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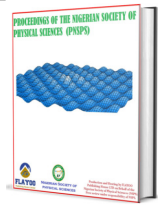

Effect of non-conducting nanoparticles on PVDF for improved insulating properties

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ABSTRACT

This study investigates the effect of incorporating non-conducting calcium carbonate ($CaCO_3$) nanoparticles into polyvinylidene fluoride (PVDF) to improve its insulating properties. PVDF is widely used as an electrical insulation polymer because of its dielectric performance, thermal stability, and mechanical strength; however, these properties can be further improved for advanced applications through nanoparticle modification. PVDF–$CaCO_3$ nanocomposite samples were prepared, characterized, and tested for dielectric and mechanical properties. The results show that adding $CaCO_3$ nanoparticles improves the insulating response of PVDF, especially at 0.5 wt% and 1.0 wt%, making the nanocomposites promising materials for high-performance insulation in electrical and electronic devices. The findings demonstrate the potential of nanoparticle-modified PVDF for improving energy efficiency and reliability in insulation systems.

Keywords: PVDF, Calcium carbonate nanoparticles, Electrical insulation, Dielectric properties, Thermal stability.

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1. INTRODUCTION

The demand for high-performance insulating materials has grown significantly with the increasing sophistication of electrical and electronic systems for advanced applications. Polyvinylidene fluoride (PVDF) is a widely used polymer known for its excellent dielectric properties, high thermal stability, and mechanical strength, making it a preferred material for electrical insulation applications [1]. However, PVDF has limitations, including dielectric losses, electrical breakdown at high voltages, and environmental degradation over time. These limitations must be addressed to maximize its potential in insulation systems.

Nanotechnology has advanced the development of polymer-based electrical insulation. Researchers have explored several approaches for enhancing the insulating properties of PVDF, including the incorporation of non-conducting nanoparticles such as $CaCO_3$, TiO_2, and Al_2O_3 [2]. When used as fillers in PVDF, these nanoparticles can improve electrical insulation by modifying the microstructure, reducing charge mobility, and increasing dielectric strength [3]. Previous studies have shown that such nanoparticles can reduce dielectric losses and improve the breakdown voltage of PVDF-based insulating materials, making them more reliable for high-voltage applications [4].

Several researchers have investigated how non-conducting nanoparticles improve the insulating properties of PVDF. In one study, TiO_2 nanoparticles were used as fillers in PVDF, and 3 wt% TiO_2 improved the material's mechanical strength and

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piezoelectric properties. The nanoparticles promoted the formation of the β phase, which enhanced the insulating response of PVDF by resisting electrical flow [5]. However, excessive TiO_2 loading, up to 10 wt%, caused agglomeration, which can reduce mechanical strength. This finding highlights the importance of nanoparticle concentration in the design of polymeric insulation materials. In the present work, lower filler loadings were selected to demonstrate their effect on PVDF insulation performance.

Although previous studies have examined the addition of non-conducting nanoparticles to polymeric insulation materials, further work is needed to identify compositions that provide maximum efficiency. Interactions between nanoparticles and the polymer matrix can alter dielectric behavior, improve charge-trapping properties, and increase resistance to electrical stress [6]. In addition, the interphase formed between the polymer and nanoparticles, as well as its homogeneity, can modify charge transport mechanisms, reduce electrical conductivity, and improve the overall insulating performance of PVDF [7]. Properly dispersed $CaCO_3$ nanoparticles in a PVDF matrix can enhance mechanical strength and dielectric breakdown strength, making the material suitable for modern electrical insulation [8]. The properties of PVDF-based nanocomposites depend on the nature, size, and concentration of the $CaCO_3$ nanoparticles used during sample preparation.

