Thermal Analysis of Cost-Effective Industrial Nanocomposites with Capacitive Control

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Abstract: The progress in electrical materials provides a foundation for the advanced processing of electric and electronic applications. The evolution of electroactive polymers (EAPs) supports the development of adaptive flexible systems, which consequently yield innovative integrated technologies for actuation and sensing. An assortment of polymer-based nanocomposites has been successfully applied in the production of Nano-tech sensors, which includes a diverse range of materials like conductive, thermoplastic, and elastomeric polymers. The charge storage capacity of insulation materials is a vital criterion for choosing materials in industrial electrical settings. Consequently, this paper explores how nanoparticles influence the capacitive charge in polyvinyl chloride under diverse thermal conditions. Experimental tests have been performed on different types and concentrations of organic and inorganic nanoparticles like Clay (Montmorillonite), ZnO, SiO_2 and TiO_2 at frequency range of 0.01 Hz to 1 MHz and under different thermal conditions ranging from 20°C to 80°C. Additionally, the research has been conducted on the best types and concentrations of nanoparticles for charging polyvinyl chloride insulation materials. A comparative study has demonstrated the effectiveness of nanoparticles that have improved electric and electronic industrial applications of polyvinyl chloride.

Keywords: Polyvinyl chloride, Capacitive charge, Nanocomposite, Nanoparticles, Polymers.

1. INTRODUCTION

Polymers are essential in outdoor insulation applications, and nanoparticles are vital for enhancing the electrical characteristics of these insulating materials. The main advantages of using nanocomposite insulating materials are their capacity to be easily shaped into complex forms and their ability to function as both structural and insulating components. The functional properties of nanocomposites like thermal and electrical conductivity, phase transitions, dimensional stability, magnetization, and enhanced modulus can be fine-tuned by selecting suitable nanoparticles. The strategic fusion of nanofillers and polymers is critical in augmenting the electrical properties of composites. Ongoing research and development in this domain focus on enhancing the performance and scalability of these films, ensuring they fulfill the demanding standards necessary for commercial use. With persistent innovations, flexible conductive films are likely to play a pivotal role in the future of electronics, paving the way for more dynamic and efficient devices [1, 2]. As the industry explores the feasibility of temperature-variable operations, the role of these materials becomes increasingly significant. A thorough comprehension of their behavior under different thermal conditions will be essential for the successful implementation of innovative power-system solutions. The challenges posed by charge accumulation in high DC fields; poor discharge resistance, low thermal conductivity, a narrow service temperature range, and inadequate stiffness have significantly restricted the broader application of these materials. On the other hand, nanodielectrics, which incorporate inorganic nanoparticles in polymer matrices, have been found to possess excellent electrical properties for various industrial applications [3, 4]. The domain of dielectric materials with elevated permittivity, known as high-k materials, has garnered substantial interest, mainly due to the critical requirements of the electronics industry. These dielectrics find broad application as electrical energy storage mediums in sophisticated electronic applications and power systems, acknowledged for their high power density and outstanding rates. Through the careful selection and combination of these materials, researchers can formulate composites that showcase specific conductivity and enhanced performance features. This strategy lays the groundwork for groundbreaking applications in numerous industries, such as electronics and insulation technologies [5-14]. In recent years, polymer

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nanocomposites have garnered considerable attention for their ability to improve polymer properties and expand their applications; studies have shown their capacity to enhance dielectric properties. However, the interfacial dynamics between the nanofillers and the polymer matrix are closely linked in these nanocomposites. The physical properties of innovative nanocomposite materials are made up of nanoparticles and their compounds, which are stabilized within a polymeric dielectric matrix. The addition of nanoparticles to polymers has resulted in the creation of new engineering materials designed to improve various characteristics of industrial products [15-22]. Recent researches have been exploring the optical parameter and characteristics of doping nanoparticles in polymer for low cost nanoelectronics applications. The influence of nanoparticles on the structural, dielectric and optical features for optics and quantum nanoelectronic applications has provided many features as comparative in using traditional electronic applications [23-28]. Moreover, there has been a concern regarding nanotechnology science for the advancement of electrical applications; the main objective of applicable nanotechnology science is to synthesize dielectric nanocomposites and enhance the physical properties of electrical applications. The types of nanoparticles are expected to affect the electrical properties of polymeric nanocomposites. The electric and optical properties of these materials have been demonstrated to be highly contingent on the size, structure, and concentration of the nanoparticles, along with the type of polymeric matrix [29-38]. The selection of the right polymer matrix is essential in the development of nanocomposite materials for industrial and electrical applications. The present study focuses on polyvinyl chloride (PVC) because of its wide industrial use and established industrial importance in electrical insulation, power cables, and engineering products, although several polymers, such as polyvinylidene fluoride (PVDF), polyethylene (PE), polypropylene (PP), and epoxy resins, have shown good dielectric, thermal, and mechanical properties. PVC is a thermoplastic that is widely used and offers a practical balance of mechanical strength, rigidity, electrical insulation, processability and adaptability to a wide range of industrial manufacturing requirements. Such properties make it a relevant matrix to study the relationship between dielectric performance and nanoparticle incorporation under different working conditions. However, the choice of PVC is not necessarily indicative of its superior thermal or dielectric properties over all other polymers. Instead, its practical industrial relevance is a strong incentive to explore methods that can improve its electrical properties while keeping the advantages of the current polymer matrix. Specifically, the incorporation of suitable inorganic nanofillers may affect the effective permittivity, interfacial polarization, dielectric response, and frequency- and temperature-dependent capacitive behavior of PVC. Hence, clay, silicon dioxide (SiO_2), zinc oxide (ZnO), and titanium dioxide (TiO_2) nanoparticles were selected to study the effect of nanoparticle type and concentration on the capacitive characteristics of PVC nanocomposites. The comparative measurements were carried out at temperatures from 20 to 80 °C and over a frequency range of 0.01 Hz–1 MHz. The main objective is to establish how much these nanofillers affect the electrical response of PVC and to assess the feasibility of the nanoparticle modification in improving the suitability of PVC for industrial electrical insulation and dielectric applications. Consequently, the aim of this research is to assess the capacitive charge of specific new nanodielectrics derived from polyvinyl chloride at various temperatures, with the goal of enhancing the limited understanding of their electrical characteristics. Polyvinyl chloride has been selected as the foundation for the polymer matrix in the development of new nanocomposites due to its significant industrial relevance in power cable insulation, high voltage applications, and synthetic thermoplastic polymers. The priority is on grasping the link between structure and properties in composite materials applied in power engineering. This entails employing both essential theoretical frameworks and experimental investigations to evaluate how material design affects capacitive control under diverse thermal conditions. The chosen nanoparticles, such as clay, fumed silica (SiO_2), zinc oxide (ZnO), and titanium dioxide (TiO_2), have been examined for their effects on capacitive charging of polyvinyl chloride. As a result, the investigation has addressed the effects of types and concentrations of nanofillers (organic and inorganic) on the capacitive charge of innovative polyvinyl chloride nanocomposites across a spectrum of frequencies and temperatures; the frequency and temperature ranges applied were made as broad as possible.

