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Experimental Investigation of the Dielectric Characterization of a Low-Density Polyethylene/Polypropylene/2D-Nanomaterial Based Polymer Nanocomposite for Electrical Insulation Application

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ABSTRACT
Many polymer composites do have the problem of fundamental microstructural mechanisms. In this study, polymer nanocomposite was developed from 2D layered nanomaterial (clay) as filler particles in Polyethylene (PE) and Polypropylene blend. The developed materials were characterized for its dielectric properties and electrical conductivity. The study deeply investigates the frequency-dependent electrical conductivity and dielectric properties of polypropylene (PP) and low-density polyethylene composite polymer blends reinforced with nanoparticles over a frequency range of 10 kHz to 200 kHz. Experimental results of the nanocomposites (NC) formed indicates that electrical conductivity for all composite polymer formulations follows an exponential increase with frequency, a behavior characteristic of AC conduction in heterogeneous polymer systems. The highest conductivity values (approximately 100) were observed in the nanopolymer PP/NC and PE/NC, suggesting the formation of efficient conductive networks and charge transport via hopping and tunneling mechanisms. Logarithmic analysis of AC conductivity reveals a linear trend consistent with Jonscher's universal power law, indicating a transition from frequency-independent to frequency-dependent regimes. The dielectric constant exhibited significant frequency dispersion, with pure PP showing high initial values (~420) that declined sharply at higher frequencies. Incorporating nanoparticles into the matrix may have introduced distinct relaxation peaks, particularly in LDPE/NC (~290 at 150 kHz), attributed to Maxwell-Wagner-Sillars interfacial polarization at the filler-matrix boundaries. These findings demonstrate that the nanoparticles reinforcement effectively tunes the electrical and dielectric behaviour of the polymer nanocomposite blends, making them suitable for advanced functional applications such as solid insulation, flexible electronics, and dielectric sensors where frequency-controllable permittivity is required.

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INTRODUCTION

Nanoparticles have found in wide varieties of applications in order to modify the properties of polymer since the beginning of this millennium. Studies into nanocomposite with polymer-based materials for electrical applications and insulators have been intensified considerably, to better understand various phenomenon in these materials so that their effective usage will be possible in numerous applications. It is known that the application of nano particles to the pure polymer matrix seems to effectively change the overall properties of the composite (Aliyu *et al*, 2025). In such a nanocomposite interface between two, one being the host polymer, play a significant role in its properties. This is primarily since the volume of the interface dominates the whole volume of the composite as the size of the nanocomposite decreases or increases depending on the incremental difference. This effect could also substantially modify the overall dielectric characteristics of the composite material (Aliyu *et al*, 2025).

Studies into polymer-based nanocomposite have been underway for the use of thermoplastics in high-voltage cables and as an insulating material (Mahdy *et al.,* 2020). At present, polymeric materials used as coaxial cables and high voltage applications are primarily various version of polyethene (PE) being one of the widely used, Andreas *et al*, (2009) with the presence technologies, the most powerful extruded high-voltage cables with PE as an insulating material used in high-voltage direct current (HVDC) system can handle up to 640kV (Wenwen *et al.,* 2029).

Along with PE and other polymers like polypropylene (PP) has found a place in electrical system as dielectric material (Muhammad *et al.,* 2024). The insulating form of (PP) has a melting point of about 481K with high crystallinity that leads to having high stiffness and tensile strength (Lee*et al.,* 2022). Although isotactic PP has high crystallinity, it is considered to be a semi crystalline material since crystallization of PP is a random process influenced by the probability of the molecules' ability to develop a crystalline structure with adjacent molecules, (Toshikatsu *et al*, 2004).

However, crystalline phase, amorphous phase and crystalline/amorphous phase interface has importance in the properties of change transfer in PP, like the phenomenon taking place in PE (Moyassari, 2017). Due to these highly desirable properties of change transfer in PP films are used in high performance pulse and low-loss RF capacitors (Tanaka *et al.,* 2004). Also, PP has been employed as an insulating medium in power cables, primarily due to its relatively high melting temperature that might possibly facilitate higher current-carrying capacity. According to Andritsch, (2017), in addition to other such microstructure properties are crystallinity amorphous phase as well as crystalline/amorphous interface, moreover it should be noted an appropriate process such as extrusion of cables should be selected in order to optimize the electrical strength since they could be influenced by the crystallinity and crystal thickness of the material (Huang, 2007).