Despite these advances, practical challenges remain in the use of PVDF-based nanocomposites. A major concern is achieving uniform dispersion of nanoparticles in the polymer matrix, because poor dispersion can negatively affect both electrical and mechanical properties [9]. Addressing this challenge is essential for realizing the full potential of non-conducting nanoparticles, such as $CaCO_3$, in enhancing the insulating capabilities of PVDF. This study therefore investigates the effect of low concentrations of $CaCO_3$ nanoparticles on PVDF to optimize its insulating performance and provide insight into its application in high-voltage insulation systems. The study also examines how nanoparticle addition affects dipole alignment, interfacial polarization, and charge mobility within the polymer matrix, with the aim of supporting the development of more durable and reliable insulation materials.

2. METHODOLOGY

2.1. MATERIALS

High-molecular-weight PVDF with 98% purity was obtained from Sigma-Aldrich. The polymer was selected because of its excellent piezoelectric properties and thermal stability. High-grade $CaCO_3$ nanoparticles with 99% purity and a molecular weight of 100.09 g mol^{-1} were obtained from Griffin and George, 285 Ealing Road, Wembley.

PVDF pellets (0.5 g) and $CaCO_3$ nanoparticles (0.5 wt% and 1.0 wt%) were weighed using a KERRO BL-P1D/2000I digital weighing machine. The PVDF was supplied in pellet form, while the $CaCO_3$ was supplied in flat-surface form.

2.1.1. Material processing

PVDF and $CaCO_3$ were mixed using a two-roll mill at 170–180 °C and 54 rpm until a molten mixture was obtained. The molten mixture was molded into 80 × 60 mm sheets using a compression molding machine. The sheets were cooled for 5 min to form solid composite samples.

The solid polymer composite sheets were cut into dumbbell and circular shapes using a sample-cutting machine. The dumbbell-shaped samples were placed in a sample holder for tensile testing, while the circular samples, each with a diameter of 20 mm to match the sample holder, were used for dielectric testing with an LCR analyzer. The thickness of each circular sample was measured using a digital vernier caliper and recorded as the length L for subsequent calculations.

2.2. MATERIAL CHARACTERIZATION

2.2.1. Dielectric loss, permittivity, and electrical conductivity measurements

A HAMEG HM8118 LCR analyzer was used to measure the dielectric properties, including capacitance and resistance, of the circular samples. The following procedure was used. First, the LCR analyzer was powered on, and open- and short-circuit tests were performed to scan the available frequency range from 1 Hz to 200 kHz. Second, each circular sample was placed securely in the sample holder, and the high and low terminals of the LCR analyzer were connected to opposite sides of the sample holder to ensure accurate and stable measurements. Third, the measurement parameters were set to capacitance and resistance, with the component type specified as a capacitor. An AC signal at selected frequencies from the LCR bridge was applied to the sample, and impedance-related parameters, including capacitance, equivalent series resistance, and quality factor, were recorded. Finally, the measured values displayed on the LCR analyzer were recorded for analysis, and the process was repeated for each sample while adjusting the frequency as required.

2.2.2. Mechanical strength analysis

Stress and strain were determined using a Monsanto tensiometer according to the operating instructions. The machine has two claws that grip a dumbbell-shaped sample. The wheel attached to the clamp was turned to increase the tension on the sample until fracture occurred. The force and elongation were then recorded for each sample and used to calculate tensile strength in MPa. Three measurements were taken for each sample, and the average force and elongation values were recorded.

3. RESULTS AND DISCUSSION

The experimental results describe the dielectric properties of PVDF doped with 0.5 wt% and 1.0 wt% $CaCO_3$ nanoparticles. The study examines how different $CaCO_3$ loadings influence the insulating behavior of the PVDF matrix. In particular, dielectric parameters such as relative permittivity and dielectric loss are analyzed as functions of frequency. The mechanical properties are also examined as functions of stress and strain.

The results are interpreted to explain how the addition of non-conducting $CaCO_3$ nanoparticles affects dipole alignment, interfacial polarization, and charge mobility within the nanocomposite. Each observation is discussed in relation to established dielectric theory and compared, where applicable, with previous studies on PVDF-based nanocomposites.