2. PHYSICAL FRAMEWORK AND OPTIMIZATION

Polymer nanocomposites have attracted much attention due to the incorporation of inorganic nanoparticles into polymer matrices, which can change their electrical and dielectric properties. The resulting material characteristics depend on the chemical

structure of the polymer, the type and concentration of the incorporated nanoparticles, their dispersion within the matrix, and the interactions developed at the polymer–particle interface. These attributes are particularly important in industrial applications requiring stable dielectric behavior under different operating conditions, such as for electrical insulation and capacitive components. The ability of polyvinyl chloride (PVC) to be processed, its mechanical strength, its chemical resistance and its established use in insulation systems make it a popular choice for industrial and electrical applications. However, the dielectric and capacitive performance may be influenced by the operation frequency, temperature, material composition and characteristics of the incorporated fillers. Thus, the addition of nanoparticles into PVC provides a way to study and control its electrical response to temperature and frequency. The physical and dielectric properties of clay, fumed silica (SiO_2), zinc oxide (ZnO) and titanium dioxide (TiO_2) can affect the overall behavior of the polymer composite. For use in capacitors or energy storage devices, these intrinsic properties translate into extremely low energy density compared to specialized polymers like PVDF or ceramic-polymer composites. Even when attempting to form composite materials, the incompatibility and poor interfacial adhesion between PVC and high-permittivity inorganic fillers often leads to defects and increased dielectric loss rather than significant capacitive enhancement. Consequently, pure or lightly modified PVC is functionally unsuitable for charge storage layers in applications requiring miniaturization, such as embedded capacitors or high-frequency circuits. Research focus has therefore shifted to alternative polymers or to fundamentally modifying PVC through chemical grafting or advanced nanocomposite design to create polar domains, though this remains a significant materials engineering challenge. The proposed method for boosting the capacitive charge of polyvinyl chloride (PVC) is to intentionally formulate it as a nanocomposite using organic or inorganic nanofillers. This approach overcomes its inherent non-polarity by introducing new, efficient charge storage mechanisms. High-permittivity inorganic nanoparticles are incorporated to directly increase the composite's dielectric constant via their intrinsic dipolar and interfacial polarization. Concurrently, the addition of conductive organic nanoparticles creates an internal conductive network. This facilitates the formation of micro-capacitors throughout the PVC matrix, where nano-interfaces between conductive and insulating regions enable significant space charge polarization. To maximize performance, core-shell structured nanoparticles are employed, where a conductive organic shell improves the dispersion and interfacial adhesion of an inorganic core within the hydrophobic PVC. A percolation-threshold design is critical, using just enough conductive filler to form a network without causing a short circuit. This synergistic combination leads to a dramatic rise in the effective dielectric constant and, consequently, the energy storage density. For electronic applications like embedded capacitors or pulse-power systems, this engineered PVC nanocomposite offers a viable path toward flexible, process able, and lightweight dielectric materials with tunable capacitive properties, bridging the gap between PVC's manufacturability and the demanding requirements of modern electronics. Therefore, in the present study, the effect of clay, fumed silica (SiO 2), zinc oxide (ZnO), and titanium dioxide (TiO 2) nanoparticles on the capacitive properties of PVC nanocomposites is studied. Measurements are performed on the samples using a Solartron frequency response analyzer in the temperature range of 20°C-80°C and frequency range of 0.01 Hz-1 MHz. The main goal of the study is to compare the electrical response measured for the specimens made of pure PVC and PVC reinforced with nanoparticles, and to study the effect of the type and the amount of nanoparticles on the electrical response. The conditions of the fillers that correspond to the favorable capacitive behavior are identified. The objective of these results is to establish an experimental basis for evaluating the potential of these materials for electrical insulation and dielectric applications.

3. NUMERICAL MODELING AND ANALYSIS

The capacitance behavior of polyvinyl chloride (PVC) nanocomposites is an important factor in determining their potential for applications in electrical and electronic devices. In parallel-plate configuration, the capacitance depends on the relative permittivity of the dielectric material, the electrode area and the thickness of the dielectric layer. The stored electrical charge can be given as (Q=CV) and the energy stored in the capacitor can be given as (U= (½)CV2) where (Q) is the stored charge, (C) is the capacitance, (V) is the applied voltage and (U) is the stored electrical energy. These relations show that the incorporation of nanoparticles into PVC can modify its dielectric properties and therefore its ability to store charge. The dielectric constant and the dielectric loss are important

parameters for cable insulation and capacitor applications since they influence the electric-field distribution, the polarization behavior and the energy dissipation under an applied electric field. A suitable dielectric material must have a suitable dielectric response over the operating temperature and frequency range. In PVC nanocomposites, the effective permittivity can be tailored by the addition of inorganic nanoparticles such as TiO2, ZnO and SiO2 and clay nanoparticles due to the intrinsic dielectric properties of the fillers and the polarization processes taking place at the polymer–particle interfaces. However, increasing the capacitance does not necessarily improve the dielectric breakdown strength or long-term electrical reliability. These properties are to be evaluated individually by means of breakdown voltage, insulation resistance and electrical aging tests. Hence, in the present study, the measured capacitive and dielectric responses of the fabricated PVC nanocomposites are reported for the given frequency and temperature conditions.

3.1. Frequency-Dependent Dielectric Behavior and Electromagnetic Response of Nanocomposites

The dielectric and electromagnetic properties of polymer nanocomposites are greatly influenced by the frequency of the applied electric field. The effects of operating frequency are discussed in terms of polarization mechanisms, charge transport, dielectric relaxation and energy dissipation in the polymer matrix. The incorporation of inorganic nanoparticles as clay, SiO_2, ZnO and TiO2 , leads to new interfaces between the dispersed nanofillers and the polymer matrix in PVC based nanocomposites. These interfaces influence the capacitive properties and are part of the overall dielectric response under a range of operating conditions. At relatively low frequencies the dielectric response is usually dominated by interfacial polarization, space-charge accumulation and dipolar orientation. The accumulation of electrical charges at the interfaces between PVC and the embedded nanoparticles can result in the Maxwell-Wagner-Sillars polarization. This phenomenon is especially important in heterogeneous polymer nanocomposites, where the electrical conductivity and permittivity of the polymer matrix are different from those of the inorganic fillers. Therefore, the concentration of nanoparticles and interfacial properties can significantly impact the measured capacitance and dielectric loss. With increasing frequency of the applied field the contribution of slow polarization mechanisms decreases, since the corresponding dipoles and interfacial charges are not able to follow the alternating electric field in time. The dielectric response at intermediate and higher frequencies is increasingly governed by faster polarization mechanisms, relaxation processes and frequency dependent charge transport. These modifications can lead to changes in the real and imaginary components of the complex permittivity, which may affect the nanocomposite's ability to store capacitive charge and dissipate dielectric energy. Additional considerations are needed for the characterization of dielectric materials at microwave and gigahertz frequencies such as electromagnetic wave propagation, impedance matching, dielectric loss and possible resonant interactions. Engineered metamaterials, in particular, employ purposely created sub-wavelength structural designs that yield controllable electromagnetic responses, possibly with resonant characteristics and anomalous effective permittivity or permeability. It is important, however, to distinguish this behavior from the standard dielectric response of randomly dispersed nanoparticles in a polymer matrix. Simply adding clay, SiO_2, ZnO or TiO_2 nanoparticles does not confer metamaterial properties unless an appropriate electromagnetic architecture is designed and experimentally verified. Therefore the present PVC nanocomposites are interpreted as a consequence of its dielectric and capacitive properties dependent on the frequency and not as metamaterial behavior. It is essential to understand the correlation between thermal conditions, interfacial polarization, frequency, and nanoparticle concentration to be able to select proper nanocomposite formulations for industrial applications like capacitive components and electrical insulation. Further investigation into the electromagnetic characteristics in microwave and gigahertz frequency bands is needed, which requires structural optimization and specific high-frequency characterization.

