposed model and the power law model, and three for the classical percolation model.

As shown in Table 5, our model is less accurate than the classical percolation model; however it can be fitted using only two data points, making it more practical when experimental datasets are scarce. With a

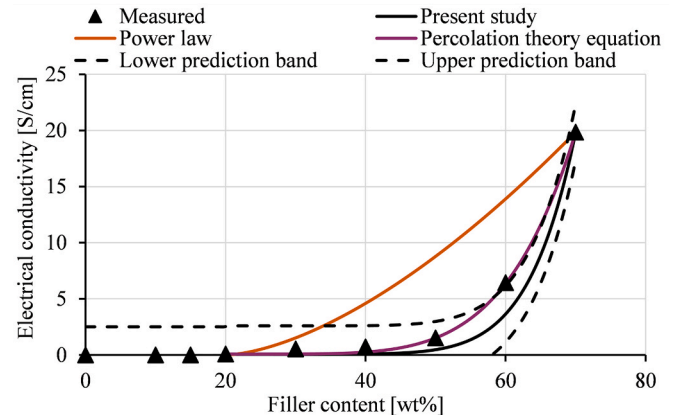


Fig. 8. Model validation with expanded natural graphite.

Table 5
Goodness of fit parameters for the power law and the classical percolation theory models applied to BNB90 graphite.

Model	MSWD [–]	R^2 [–]
power law	1.5962	0.639
classical percolation theory	0.05272	0.999
present work	1.1793	0.973

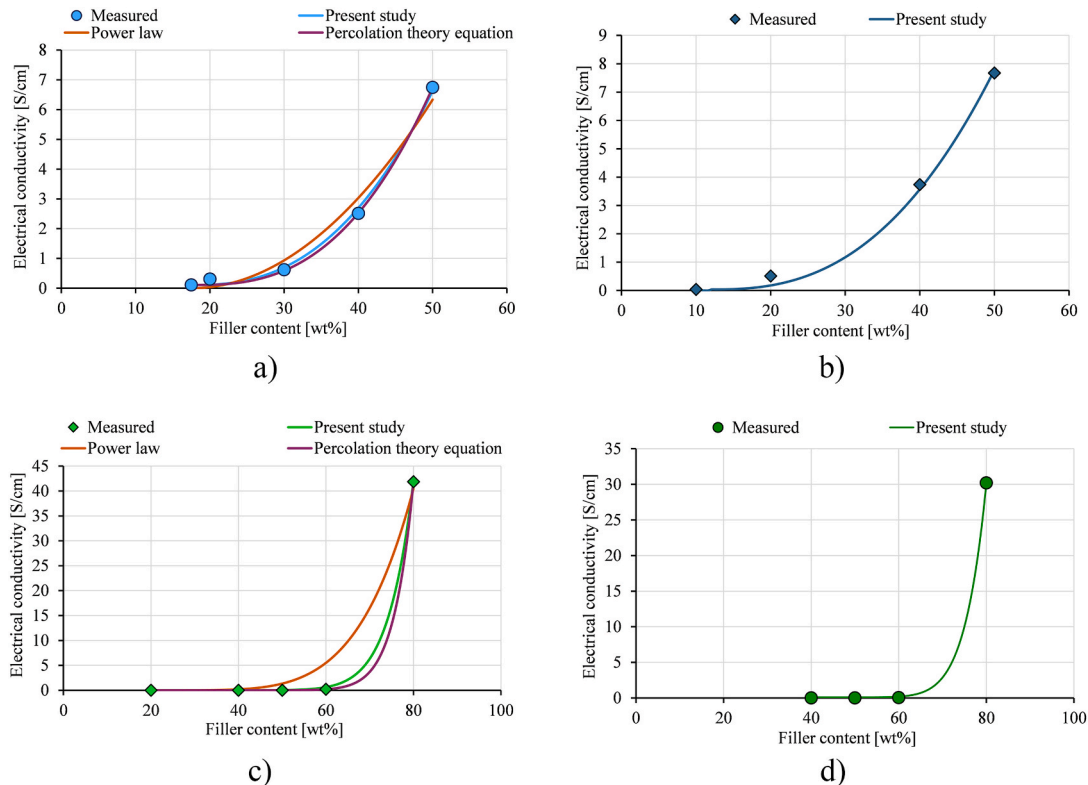


Fig. 7. Measured and calculated values of specific conductivity of samples for ENS250G (a), ENS260G (b), SFG150 (c), and KS5-75 TT (d).