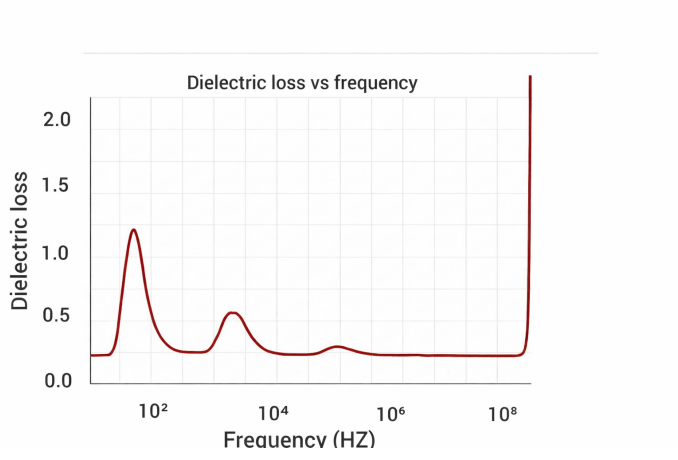

Figure 1. Dielectric loss variation with frequency for 0.5 wt% $CaCO_3$-doped PVDF.

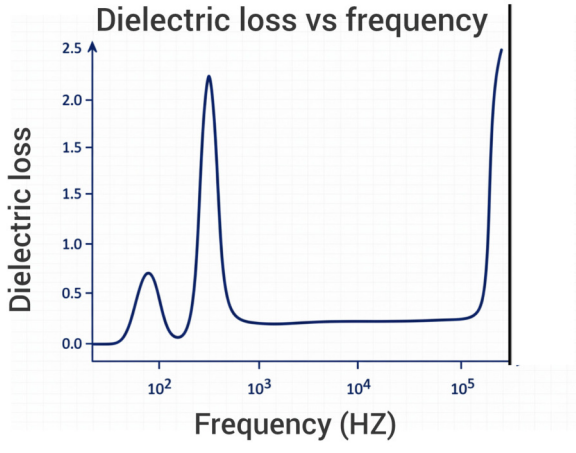

Figure 2. Dielectric loss variation with frequency for 1.0 wt% $CaCO_3$-doped PVDF.

3.1. DIELECTRIC PROPERTIES OF PVDF-DOPED POLYMER NANOCOMPOSITES

The dielectric behavior of PVDF doped with 0.5 wt% and 1.0 wt% $CaCO_3$ was analyzed in terms of dielectric loss, relative permittivity, and electrical conductivity as functions of frequency.

3.1.1. Dielectric loss of $CaCO_3$–PVDF polymer nanocomposites

The frequency dependence of the 0.5 wt% and 1.0 wt% $CaCO_3$–PVDF polymer nanocomposites is shown in Figures 1 and 2, respectively.

The dielectric loss (tan δ) of the 0.5 wt% $CaCO_3$–PVDF composite decreases with increasing frequency, although a few spikes occur at low frequency, possibly because of particle vibrations. At low frequencies, dipoles and interfacial charges have enough time to align with the electric field, resulting in higher energy loss due to strong interfacial polarization. As the frequency increases, rapid field reversal makes dipole alignment more difficult, thereby reducing polarization effects and lowering dielectric loss. This trend agrees with the behavior reported for conductive carbon-nanotube-filled PVDF [7], where limited dipole mobility at high frequencies reduces energy dissipation up to about 10^4 Hz [2]. This response is typical of PVDF doped with nonconducting nanoparticles.

For the 1.0 wt% $CaCO_3$–PVDF composite, the dielectric loss also decreases with increasing frequency, with two initial spikes at low frequency. The higher nanoparticle content likely creates more interfacial regions, causing higher loss at low frequencies because of enhanced charge buildup and interfacial polarization [2]. The spikes occur between approximately 10^2 and 10^3 Hz. At higher frequencies, dipoles and interfacial charges can no longer follow the rapidly changing electric field, resulting in a substantial reduction in dielectric loss. This behavior agrees with reported trends for $CaCO_3$-filled PVDF, where increased frequency limits dipole relaxation and reduces energy dissipation [7].