3.2. Model Design and Analysis

Nanocomposite-based capacitive materials have become promising options for next-generation energy storage and electronic applications due to their customizable electrical, dielectric, and structural features. The addition of nanoscale fillers into polymer or ceramic matrices results in a significant boost in dielectric constant, breakdown strength, and charge storage capacity, which enables these materials to operate effectively under diverse conditions. A theoretical analysis of nanocomposites polymers materials is vital for grasping the core mechanisms that influence their electrical properties, energy storage

abilities, and dielectric efficiency. Through the detailed analysis of critical metrics like permittivity, dielectric loss, conductivity, and energy density, researchers can forecast and improve the performance of materials in practical applications such as capacitors, sensors, and flexible electronics. The study highlights the modeling and examination of the dielectric response and capacitive characteristics of nanocomposites when subjected to electric fields. It clarifies how elements like filler content, dispersion, interfacial polarization, and material structure influence overall performance. These theoretical frameworks are instrumental in directing material design and promoting the development of cost-effective and efficient energy storage systems. The equations are significant for assessing the electrical characteristics, energy storage capabilities, and dielectric performance of capacitive materials derived from nanocomposites in industrial settings. To investigate the capacitive behavior of these nanocomposites, key electrical equations are utilized, specifically the Capacitance (C) of a Parallel Plate Capacitor, as outlined here: $C = (\varepsilon_0 \times \varepsilon_r \times A) / d$

Where:

- C = Capacitance (Farads)
- ε_0 = Vacuum permittivity (8.854×10^{-12} F/m)
- ε_r = Relative permittivity (dielectric constant) of the nanocomposite
- A = Electrode area (m^2)
- d = Thickness of the dielectric layer (m)

In contrast, dielectric loss is essential for assessing the efficiency and possible applications of nanocomposite materials in energy storage, insulation, and high-frequency electronic systems. It reflects the energy that is lost as heat when a dielectric material is subjected to an alternating electric field. In nanocomposites, the addition of nanofillers significantly influences dielectric loss, which can be linked to interfacial polarization, space charge effects, and the fundamental properties of both the matrix and filler materials. This section seeks to establish a theoretical framework for assessing dielectric loss in nanocomposites, providing valuable insights for optimizing material design to achieve minimal energy loss and improved dielectric stability across different electrical and thermal environments. The fundamental dielectric equations are presented as Dielectric Loss (tan δ) termed with energy storage as real part of permittivity (ε') and energy dissipation as imaginary part of permittivity (ε") as expressed as $\tan \delta = \varepsilon''/\varepsilon'$. A theoretical framework of complex permittivity has been constructed for modeling and examining the complex permittivity behavior of nanocomposites. This approach provides better control over their dielectric properties, which is vital for sophisticated electronic and energy-related applications. The key equations for Energy Stored in the capacitor termed with capacitance (C) and voltage (V) as expressed as $E = ½ \times C \times V^2$. The electrical properties of polymer nanocomposites are determined not only by the intrinsic properties of the polymer matrix and the inorganic fillers, but also by the interactions at the interfaces between the polymer and the particles. Fumed silica is especially interesting because of its high surface area and nanostructure, which can affect charge distribution, interfacial polarization, and particle dispersion in a polymer-based composite. However, the functional role and chemical composition of the polymer matrix have a great influence on the electrical response obtained. Previous studies have reported the modification in ionic conductivity of PVdF-HFP-based plasticized nanocomposite polymer electrolytes by incorporation of nano-size fumed silica. The electrolyte systems include polymer host, dissolved ionic salt and plasticizer which function as a mechanism for ion dissociation and transport. Interfacial or space-charge effects have been attributed to the contribution of silica. These mechanisms are important for the understanding of the interactions between silica and polymers. Nevertheless, they should not be directly compared with the dielectric response of insulating nanocomposites based on PVC. In the present work, fumed SiO 2 nanoparticles are added to PVC and their effect is studied by capacitive and dielectric measurements instead of ionic-conductivity measurements. Therefore the electrical response is discussed in terms of the capacitance, dielectric polarization and temperature and frequency dependent behavior. This distinction is important because capacitive response in an insulating PVC nanocomposite and ionic conductivity in a plasticized polymer electrolyte are different electrical characteristics requiring different experimental interpretations [39-41]. The dielectric properties of polymer nanocomposites are determined by the combination of the polymer matrix, the embedded nanoparticles and the interfaces that form between these two phases. Previous studies have demonstrated that the introduction of nanoparticles can alter the effective dielectric permittivity, dielectric loss, charge distribution, and relaxation behavior of polymer-based

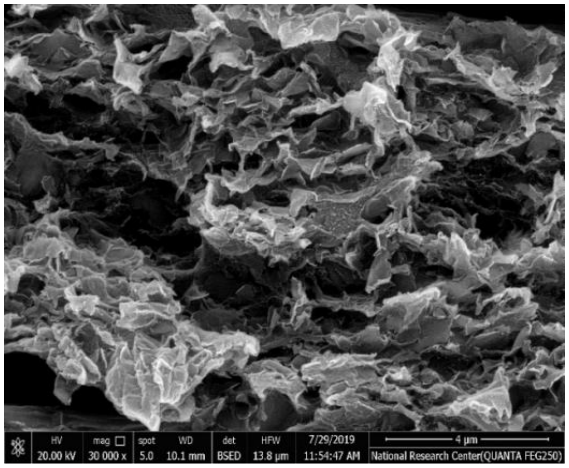
materials. Specifically, the dielectric response is a function of the inherent permittivity of each constituent, as well as the volume fraction, particle geometry, dispersion and interfacial effects. The effective-medium theory is one of the most popular methods used to describe the effective dielectric properties of heterogeneous materials . The Maxwell-Garnett model gives an approximation for the relationship between the permittivity of a continuous matrix and the permittivity of dispersed spherical inclusions [42,43].

4. Fabrication Methodology and Measurements

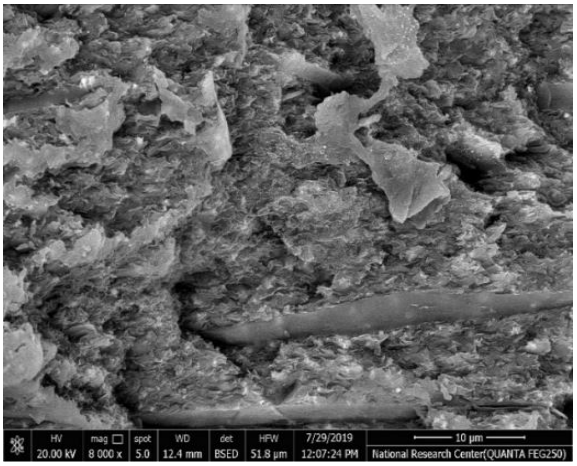
All nanoparticles chosen for this study are spherical in shape and have a diameter of 10nm for each grain size. They serve as catalysts, making them the optimal filler among base matrix industrial materials. Furthermore, Polyvinyl Chloride recognized as the most commonly utilized thermoplastic, exhibits greater strength and rigidity compared to other general-purpose thermoplastics and it possesses a significant tensile strength and elasticity modulus. Fabrication methodology is SOL-GEL technique that was utilized to create polyvinyl chloride nanocomposites by incorporating nanoparticles into industrial polymers; Dissolve PVC in tetrahydrofuran (THF). Add the organic or inorganic nanoparticles. Stir the mixture by using mixer and ultrasonic devices to allow hydrolysis and condensation, forming an organic or inorganic sol within the polymer solution. Cast the solution onto a substrate and allow the solvent to evaporate, promoting *in situ* gelation and film formation. Finally, dry the composite film to obtain a reinforced PVC nanocomposite [44-46]. The clay nanoparticles used in this work were montmorillonite (MMT). The clay mineral was selected as inorganic nanofiller to be incorporated into the polyvinyl chloride (PVC) matrix. Due to its surface-active nature, high specific surface area and layered structure, it is a potential reinforcement material for polymer nanocomposites. The clay nanoparticles were added to the PVC matrix at the concentration of 1 wt.% and 5 wt.% to study the effect of the clay nanoparticles on the capacitive charge under different temperature and frequency conditions. The nanocomposite films of clay/PVC were obtained by solution based fabrication procedure.