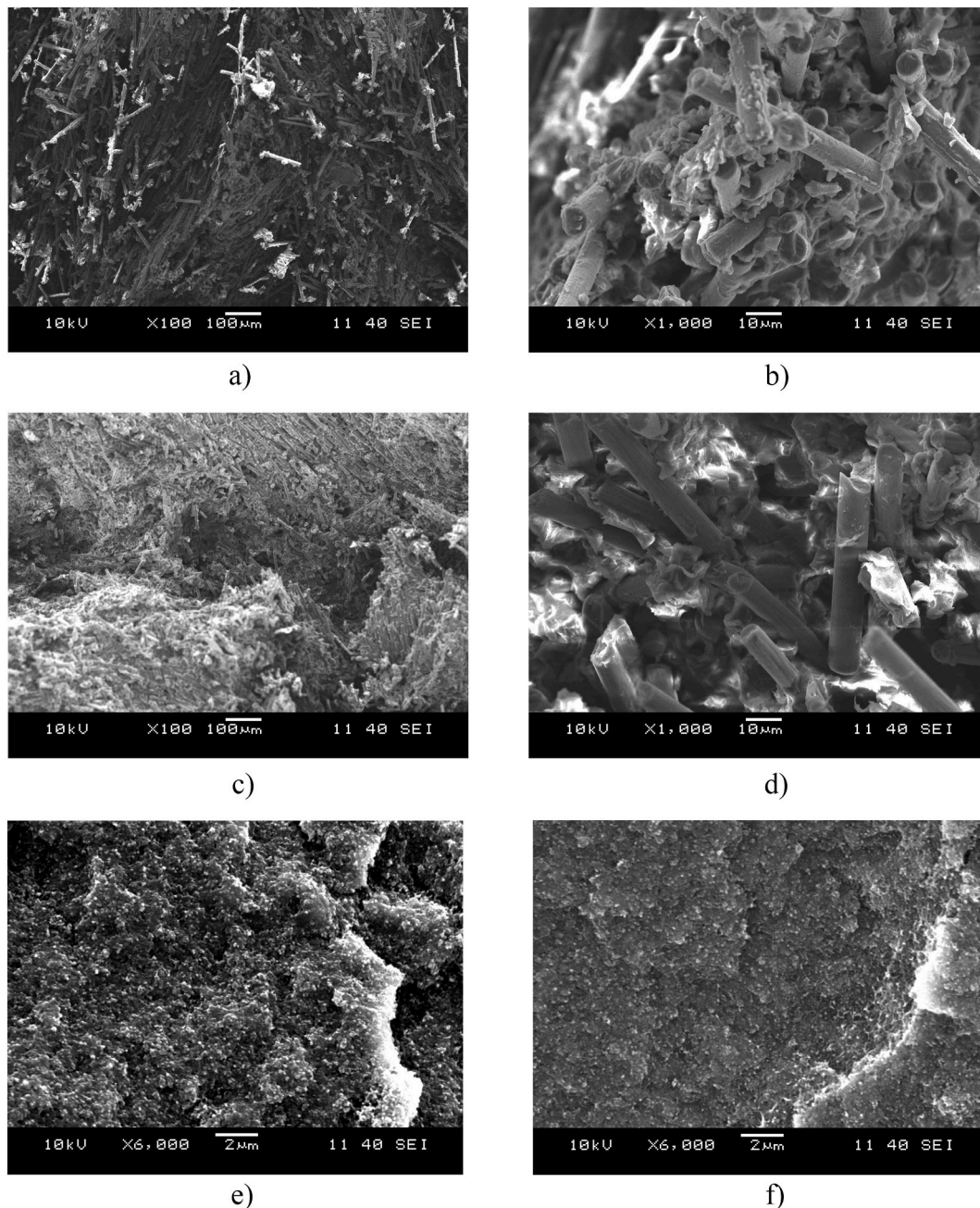


Fig. 9. SEM images of the composite plates with PX35-C (a, b), PX35-M (c, d), ENS250G (e), ENS260G (f), SFG150 (g, h), and KS5-75 TT (i, j).

sufficiently large set of previously collected data for different fillers, the model could even be parameterized to predict conductivity without new measurements, providing a valuable semi-empirical design tool.

3.4. Morphology

Scanning electron microscopy was used to examine the matrix material's structure, and size and dispersion of the fillers. Fig. 9 shows representative fracture surfaces of composites containing graphite and carbon fibers at two magnifications (100x and 1000x) and carbon black at 6000x magnification. The images revealed that the dispersion and filler–matrix interaction vary with morphology. For both graphite grades (SFG150 and KS5-75 TT), the lamellar flakes are embedded within the matrix, with relatively smooth fracture surfaces and limited signs of large agglomerates. The larger flakes of SFG150 appear more

uniformly distributed, forming extended contact surfaces that are consistent with the high electrical conductivity values reported in Section 3.2. In contrast, KS5-75 TT exhibits rougher particle edges and occasional micro-voids at the filler–matrix interface, which may account for the higher contact resistance and lower conductivity.