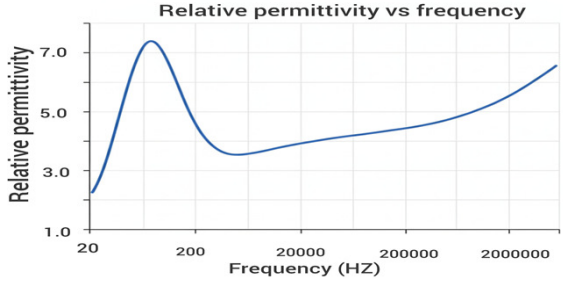

Figure 3. Relative permittivity variation with frequency for 0.5 wt% $CaCO_3$-doped PVDF.

3.1.2. Relative permittivity of $CaCO_3$–PVDF polymer nanocomposites

The relative permittivity of the 0.5 wt% and 1.0 wt% $CaCO_3$-doped PVDF composites is shown in Figures 3 and 4, respectively.

The relative permittivity of the 0.5 wt% $CaCO_3$–PVDF composite initially increases and then decreases with increasing frequency. At low frequencies, dipoles and interfacial charges can readily align with the applied electric field, resulting in higher permittivity due to strong interfacial polarization. As the frequency increases, rapid field oscillation prevents effective dipole alignment, causing the permittivity to decrease and then rise along the frequency range considered [7]. This frequency-dependent behavior agrees with the established dielectric response of $CaCO_3$-filled PVDF, where reduced dipole mobility at high frequencies limits polarization [2].

For the 1.0 wt% $CaCO_3$–PVDF composite, the relative permittivity is higher at low frequencies because the increased nanoparticle content introduces more interfacial regions for charge accumulation, thereby enhancing polarization. A small peak appears at about 2000 Hz, producing a stretched fluctuation in the curve. Similar to the 0.5 wt% composite, the permittivity decreases as frequency increases and then fluctuates steadily. The higher frequency reduces the ability of dipoles and interfacial charges to

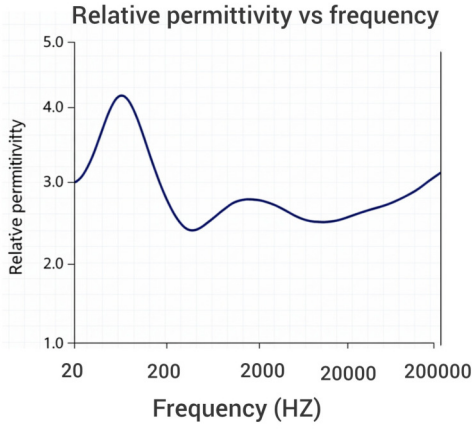

Figure 4. Relative permittivity variation with frequency for 1.0 wt% $CaCO_3$-doped PVDF.

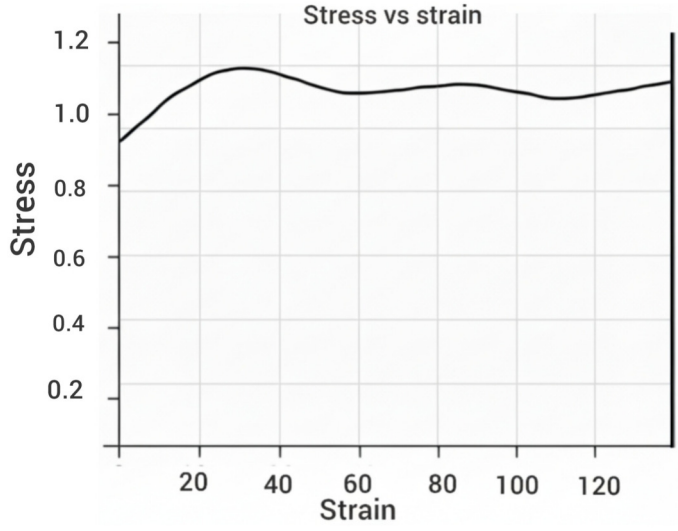

Figure 6. Stress–strain curve for 1.0 wt% $CaCO_3$-doped PVDF.