Thermoplastic polymers, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS) are the main products of industrial engineering, which are employed in several electrical application fields. In high-voltage equipment, polymers are commonly used in the insulation systems because of their exceptional mechanical, electrical, chemical, and thermal properties and their low production cost (Pielichowska, 2022). In insulation materials which are produced by mixing different polymers at different weight ratios do maintain lower production cost. Usually, polymers are used to modify the physical, electrical, structural and mechanical properties of the final products. The most useful properties of PE and PP are oil resistance, rigidity, good stiffness, and thermal stability (Suleiman et al., 2023). In addition, the poor impact strength of PP and its weak young's modulus restrict its application. These poor properties may be enhanced by mixing PP with PE with nanoparticles (Xi *et al.*. 2013). In these blends, the impact and tensile strength are improved. The polymer blends compromise significant processing benefits in the melting polymer fraction (Andreas, 2009). This is because the exact percolation threshold where hopping and tunneling mechanisms transition from localized trap-assisted conduction to breakdown-induced continuous leakage currents is difficult to predict. Aggregation creates local electric field distortions (field concentration points) that alter dielectric loss at high frequencies (10--200 kHz).

MATERIALS AND METHODS

Materials

Surface modified nanoclay (Sigma-Aldrich), low density polyethylene (LDPE) and Polypropylene (PP) were purchased from LP Limited Plastics, LCR Bridge (HM8118, Rohde & Schwarz) and Tensile tester (HST, WDW-5) both available at the materials science laboratory.

Table 1: Properties of the Nanoclay

Properties	Description
Particle size	≤ 20 µm
Form	Powder
Composition	25-30 wt.% trimethyl stearyl ammonium
Matrix	Montmorillonite clay base material

Table 2: Sample Preparation

Identifier	Description	Filler Particle Conc.	Film Thickness (mm)
PPP	Pure Polypropylene Sample	-	2.90
PLDP	Pure Low Density Polyethylene Sample	-	2.90
PPLDPB	Polypropylene- Low Density Polyethylene (0.5:0.5) Blend	-	2.60
PPNCC	Polypropylene-Nanoclay Polymer Nanocomposite	0.11 g/g	2.80
LDPNCC	Low Density Polyethylene- Nanoclay Polymer Nanocomposite	0.11 g/g	2.90
PBNCC	Polymer Blend Nanoclay Composite Based on Polyethylene and Low-Density Polyethylene	0.11 g/g	2.90

Experimental Set-up

The pure sample of low-density polyethylene (LDPE) 50g, polypropylene (PP) 50g, LDPE/PP (mixture) 25/25g, PP/Nano clay (mixture) 45/5g, LDPE/Nano clay (mixture) 45/5g and PP/LDPE/Nano clay (mixture) 22.5/22.5/5g which are in the form of pellets alongside a nano-clay (powdered form) will be measured with a digital weighing machine (KERRO BL-P1D/20001), as shown in the figure below:

(a)  (b)

Plate 1: (a) Digital Weighing Machine, (b) Six 50g Measured Samples

Processing

i. The six measured samples of the polymer which are in the form of pellets will now be taken to a two-roll mill machine rolling at 54 rpm. The temperature of the roller will be increase to a certain range (150-180°C) due to the hard nature of the material. Measured sample will be placed between the roller, the repeating thermal contact of the roller and the sample can transform it to a molten form.
ii. The molten form of the polymer will be placed on a moulder to obtain an 80X60mm shape and will be taken to a compressing machine where it can be compressed to fit into the moulder for a required shape.

After compressing it, the moulder containing the polymer will be removed from the compressor and then allowed to cool, after some time (5min), an 80X60mm hard-Solid polymer is obtain from the moulder.


(a)


(b)

Plate 2: (a) Two Roll Mill Machine, (b) Blended Sample

Method

The solid polymer will be cut into two different shapes each (Dumbbell and circular) using cutting machine, then will be placed on a sample holder. The sample holder containing the dumbbell solid polymer will now be placed on the tensile machine and LCR meter for that of circular shape to carry out both tensile test and LCR test respectively, the result of each sample will be determined and recorded respectively.

The LCR (HAMEG HM8118) analyser was powered "ON", open and short circuit test was performed in other to scan the number of possible frequencies available. The range of frequencies available were from 1Hz to 200000Hz respectively.