In the case of carbon fibers, the difference between chopped (PX35-C) and milled (PX35-M) fibers is clearly visible. Chopped fibers appeared elongated, with partial alignment in some regions, suggesting improved reinforcement compared to milled fibers. This morphology explains their contribution to flexural strength. By contrast, the milled fibers appear shorter and less uniformly oriented, leading to less efficient reinforcement but a more homogeneous distribution.

For carbon blacks, the ENSACO grades display highly porous and branched aggregate structures. At higher magnification, the aggregates appear finely dispersed in the matrix, although some localized clustering

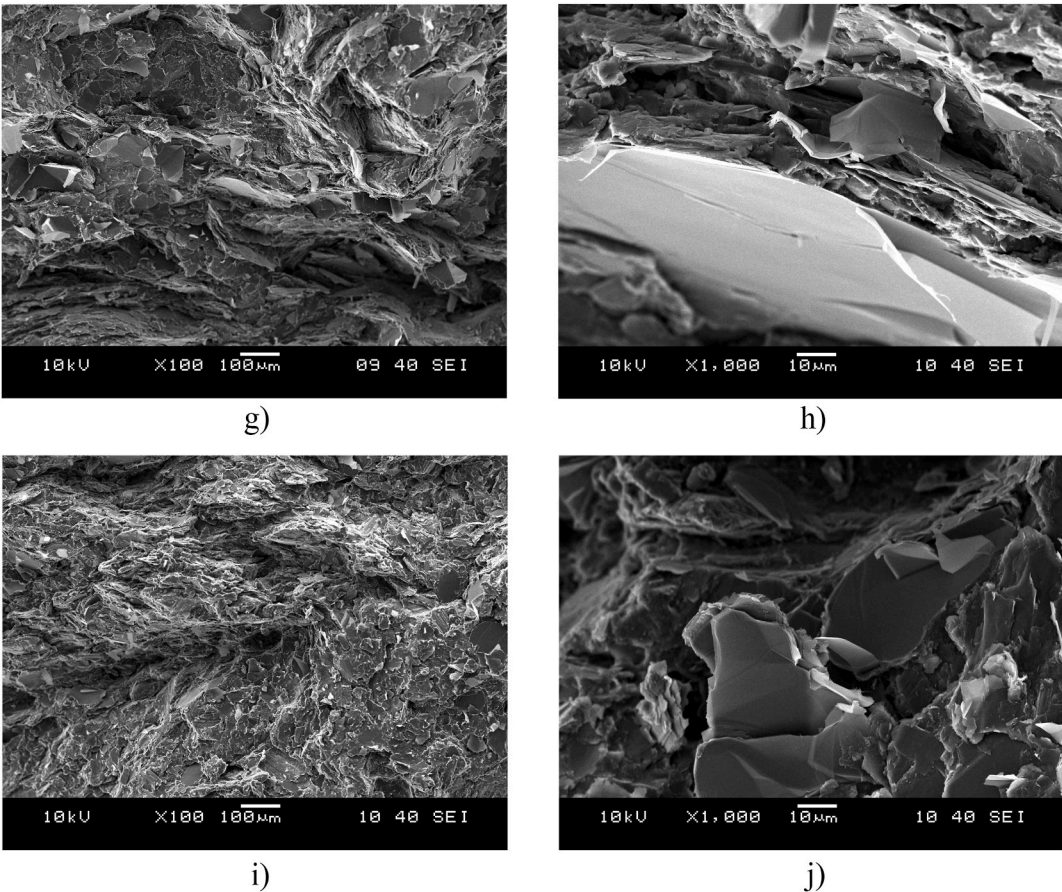


Fig. 9. (continued).

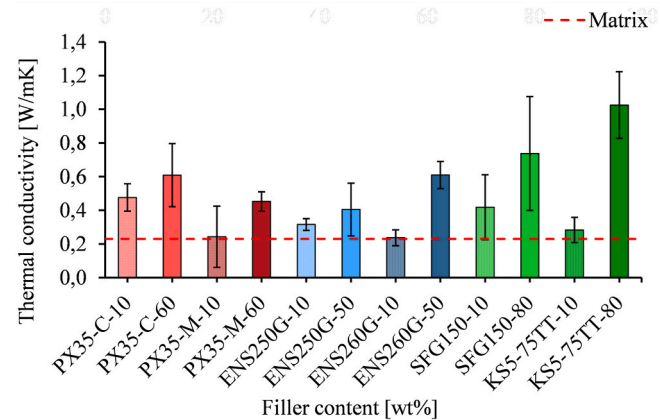


Fig. 10. Thermal conductivity results for the lowest and highest filler content for each type of filler.

is visible. The open and branched morphology of ENSACO 260G in particular is consistent with its lower percolation threshold and higher conductivity compared to ENSACO 250G.