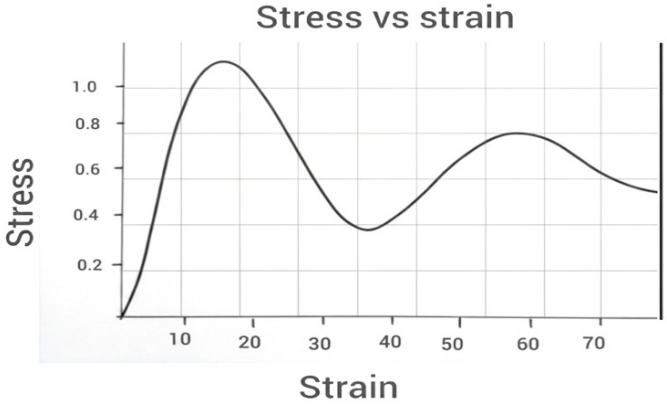

Figure 5. Stress–strain curve for 0.5 wt% $CaCO_3$-doped PVDF.

respond to the alternating field, leading to lower permittivity.

3.2. MECHANICAL PROPERTIES OF $CACO_3$–PVDF POLYMER NANOCOMPOSITES

The stress–strain curves for the polymer nanocomposite samples are shown in Figures 5 and 6.

Young's modulus quantifies the stiffness of a material and is determined from the slope of the linear elastic region of the stress–strain curve. The curve in Figure 5 shows a linear relationship between stress and strain up to the point considered as the yield point. The stress increases consistently and reaches a maximum value of approximately 19 MPa, after which it fluctuates within the strain range, especially for the 0.5 wt% loading. The initial linear portion of the curve represents the elastic deformation region of the material [10]. Based on the slope of this elastic region, the Young's modulus of the PVDF nanocomposite with 0.5 wt% $CaCO_3$ is estimated to be 0.8–1.2 GPa.

This estimated modulus is consistent with the known stiffness of pure PVDF, which is typically 1.5–2.0 GPa, as reported in previous studies [8, 10]. This agreement indicates that incorporating a low concentration of $CaCO_3$ filler does not significantly alter the inherent mechanical stiffness of the polymer matrix.

From the stress–strain plot for PVDF doped with 1.0 wt% $CaCO_3$ (Figure 6), the stress values range from 0.9 to 1.9 MPa, while the corresponding strain extends to approximately 140 units. The initial region of the curve shows a nearly linear increase in stress with strain, indicating elastic deformation before a slight decline at higher strain levels, followed by extended linear deformation [10]. Using the approximate slope of the initial linear portion, the calculated Young's modulus is 3.5–4.0 GPa, which is higher than that of the 0.5 wt% sample.

This improvement shows that calcium carbonate particles can enhance the stiffness of the PVDF matrix. The enhancement is mainly attributed to the rigid nature of the $CaCO_3$ particles, which restrict the mobility of PVDF polymer chains. Efficient stress transfer from the polymer matrix to the rigid filler particles also contributes to the increased Young's modulus of the nanocomposite samples.

4. CONCLUSION

The addition of non-conducting $CaCO_3$ nanoparticles enhanced the dielectric and mechanical properties of PVDF. The 0.5 wt% $CaCO_3$ composite showed better dielectric stability and lower loss than the 1.0 wt% composite, while the 1.0 wt% composite showed improved stiffness and higher low-frequency permittivity. The increase in Young's modulus with filler content confirms that $CaCO_3$ nanoparticles can reinforce the PVDF matrix, with the 1.0 wt% composite showing a calculated Young's modulus of 3.5–4.0 GPa. These improvements make $CaCO_3$–PVDF composites promising materials for high-performance electrical insulation, particularly where enhanced mechanical strength and controlled dielectric behavior are required. Future studies should examine a broader range of $CaCO_3$ concentrations, such as 0.1–2.5 wt%, to identify the optimum loading for specific insulation applications. Surface modification of $CaCO_3$ nanoparticles should also be investigated to improve dispersion and interfacial adhesion within the PVDF matrix.