Scanning Electron Microscopy (SEM) is essential for analyzing the morphology and dispersion of inorganic nanoparticles within a polyvinyl chloride (PVC) matrix. Since PVC is non-conductive, samples must be sputter-coated with a thin gold or carbon layer to prevent charging and improve image quality. High-resolution SEM imaging reveals the size, distribution, and agglomeration state of nanofillers like silica or clay. It is particularly useful for examining fracture surfaces to assess nanoparticle-matrix adhesion and composite toughening mechanisms. PVC nanocomposites were prepared with two loadings of nanoparticles (1 and 5 wt.%) to study the effect of filler loading on the capacitive properties. To investigate the effect of increasing the amount of inorganic nanofillers in the PVC matrix, 1 wt. % concentration was chosen to represent relatively low nanoparticle content and 5 wt. % concentration was used as a higher-loading condition. This concentration range allows for a comparative analysis of the effects of nanoparticle loading on clay, SiO2, ZnO and TiO2 under identical measurement conditions. Thus, the choice of 5 wt.% was to provide a higher-concentration comparison to the 1 wt.% samples, not to assume that this concentration is the optimum value for each nanoparticle system. The electrical response was studied as a function of temperature and frequency to assess the effect of nanoparticle composition and concentration on the measured capacitance. This direct visualization is critical for correlating microstructure with the enhanced mechanical, thermal, or barrier properties of the PVC nanocomposite. So that, the Scanning Electron Microscope (SEM) images presented in Fig. (**1**) demonstrate the penetration of nanoparticles that are uniformly dispersed in the polymer matrix of polyvinyl chloride, illustrating a flaky morphology with a significant surface area. Measuring the capacitance of a system over a spectrum of frequencies, dielectric spectroscopy evaluates the dielectric characteristics of a medium as a function of frequency.

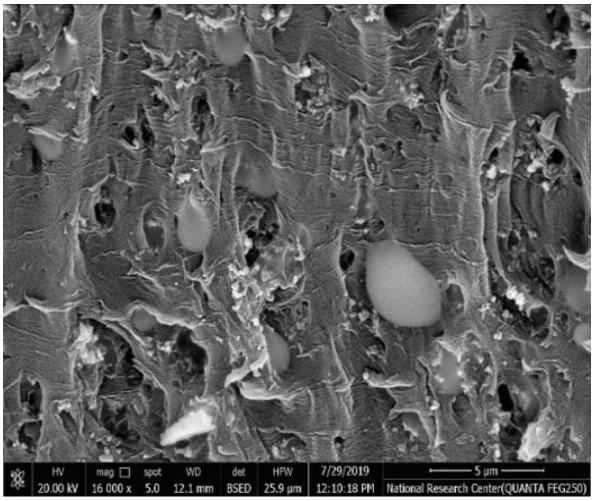
This study explores how nanoparticles influence capacitive polyvinyl chloride, with measurements taken across a frequency spectrum from 0.01 Hz to 1 MHz at various temperatures (20°C - 80°C). The Solartron analyzer is a premier instrument for high-precision capacitive characterization of dielectric materials. It operates as a Frequency Response Analyzer (FRA) to measure a sample's complex impedance across a wide AC frequency spectrum. The device directly calculates the complex permittivity, resolving both the dielectric constant (ε') and the loss factor (ε''). It is typically used with a temperature-controlled sample holder to study molecular relaxations and conductivity in polymers, composites, and insulators. This analysis is critical for research in energy storage, capacitors, and advanced functional materials. From this, it directly extracts



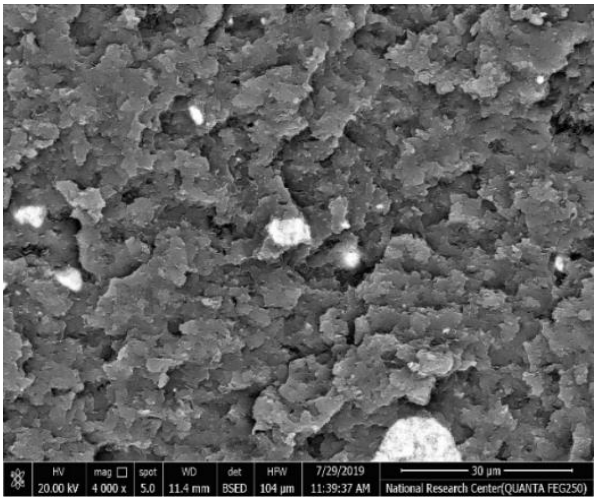
(**a**) Clay/ PVC nanocomposite



(**b**) SiO_2 / PVC nanocomposite



(**c**) ZnO /PVC nanocomposite



(**d**) TiO_2/ PVC nanocomposite

Figure 1: SEM images for polyvinyl chloride nanocomposites.

the frequency-dependent complex capacitance (C*), separating the real capacitance (C') from the loss-related imaginary component (C''). This enables detailed analysis of a material's charge storage efficiency, dielectric relaxation, and energy loss mechanisms. The data is essential for developing and optimizing capacitors, thin-film dielectrics, and energy storage devices. The SOLARTRON dielectric response method involves assessing the dielectric characteristics of a sample placed between two electrodes as a function of frequency. The dielectric constant was measured as a function of frequency ranging from 0.01 Hz to 1 MHz at different temperatures for all test samples. This measurement is essential for the expert characterization of nanocomposite materials under varying thermal conditions. Vibration testing was conducted in accordance with IEC68 (BS2011), and the device is designed to comply with IEC348 (BS4743). The experimental dielectric characterization in this work was carried out under controlled thermal conditions within the 20 °C to 80 °C range, in the frequency range of 0.01 Hz–1 MHz. The frequency range was selected to study the capacitive response and frequency dependent dielectric characteristics of the prepared PVC nanocomposites. The measurements were used to determine the effect of temperature, filler concentration and type of nanoparticle on the measured capacitive charge. It should be mentioned that the present experimental study does not include measurements at gigahertz or microwave frequencies. Therefore the results cannot be taken as direct evidence of microwave resonances, engineered metamaterial response or effective electromagnetic parameters at gigahertz frequencies. For such investigations, dedicated microwave measurement systems and additional electromagnetic

characterization are necessary. Also, the electrical characterization performed in this study is intended to evaluate the dielectric and capacitive properties of PVC-based nanocomposites, and not their performance as semiconductor or transistor devices. The measurements were carried out using a two-electrode configuration to determine the frequency dependent capacitance and dielectric response of the prepared specimens. Carrier mobility and ON/OFF current ratio (I_{ON}/I_{OFF}) have not been determined experimentally accordingly. Carrier mobility requires the characterization of charge transport through a suitable semiconductor channel, and the ON/OFF current ratio requires a gate-controlled switching configuration such as a field-effect transistor. Since the present experimental design does not contain source, drain and gate electrodes or transistor transfer characteristics, these parameters cannot be reliably extracted from the dielectric measurements. The electrical performance is thus evaluated in terms of capacitive charge storage and dielectric response within the investigated frequency and temperature conditions.

5. RESULTS AND DISCUSSION

The integration of energy storage technologies, like super capacitors, batteries, and advanced super batteries, supports the effective capture and conversion of renewable energy sources into usable power. This capability is critical for enhancing the efficiency and reliability of energy systems that depend on intermittent renewable resources. Dielectric Spectroscopy is an effective experimental approach used to explore the dynamic characteristics of a sample through the assessment of its frequency-dependent dielectric response. As a result, it has been utilized with two parallel plates to compress nanocomposite specimens, ensuring a consistent distribution of electric fields. This technique is founded on the measurement of capacitance as a function of the frequency of a sample situated between two electrodes. Capacitance (C) was evaluated over a frequency spectrum ranging from 10^{-2}Hz to 10^{6}Hz at various temperatures for all tested samples. Capacitive charge measurements have been performed on polyvinyl chloride nanocomposite materials under varying thermal environmental conditions. The incorporation of different nanoparticles into the PVC matrix alters its charge storage behavior as evidenced from the measured capacitive response. It is found that the dielectric response depends on the type and concentration of the incorporated nanoparticles and the measurement temperature and frequency as shown in the variations of the clay/PVC, SiO2/PVC, ZnO/PVC and TiO2/PVC specimens. Such variations are important for the development of polymer-based dielectric materials for capacitor components, cable insulation, and flexible electronic systems, where capacitance, dielectric loss, and operational stability are important criteria for selection. In particular, frequency and temperature dependent measurements are essential to determine the conditions under which the capacitive response changes, providing valuable information to assess the suitability of each formulation for a specific application. The present measurements, however, do not determine directly the dielectric breakdown strength, the maximum allowable operating voltage or the quality of signal transmission. These performance characteristics would have to be verified by additional electrical strength and application-specific testing.