Overall, the SEM analysis confirms that filler morphology governs both the dispersion state and the nature of filler–matrix interfaces, which in turn explains the observed differences in conductivity and mechanical properties. Good wetting and homogeneous distribution were achieved for most systems, although interfacial voids and agglomerates were more pronounced for KS5-75 TT graphite and ENSACO carbon blacks, in line with their less favorable performance.

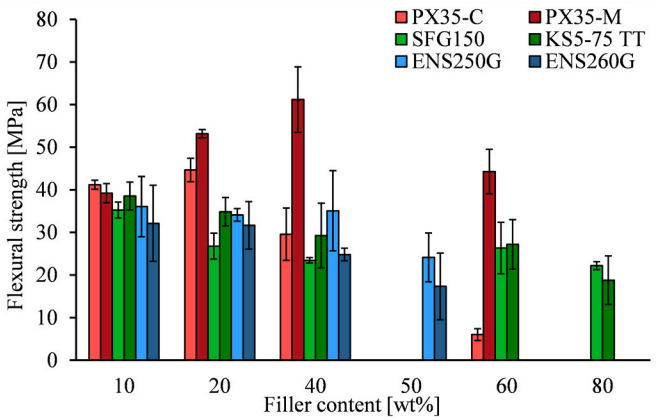


Fig. 11. Flexural strength of the composites according to the three-point bending test.

3.5. Thermal conductivity measurements

The thermal conductivity results (Fig. 10) show that only the graphite fillers provided a significant improvement. The basic processes of heat transmission in solids are mediated mainly by lattice vibrations (phonons). Because of its highly organized, crystalline lattice structure, graphite has a high intrinsic thermal conductivity due to effective phonon transport and little scattering. On the other hand, the structure of carbon black is primarily amorphous or disordered, resulting in strong phonon scattering and extremely low thermal conductivity. The one-dimensional character of carbon fibers and their strong thermal

barrier resistance to the many fiber–polymer interfaces limit their contribution, despite their organized graphitic structure.

3.6. Three-point bending tests

The flexural strength of the composites (Fig. 11) generally declined as filler content increased, with the notable exception of milled carbon fiber (PX35-M), which served as reinforcement up to 60 wt%. Flexural strength exhibited significant variability at high filler contents. For example, in the case of KS5-75 TT at 80 wt% loading, the relative standard deviation reached ~30 %, reflecting strong inhomogeneity across the plates. This discrepancy can be explained by macro-scale inhomogeneity, which develops when these extremely viscous materials are compressed. Zones rich in polymer and fillers may occur across the molded plate due to filler migration brought on by flow dynamics, especially between the center and the edges. These inconsistencies cause stress concentrations, which lead to varied mechanical performance.

4. Conclusions

In this study, polypropylene composites filled with different carbon-based fillers were investigated to evaluate their multifunctional performance for potential application in fuel cell bipolar plates. The results demonstrated clear structure–property relationships governed by filler morphology, underscoring the compromises between electrical conductivity, mechanical strength, and processability. Graphite flakes (SFG150) provided the highest conductivity but at the expense of flexural strength, whereas high-structure carbon blacks (ENSACO) reduced processability despite achieving low percolation thresholds. Carbon fibers improved flexural strength but offered limited conductivity. These findings highlight the limitations of single-filler systems and suggest that hybrid-filler strategies may offer a route to balanced performance.

A semi-empirical model adapted from a thermal conductivity equation was successfully applied above the percolation threshold. Compared with classical percolation theory and the power law, the proposed model achieved high predictive accuracy ($R^2 > 0.997$) while requiring only a few easily measurable parameters. Its simplicity and robustness make it practical for preliminary material design, although detailed models remain necessary for microstructural analysis. However, the applicability of the model is limited to the post-percolation regime, and it does not explicitly capture microstructural factors such as filler orientation or dispersion quality, which remain better addressed by more complex physical models.

Overall, the proposed methodology offers a balance between predictive accuracy and practical usability, positioning it as a valuable tool for rapid screening and formulation of conductive polymer composites, provided that its limitations are acknowledged in comparison with more detailed but computationally intensive models.

Author declaration statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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