DATA AVAILABILITY

The data will be available on request from the corresponding author.

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 manuscript.

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References

[1] S. Gudrun and M. M. Matthew, ''Properties of polymer–nanoparticle composites'', Current Opinion in Colloid and Interface Science **8** (2003) 103. https://doi.org/10.1016/S1359-0294(03)00008-6.

[2] A. Aliyu, S. Umar, A. A. Abdelmalik, A. I. Galadima & S. S. Maidawa, ''Dielectric response analysis of polyvinylidene fluoride doped with alumina, titanium oxides, and calcium carbonate nanoparticles'', UMYU Scientifica **4** (2025) 475. https://doi.org/10.56919/usci.2542.049.

[3] Y. Mariappan & M. Rengaraj, ''A comprehensive review on nanotechnology for enhancement in performance of transformer liquid insulation'', Materials Today: Proceedings **47** (2021) 229. https://doi.org/10.1016/j.matpr.2021.04.128.

[4] H. Hongpu, H. Yuehao, P. Yuanfeng, W. Yangrui, L. Hong & F. Yefeng, ''Improved dielectric and breakdown traits of polymer composites filled with KH-550 encapsulated multilayer black phosphorus'', Current Applied Physics **63** (2024) 7. https://doi.org/10.1016/j.cap.2024.04.003.

[5] W. Qian, Z. Hang, Y. Lei, D. Xiaoyu, W. Xiuping & B. Jinbo, ''Improved energy storage performance in sandwiched poly(vinylidene fluoride)-based composites assembling with in-plane-oriented BN nanosheets and TiO_2 nanowires'', ACS Applied Energy Materials **5** (2022) 15948. https://doi.org/10.1021/acsaem.2c03542.

[6] K. Ashok, M. Batra, E. Edwards, A. Almuatasim & E. Adnan, ''Dielectric behavior of P(VDF-TrFE)/PZT nanocomposite films doped with multiwalled carbon nanotubes (MWCNT)'', American Journal of Materials Science **5** (2015) 55. http://article.sapub.org/10.5923.s.materials.201502.09.html.

[7] R. M. Rudenko, O. O. Voitsihovska, V. M. Poroshin, M. V. Petrychuk, N. A. Ogurtsov, V. Y. Noskov & A. A. Pud, ''Influence of carbon nanotubes on the electrical conductivity of PVDF/PANI/MWCNT nanocomposites at low temperatures'', Ukrainian Journal of Physics **67** (2022) 140. https://www.researchgate.net/profile/Alexander-Pud/publication/359666844_Influence_of_Carbon_Nanotubes_on_the_Electrical_Conductivity_of_PVDFPANIMWCNT_Nanocomposites_at_Low_Temperatures/links/62ebc44b0b37cc34476db5fc/Influence-of-Carbon-Nanotubes-on-the-Electrical-Conductivity-of-PVDF-PANI-MWCNT-Nanocomposites-at-Low-Temperatures.pdf.

[8] S. Kaniknun & T. Prasit, ''Enhanced dielectric properties of PVDF polymer nanocomposites: A study on gold-decorated, surface-modified multiwalled carbon nanotubes'', Heliyon **10** (2024) e26693. https://doi.org/10.1016/j.heliyon.2024.e26693.

[9] Y. Tetsuya, T. Yuya & T. Naoya, ''Dispersion of nanomaterials in polymer composite materials'', MATEC Web of Conferences **333** (2021) 11003. https://doi.org/10.1051/matecconf/202133311003.

[10] Y. Huang, K. Yasuda & C. Wan, ''Intercalation: Constructing nanolaminated reduced graphene oxide/silica ceramics for lightweight and mechanically reliable electromagnetic interference shielding applications'', ACS Applied Materials & Interfaces **12** (2020) 55148. https://doi.org/10.1021/acsami.0c15193.