The frequency-dependent capacitive response observed in the investigated PVC nanocomposites can be attributed to different polarization and charge-transport mechanisms taking place at the nanoparticle–polymer interfaces and in the polymer matrix. The measured dielectric response is strongly affected by interfacial polarization and space-charge accumulation at rather low frequencies. With increasing frequency these mechanisms become less and less efficient since the accumulated charges and molecular dipoles are not able to follow the rapidly alternating electric field. This behavior is responsible for the reduction of the capacitive charge observed at higher measurement frequencies. The introduction of inorganic nanoparticles changes the distribution of dielectric interfaces, and consequently the polarization processes in the PVC matrix. Thus, the magnitude of the capacitive response depends on the thermal conditions, concentration, dispersion and composition of the nanoparticles. Temperature also affects the mobility of molecules and charge transport which in turn causes variations in the measured capacitance. However, the frequency-dependent trends found in this study are limited to the experimentally explored range of 0.01 Hz to 1 MHz and should not be directly extrapolated to gigahertz frequencies where other electromagnetic effects could become important. The electrical performance parameters discussed in this section are to be understood considering the dielectric characterization approach used in this work. The measured capacitance shows the capability of the PVC-based nanocomposites to respond to an applied alternating electric field and store the electrical energy under different frequency and temperature conditions.

Dielectric polarization and interfacial effects, nanoparticle dispersion, and charge accumulation in the composite structure control this response. However, the measured capacitive response cannot be understood as a direct measurement of carrier mobility or transistor switching performance. In particular, the I_{ON}/I_{OFF} ratio is relevant to current modulation in semiconductor switching devices and cannot be accessed with the two-electrode dielectric measurement configuration used here.

5.1. Capacitive Charge Characterization for Pure PVC Materials

The performance of PVC in electrical applications is contingent upon its chemical structure and design, as well as the level of molecular alignment. Charge storage within the electrodes can happen in both surface and solid phases, using mechanisms like double layer charging, faradaic reactions, or a blend of these approaches. Figure (**2**) presents the capacitive charge of pure polyvinyl chloride samples measured against frequency at different temperatures (up to 80°C). The results indicate that the capacitive charge increases with higher environmental temperatures (20°C - 80°C), but conversely, it decreases as power frequencies rise, notably at high frequencies.

5.2. Effect of Clay Nanoparticles on PVC Capacitive Charge Characterization

The addition of clay minerals to polyvinyl chloride not only improves the material's functional characteristics but also promotes sustainability due to the natural prevalence and low ecological impact of these clays. As research continues to explore the full potential of clay-reinforced composites, their utilization in diverse sectors is projected to grow, creating opportunities for innovative progress in material engineering. Thus, Fig. (**3**) presents a decline in the capacitive charge of 1wt. % clay/PVC nanocomposites when compared to pure polyvinyl chloride specimens; on the other hand, the measured capacitive charge grows with rising environmental temperatures (20°C-80°C). There are comparable results at different temperatures (20°C-40°C), and a decrease in capacitive charge is evident with increasing power frequencies, particularly at high frequencies. In contrast, Fig. (**4**) illustrates the relationship between increasing capacitance and the percentage of clay nanofillers in the nanocomposites, as compared to the 1 wt.% clay/PVC nanocomposite samples. Consequently, the capacitive charge results for the 5 wt.% clay/PVC are similar at different temperatures (20°C - 40°C) when compared to the 1 wt.% clay/PVC nanocomposites as a function of frequency.

5.3. Effect of SiO2 Nanoparticles on PVC Capacitive Charge Characterization

In modern industrial settings, the enhancement of electric and electronic insulation materials has been notably achieved by integrating chemically modified silica nanoparticles (silicon dioxide, SiO2) into Polyvinyl Chloride (PVC). PVC stands out as one of the most

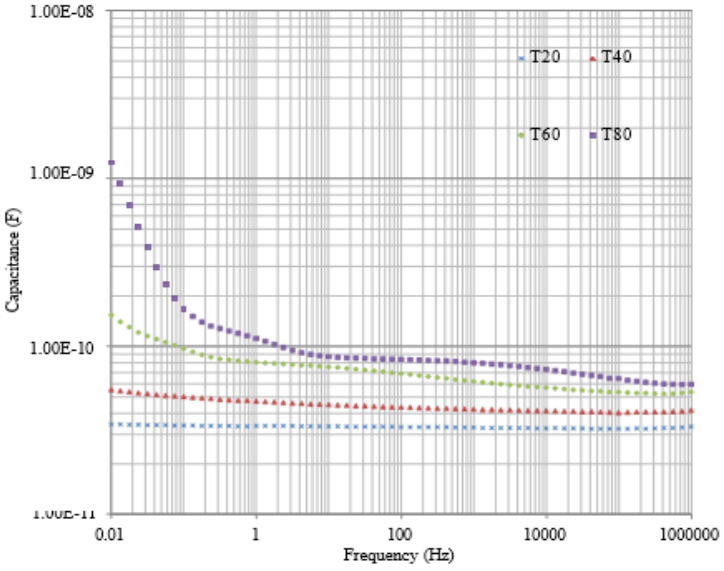


Figure 2: Measured capacitive charge of pure polyvinyl chloride.

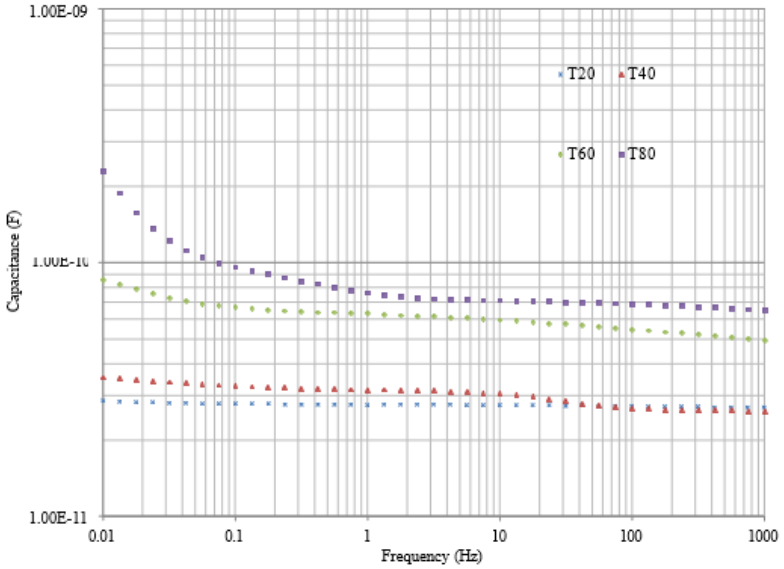


Figure 3: Measured capacitive charge of 1wt. % clay/PVC nanocomposites.