The diameter of the samples was kept constant at 20mm which was that of the sample holder and the value of the thickness of each sample were measured with a digital vernier calliper and recorded as the length "L". Shown in the fig, below.

(a) 

(b) 

Plate 3: (a) Six Samples (Circular in Shape), (b) Digital Vernier Calliper

LCR Analyzer

LCR (Inductance-Capacitance-Resistance) analyser is a useful tool for measuring the electronic characteristic of passive electronic components such as resistors, capacitors and inductors.

Here are the general steps to make use of an LCR analyser.

It will be ensured that the LCR is properly set up and connected to the power source, sample will be also connected to the appropriate terminals of the LCR analyser making sure the connection is secured and accurate. The measurement parameters will be set according to the components to be tested, the component type need to be specific (Resistors, Capacitors, and Inductor)

Measurement will be carried out once the analyser is properly set up. The LCR analyser will apply an AC signal at the specific frequency to the component and measure its impedance or other parameters, LCR analyser will display the measured value on its screen, it will provide information such as impedance magnitude, phase angle, equivalent series resistance (ESR) quality factor (Q) and other parameters depending on the instrument capabilities, measured values will be recorded for further analysis. The process will be repeated for other components by adjusting the measurement parameters as required.

Plate 4: The LCR Meter

Plate 5: The Setup LCR Machine with a Sample

The experiment will be set up, with the sample placed on the holder, high and low terminals of the LCR are connected to the either side of the sample holder as shown below. Several readings were observed, values of the capacitance and resistance of the polymer was recorded as shown in the appendix.

RESULTS AND DISCUSSION

Electric Characterization

Electrical Resistivity

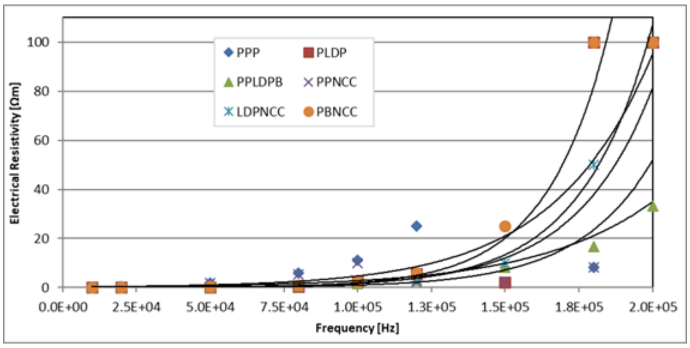

Figure 1: Electrical Resistivity of all Prepared Samples

The electrical resistivity of all prepared samples demonstrated a strong dependence on the applied alternating electric field, increasing as frequency also increases. At low frequencies, the resistivity remains nearly constant and steady, which is attributed to restricted charge carrier mobility due to trapping at localized energy states and interfaces (Barrau *et al.,* 2003). However, above 100 kHz, a significant rise is observed, suggesting that carriers gain sufficient energy to overcome potential barriers (Verma *et al*., 2021).

The resistivity response with frequency varies by different composition PP/NC and PE/NC exhibited the highest values (approx. 100 at 200 kHz), indicating the formation of efficient conductive (Zhang *et al*., 2015). Conversely, the blend showed the lowest conductivity, as the incorporation of LDPE enhances the insulating nature of the matrix and limits resistive pathway formation (Huang *et al*., 2007). This exponential rise in resistivity is characteristic of hopping mechanisms between localized states, common in heterogeneous polymer composites where the large filler-matrix interfacial area facilitates charge accumulation (Barrau *et al*., 2003: Limares *et al*., 2008).