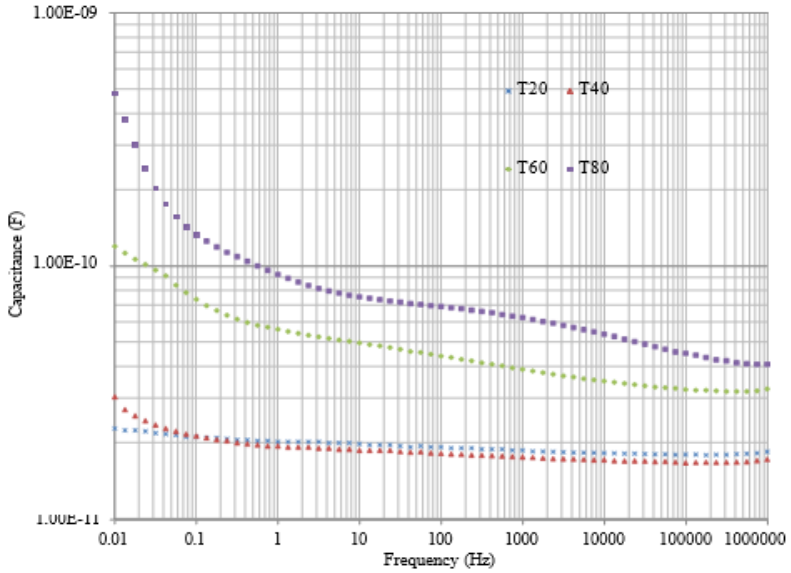


Figure 4: Measured capacitive charge of 5wt. % clay/PVC nanocomposites.

widely used insulation materials in the industry, and the inclusion of these nanoparticles improves the dielectric and mechanical characteristics of the end product. Figures (**5, 6**) demonstrate a decrease in the capacitive charge of SiO2/PVC nanocomposites across the concentration spectrum (1wt.%:5wt.%) of fumed silica nanoparticles in comparison to pure polyvinyl chloride samples; conversely, the measured capacitive charge escalates with higher environmental temperatures (20°C-80°C). Moreover, the experimental results highlight a divergence in outcomes at varying temperatures (20°C-40°C), particularly at high power frequencies.

5.4. Effect of ZnO Nanoparticles on PVC Capacitive Charge Characterization

The distinctive characteristics of nano-ZnO render it a compelling additive for enhancing the performance of PVC materials. Utilizing its minute size and extensive surface area, nano-ZnO can greatly affect the physical properties of PVC, resulting in improvements in its overall functionality. Additionally, the quantum effects linked to these nanoparticles play a significant role in their ability to enhance the properties of the material. Figures (**7, 8**) depict the measured capacitive charge of 1wt.% ZnO/ PVC contrasts, demonstrating a decline in

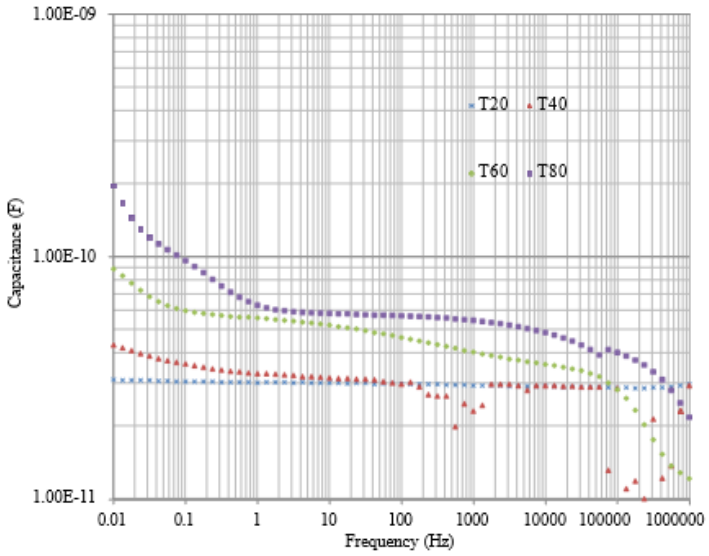


Figure 5: Measured capacitive charge of 1wt. % SiO_2/PVC nanocomposites.

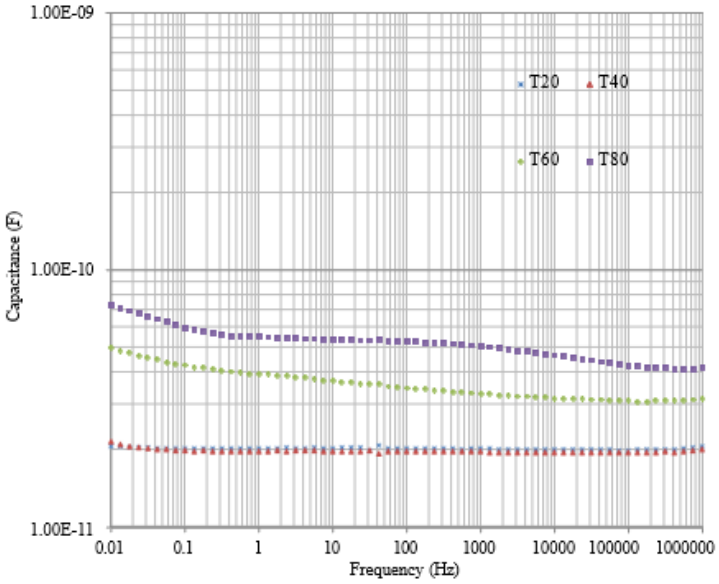


Figure 6: Measured capacitive charge of 5wt. % SiO_2/PVC nanocomposites.

capacitive charge relative to pure polyvinyl chloride specimens; nonetheless, the measured capacitive charge enhances with rising environmental temperatures (20°C-80°C). The experimental outcomes reveal a discrepancy between results at varying temperatures (20°C-40°C), especially at high power frequencies. Consequently, nano-ZnO/PVC nanocomposites are poised for widespread application across multiple industries, such as coatings, rubber goods, plastics, and fibers. The distinctive composition of the polyvinyl chloride/zinc oxide nanocomposite (PVC/ZnO), along with its functional characteristics, makes it a flexible material ideal for a variety of uses.

5.5. Effect of TiO2 Nanoparticles on PVC Capacitive Charge Characterization

The core of modern technology is established on metal and carbon-based nanofillers, which are acknowledged for their exceptional properties and potential applications in various fields, including energy storage, optoelectronics, and biomedical uses. Therefore, Fig. (**9**) depicts the decline in the capacitive charge of 1wt. % TiO_2/PVC nanocomposites in relation to pure polyvinyl chloride specimens; nonetheless, the measured capacitive charge grows with rising environmental temperatures (20°C-80°C). There are

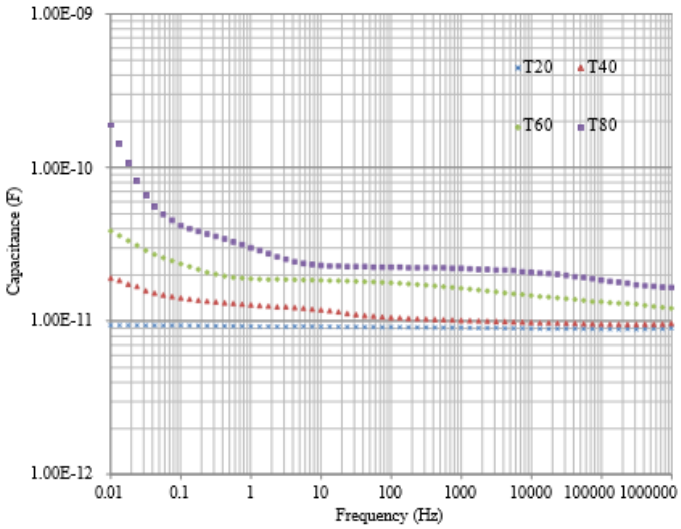


Figure 7: Measured capacitive charge of 1wt. % ZnO/PVC nanocomposites.

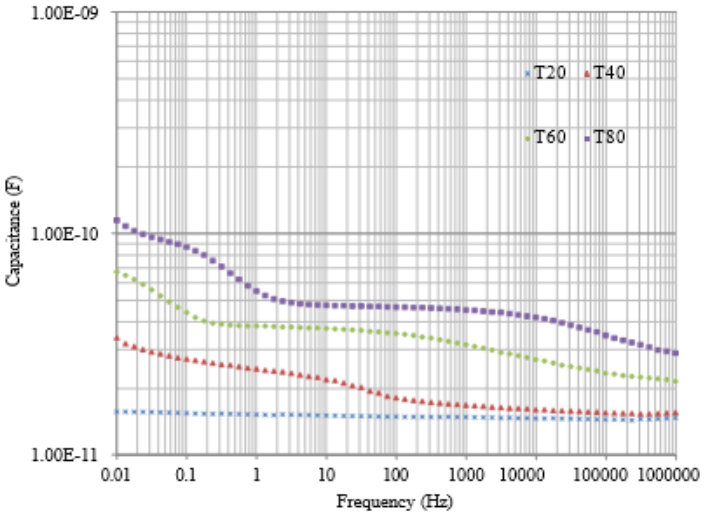


Figure 8: Measured capacitive charge of 5wt.%ZnO/PVC nanocomposites.

semi-matching results were found at variant temperatures (20°C-40°C). Regardless, there is a reduction in capacitive charge as power frequencies increase, particularly at high frequencies. In contrast, Fig. (**10**) shows the capacitance of 5wt.% TiO_2/PVC nanocomposites, which increases with a higher concentration of titanium dioxide nanoparticles in polyvinyl chloride nanocomposites compared to the 1wt.%TiO_2/PVC nanocomposite samples. This study examines the effects of integrating pure titanium oxide nanoparticles (TiO2 NPs), produced via the sol-gel technique, into polyvinyl chloride (PVC). The properties of TiO_2 nanoparticles, especially their nonstructural features such as size, shape, and surface area, are crucial in influencing the capacitive charge control of PVC. Additionally, the enhanced segmental mobility of the polymer chains greatly impacts the overall effectiveness of the blend. The interplay of these elements leads to a more conductive material, rendering the TiO_2-infused PVC blend appropriate for a range of applications that demand improved electrical characteristics.

6. EXPERIMENTAL SIGNIFICANT AND VALIDATION

6.1. Optimal Nanoparticles for Capacitive Charges

Among the candidates of Clay, SiO_2, ZnO, and TiO_2, the titanium dioxide (TiO_2) stands as the optimal nanoparticle for enhancing the capacitive charge of polyvinyl chloride (PVC). While montmorillonite clay can improve mechanical and barrier properties, its

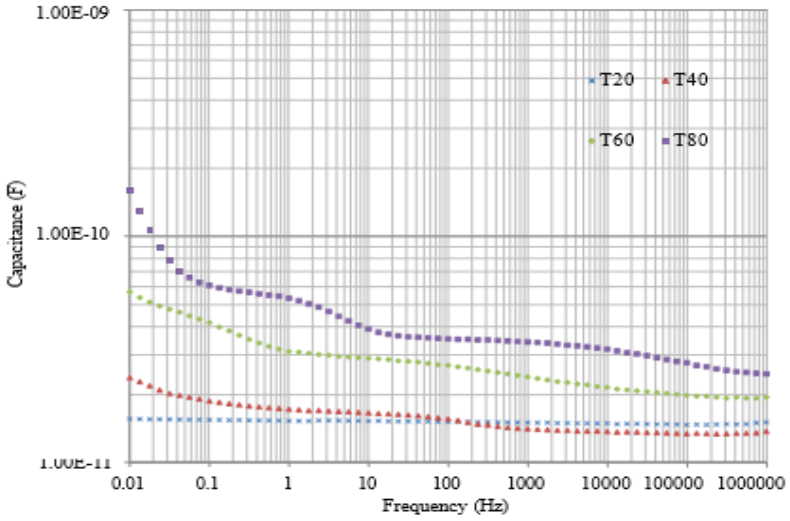


Figure 9: Measured capacitive charge of 1wt. % TiO_2/PVC nanocomposites.

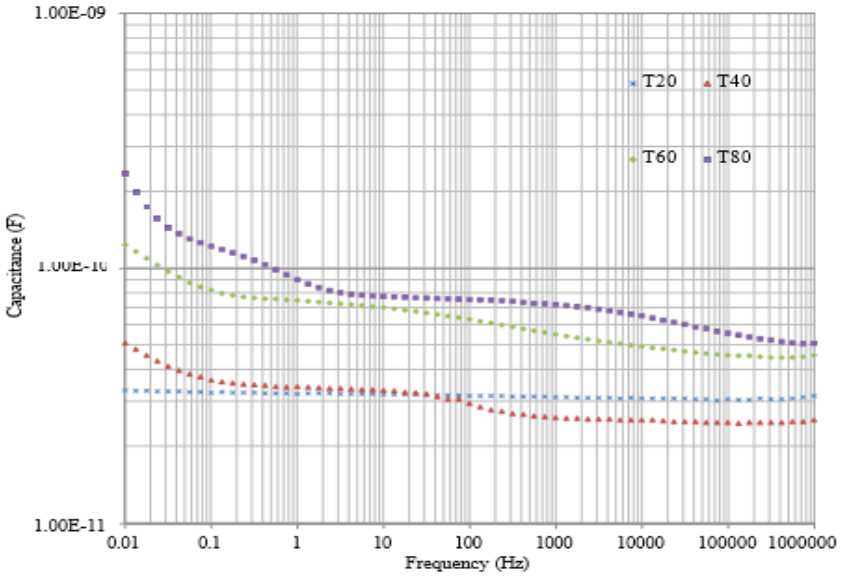


Figure 10: Measured capacitive charge of 5wt. % TiO_2/PVC nanocomposites.

layered structure and moderate permittivity offer only a modest boost to dielectric constant, often insufficient for significant charge storage. Silica (SiO_2), with its very low dielectric constant and primary role as a mechanical reinforcer, provides negligible direct improvement to PVC's capacitance. Zinc oxide (ZnO) is a stronger contender due to its higher intrinsic dielectric constant and useful piezoelectric properties, but its performance is often limited by aggregation and a narrower bandgap compared to TiO_2. On the other hand, TiO_2 nanoparticles, particularly in the anatase crystalline phase, are superior due to their high dielectric constant, excellent electronic polarizability, and favorable wide bandgap, which helps maintain high electrical resistivity and low loss. Their surface chemistry allows for effective functionalization (e.g., with silanes), promoting superior dispersion within the PVC matrix to maximize interfacial polarization area without creating conductive pathways. This results in a composite with a significantly increased effective dielectric constant, directly translating to higher capacitive charge density. Furthermore, TiO_2's UV-stabilizing properties synergistically benefit PVC's durability in electronic applications. For a balance of dielectric enhancement, processability, and stability, surface-modified TiO_2 nanoparticles present the most effective and direct solution for capacitive PVC nanocomposites within this group.

Regarding the measurements mentioned above, the effect of clay nanoparticles is evident, as the observed capacitive charge decreases when the concentration of clay nanoparticles is increased to 1wt.% compared to pure polyvinyl chloride samples. In contrast, in clay/PVC nanocomposites, the measured capacitive charge increases with a higher concentration of clay nanoparticles, reaching up to 5 wt.% when compared to samples with 1 wt.% clay/PVC nanocomposites. Additionally, there is a reduction in the capacitive charge of SiO_2/PVC nanocomposites as the concentration of fumed silica varies (up to 5wt.%). A divergence has been observed in the results at different temperatures (up to 40°C), particularly at high power frequencies. Zinc oxide nanoparticles significantly influence polyvinyl chloride, as indicated by the data presented above. Specifically, the capacitive charge diminishes with an increase in zinc oxide nanoparticles up to 5wt.%. The characterization of titanium dioxide nanoparticles has been highlighted in the previously mentioned results, indicating that titanium dioxide is the most effective nanoparticle at a concentration of (1wt.%) for enhancing the capacitive charge in polyvinyl chloride nanocomposites at elevated temperatures (80°C). Table **1** shows a comparative result for maximum capacitive charge of polyvinyl chloride nanocomposites under variant thermal conditions. Nowadays, it has been investigated on Recent Advances of electric, dielectric and optical light characterization for modern cost-fewer polyvinyl chloride nanocomposites thin films and SR/MWCNTs nanostructures with distinct design patterns of polymeric nanocomposites for nanoelectronic applications and piezoelectric sensors under thermal Conditions [47-51].