Electric Conductivity

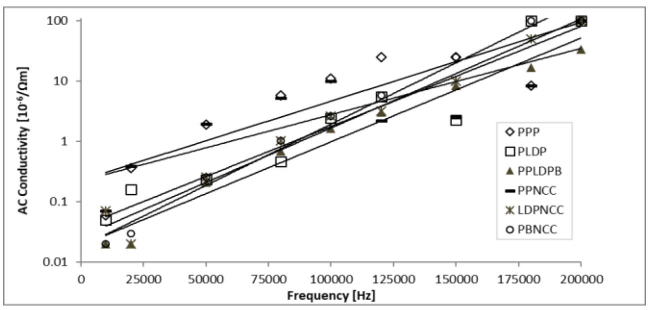

Figure 2: AC Conductivity Results

The AC conductivity results, when looked at on the logarithmic scale, show a continuous linear increase with frequency. This nearly linear trend suggests that conduction occurs predominantly through a hopping mechanism, where charge carriers move between localized states in the new matrix formed (Barrau *et al*., 2003). Such behavior is consistent with Jonscher's universal power law, where conductivity follows a relationship (Greenhoe *et al*., 2016).
Among the samples, PPP, PBNCC, and PPNCC reached approximately 100, indicating reduced resistance to carrier motion and more efficient transport pathways (Zhang *et al*., 2015). The observed enhancement in nanocomposites like LDPNCC, which reached 50, reflects an increase in interfacial polarization (Prashantha *et al*., 2010). The large number of interfaces in these systems provides Maxwell-Wagner-Sillars polarization effect, which contributes significantly to the electrical response at higher frequencies as it carriers respond more readily to the applied field (Linares *et al*., 2008).

Dielectric Characterization

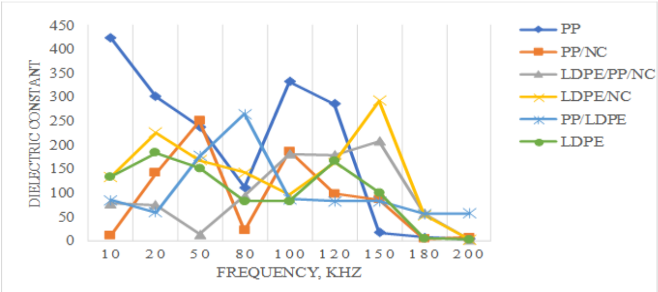

Figure 3: Dielectric Characterization

The dielectric response (10–200 kHz) exhibits complex, frequency-dependent behavior typical of polar and interfacial polarization-dominated materials. The dielectric constant generally decreases with increasing frequency, a phenomenon known as dielectric dispersion (Huang et al., 2007). Pure PP displayed the highest initial dielectric constant (~420 at 10 kHz) but declined to ~340 near 100 kHz, indicating that dipolar polarization decreases as the frequency exceeds the relaxation time of polar groups (Prashantha *et al*., 2010).
The incorporation of nanoparticles significantly modifies this behavior. PP/NC showed a peak near 50 kHz (~250), while LDPENC peaked sharply and clearly near 150 kHz (~290). These peaks are attributed to the Maxwell-Wagner-Sillars effect, where charge separation would likely occur at the nanofiller-matrix boundaries (Huang *et al*., 2007). The addition of these nanofillers increases the total polarizability of the system (Mahrous *et al*., 2018). However, at frequencies above 150 kHz, the dielectric constants of all compositions converged to lower values (<50) as the polarization mechanisms failed to keep pace with the rapidly oscillating electric field (Huang *et al*., 2007). Other deductions are:

i. Dielectric Relaxation & Dispersion Peaks:
Sudden changes in peaks, or drops in ε' across frequencies (such as the sudden drop for pure PP after 120 kHz or the peak for LDPE/NC around 150 kHz) indicate regions of dielectric relaxation. In these dispersion regions, dipoles struggle to align rapidly enough with the alternating electric field, resulting in elevated dielectric loss (ε''). Consequently, peaks in $\tan\delta$ typically occur near frequencies where ε' undergoes sharp drops.

ii. Interfacial Polarization (Maxwell-Wagner-Sillars Effect):
At lower frequencies (10–50 kHz), higher values of dielectric constant (especially in pure PP and nanocomposites/blends) are often caused by charge accumulation at phase boundaries or interfaces. As frequency increases, these heavy interfacial charges cannot keep up, causing ε' to fall off and generating dissipation losses.

iii. Behavior at High Frequencies (> 180 kHz):
Near 180–200 kHz, the dielectric constants for nearly all polymer blends approach very low baseline values. When ε' approaches zero, even small residual electrical losses (ε'') can cause $\tan\delta$ ratios to appear high or unstable.

CONCLUSION

The electrical and dielectric properties of PP/LDPE blends are profoundly influenced by both the frequency of the applied field and the incorporation of nanoparticle fillers. The electrical conductivity follows a power-law trend indicative of a hopping transport mechanism, with PPNCC and PBNCC providing the most efficient conducting networks. While the dielectric constant is generally enhanced by nanocellulose through interfacial polarization, it remains highly frequency-sensitive, exhibiting characteristic relaxation peaks. These results highlight the potential of these nanocomposites for applications in electromagnetic shielding and flexible electronics, where tailored dielectric performance is essential.

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