Table 1: Max. Capacitive Charge for Polyvinyl Chloride Nanocomposites

	Materials	**Temperature (°C)**	**Max. Capacitive Charge (pF)**		
	PURE PVC	20	34.3		
		40	54.1		
		60	139		
		80	124		
Materials	**Temperature (°C)**	**Max. Capacitive Charge (pF)**	**Materials**	**Temperature (°C)**	**Max. Capacitive Charge (pF)**
1wt.% Clay/PVC	20	28.5	**1wt.% ZnO/PVC**	20	9.20
	40	35.2		40	18.1
	60	35		60	35.4
	80	228		80	187
5wt.% Clay/PVC	20	22.8	**5wt.% ZnO/PVC**	20	15.5
	40	30.4		40	31.5
	60	111		60	63.9
	80	478		80	106
1wt.% SiO_2/PVC	20	30.7	**1wt.% TiO_2/PVC**	20	15.6
	40	41.9		40	22.8
	60	82.8		60	53.5
	80	194		80	159
5wt.% SiO_2/PVC	20	20.6	**5wt.% TiO_2/PVC**	20	33.0
	40	20.9		40	47.8
	60	49.8		60	116
	80	73.0		80	233

6.2. Comparative Effect of Different Nanoparticles on the Capacitive Characteristics of PVC

The effect of the type and concentration of the nanoparticle on the capacitive properties of PVC was studied by comparing pure PVC with clay/PVC, SiO2/PVC, ZnO/PVC and TiO2/PVC nanocomposites. The measurements were performed in the temperature range of 20-80 °C and nanoparticle concentrations of 1 wt.% and 5 wt.% in the frequency range 0.01 Hz-1 MHz. The capacitive response is affected by the type and concentration of the embedded nanoparticles, as well as by the measurement temperature and frequency (see Figures **2–10**). The response of clay/PVC nanocomposites measured at 1 wt.% clay is less than that of pure PVC. However, higher response than the 1 wt.% sample is observed at 5 wt.% clay. The measured response is generally smaller in the SiO2/PVC composites than in pure PVC, with variations between the two nanoparticle concentrations. The ZnO/PVC composites also show lower measured values compared to pure PVC at the experimental conditions reported. In contrast, the TiO 2 /PVC results show a concentration dependent response, where the 5 wt.% composite shows a higher capacitance than the 1 wt.% composite. The temperature-dependent measurements also demonstrate that the measured capacitive response generally increases with the increase in temperature from 20 to 80 °C. Conversely, the measured response decreases with the increase of frequency, especially at higher frequencies. These observations indicate that the electrical behavior of PVC nanocomposites cannot be evaluated only based on nanoparticle composition but filler concentration, temperature and frequency must also be considered. Overall, the comparison results show that the capacitive behavior of PVC is differently affected by clay, SiO2, ZnO and TiO2, which highlights the significance of the choice of the type and amount of nanoparticle for a specific dielectric application.

7. CONCLUSIONS

The capacity of polyvinyl chloride (PVC) to store charge in a capacitor is a fundamental functional property which extends the range of its potential uses beyond the conventional electrical insulation applications. The dielectric response of the material is relevant for the development of polymer-based capacitors, cable insulation systems and flexible electronic components. The performance and electrical energy storage of the material is influenced by capacitance, relative permittivity and dielectric loss in the presence of an applied electric field. The capacitance of a PVC-based dielectric is particularly dependent on its effective relative permittivity, electrode area and dielectric thickness. The incorporation of nanoparticles into the PVC matrix allows the modification of these characteristics and the control of the capacitive response by tuning the type and concentration of filler. The results of the present experiment show that the capacitive responses of clay, SiO2, ZnO and TiO2 nanoparticles are different in the frequency and temperature ranges considered. The results provide a basis for selection and optimization of PVC nanocomposite formulations for prospective energy-storage and dielectric applications. In this work, the capacitance behavior of PVC nanocomposites with clay, SiO2, ZnO, and TiO2 nanoparticles at different concentrations and temperatures was studied. dielectric response is found to be dependent on the type of nanoparticles, filler concentration and temperature as observed from the measurements performed in the frequency range of 0.01 Hz to 1 MHz and at temperature of 20-80 °C. The highest measured capacitance of the specimens tested at 80 °C was 478 pF for the 5 wt.% clay/PVC specimen. The results also showed that the capacitance of all the fillers did not increase consistently with the increase in concentration of nanoparticles. The results of this study indicate that the selection of suitable nanoparticle compositions and operating temperatures is a key factor in the design of PVC-based dielectric materials for electrical applications. Titanium dioxide nanoparticles are activated to augment the capacitive charge in relation to pure polyvinyl chloride specimens; the ideal concentration of nanoparticles is 5wt.% for maximizing capacitive charge in polyvinyl chloride nanocomposites at different temperatures (up to 80°C). A significant capacitive charge is noted at elevated temperatures, attributed to the effects of nanoparticles embedded in the polyvinyl chloride structure. Low concentrations of fumed silica nanoparticles are observed to enhance the capacitive charge compared to pure polyvinyl chloride specimens; however, the measured capacitive charge significantly decreases in the nanocomposites as the concentration of fumed silica nanoparticles increases (up to 5wt.%). Furthermore, the divergence in capacitive charge has been noted at low temperatures, particularly at elevated power frequencies. Clay (Montmorillonite) nanoparticles are diminishing the capacitive charge in relation to pure polyvinyl chloride under ambient thermal conditions; nonetheless, the most effective clay nanoparticles for boosting capacitive charge in polyvinyl chloride nanocomposites

at high temperatures (80°C) have been determined. A closed capacitive charge effect is observed at lower temperatures, especially at high power frequencies. The presence of zinc oxide nanoparticles is leading to a more pronounced reduction in capacitive charge in the nanocomposites as the concentration of nanoparticles increases (5wt.%). Divergence in capacitive charge has been noted at lower temperatures, particularly at high power frequencies.

Future work might involve the extension of the electrical characterization of PVC-based nanocomposites to their use in semiconductor devices and charge-carrier transport. In this context carrier mobility could be studied by fabricating appropriate transport devices and measuring their current-voltage characteristics under controlled electrical conditions. Further studies could focus on the I_{ON}/I_{OFF} ratio by integrating selective nanocomposite materials in gate-controlled device structures like field-effect transistors. Such investigations would require electrode design, additional device fabrication and electrical characterization in addition to the dielectric spectroscopy approach used in this study. The present studies may provide further information about the possible applications of nanocomposites in advanced electronic devices and switching and charge transport behavior.

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HIGHLIGHTS

1. Achieving optimum physical properties for polyvinyl chloride nanocomposites.
2. Experiments have been conducted to control the capacitive charging in polyvinyl chloride nanocomposites.
3. Extrapolation of charging capacity of polyvinyl chloride has proved by controlling on types and concentrations of nanoparticles.
4. Industrial applications of polyvinyl chloride oriented via nanoparticles types and concentrations.

FUNDING AND/OR CONFLICTS OF INTERESTS/COMPETING INTERESTS

The authors declare that have no known financial or personal conflicts of interest that could have influenced the research reported in this manuscript, its authorship, or its publication.

AVAILABILITY OF DATA AND MATERIALS

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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