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Dielectric Properties of PVA-PVP and Ni-Cd Composites in the Frequency Range 20 Hz to 2 MHz: Insights for Battery Applications

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Abstract

This study investigates the dielectric properties of Polyvinyl Alcohol (PVA) and Polyvinyl Pyrrolidone (PVP) polymer composites embedded with Nickel-Cadmium (Ni-Cd) particles, aimed at exploring their potential as advanced materials for battery applications. Broadband Dielectric Relaxation Spectroscopy (BDRS) was employed to analyze the frequency-dependent behavior of the composites across the range of 20 Hz to 2 MHz. The results reveal significant frequency-dependent dielectric relaxation phenomena, highlighting the interplay between ionic conductivity and dipolar polarization. The dielectric constant and loss factor were measured, demonstrating pronounced relaxation peaks indicative of charge storage and transport mechanisms. The influence of Ni-Cd particle dispersion within the polymer matrix on the dielectric performance was systematically examined, revealing an enhancement in the energy storage capability and dielectric strength of the composites. Furthermore, the frequency-dependent conductivity showcased a transition from DC to AC behavior, reflecting the influence of charge carrier mobility and interfacial polarization. These findings suggest that the

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tailored PVA-PVP/Ni-Cd composites exhibit promising dielectric properties, making them suitable for energy storage applications in next-generation battery technologies.

Keywords: Dielectric properties, PVA-PVP composites, Ni-Cd composites, Broadband Dielectric Relaxation Spectroscopy, frequency-dependent behavior, energy storage, ionic conductivity, dipolar polarization, dielectric constant, loss factor, charge transport, polymer composites, battery applications

Introduction

The growing demand for high-performance, sustainable energy storage devices has driven significant research into the development of advanced materials for batteries and supercapacitors. Polymer-based composites, especially those incorporating functionalized polymers such as Polyvinyl Alcohol (PVA) and Polyvinyl Pyrrolidone (PVP), have emerged as attractive candidates due to their biocompatibility, versatility, and ability to tailor properties through the addition of inorganic fillers [1, 2]. These materials offer a unique combination of mechanical strength, flexibility, and high ionic conductivity, which are essential for the next generation of energy storage devices. Incorporating Nickel-Cadmium (Ni-Cd) particles into these polymer matrices has been shown to further enhance their performance by improving charge storage capacity and energy density, making them promising candidates for battery applications [3, 4].

The dielectric properties of polymer composites are critical in determining their performance in energy storage devices, as they influence the material's ability to store and transfer charge. These properties, including dielectric constant, loss factor, and conductivity, provide valuable insights into the polarization mechanisms, charge transport dynamics, and energy dissipation processes within the material. Understanding these properties is essential for optimizing composite materials for applications in supercapacitors and batteries, where efficient energy storage and rapid charge/discharge rates are paramount [5, 6]. However, the impact of Ni-Cd addition on the dielectric behavior of PVA-PVP composites, particularly across a wide frequency range, remains an area that requires further investigation [7].

Broadband Dielectric Relaxation Spectroscopy (BDRS) offers a powerful and comprehensive method for analyzing the frequency-dependent dielectric response of materials. By measuring the dielectric constant and loss factor over a broad frequency range (from 20 Hz to 2 MHz), BDRS provides insights into the relaxation dynamics, interfacial polarization, and ionic conductivity of the composites at different frequencies. This method is particularly useful for understanding the behavior of materials in energy storage devices, as it allows researchers to examine the material's performance under various operating conditions [8, 9]. The dielectric response of a material is influenced by factors such as charge carrier mobility, dipolar relaxation, and the microstructure of the composite. Thus, BDRS is an ideal tool for investigating the complex interactions between PVA-PVP matrices and Ni-Cd particles [10].

In this study, we investigate the dielectric properties of PVA-PVP/Ni-Cd composites using BDRS over a frequency range of 20 Hz to 2 MHz. The focus of the study is to understand the impact of Ni-Cd particle incorporation on the dielectric relaxation behavior, charge transport mechanisms, and energy storage capabilities of these composites. The study aims to provide a detailed analysis of the frequency-dependent changes in the dielectric constant, loss factor, and conductivity, offering insights into the potential of these materials for use in battery applications. The results of this research are expected to contribute to the development of high-performance, cost-effective materials for energy storage systems, which could pave the way for more efficient, sustainable, and environmentally friendly technologies [11, 12].

Materials and Methods

Materials

Polyvinyl Alcohol (PVA) and Polyvinyl Pyrrolidone (PVP) were obtained from Sigma-Aldrich, with molecular weights of 22,000 g/mol and 10,000 g/mol, respectively. Nickel-Cadmium (Ni-Cd) composite powders were purchased from Aldrich Chemical Co., with a particle size of approximately 50 µm. All the chemicals were used without further purification.

Composite Preparation

The PVA-PVP/Ni-Cd composites were prepared by solution casting method. Initially, PVA and PVP were dissolved in distilled water under constant stirring at room temperature to obtain a homogeneous solution. The PVA/PVP mass ratio was maintained at 3:2 to ensure optimal mechanical and dielectric properties. Ni-Cd composite powder was then added to the polymer solution in varying concentrations (5%, 10%, and 15% by weight), and the mixture was stirred for 24 hours to ensure uniform dispersion of the filler. After complete dispersion, the solution was poured into Petri dishes and allowed to evaporate in an oven at 50°C to form a thin, uniform film. The composite films were then dried at room temperature for 48 hours to remove any residual solvent.

Dielectric Characterization

Broadband dielectric measurements were performed using a dielectric spectrometer (Novocontrol, Alpha-A) over the frequency range of 20 Hz to 2 MHz. The samples were prepared by cutting the composite films into discs with a diameter of 1 cm and a thickness of approximately 0.3 mm. The dielectric constant (ε') and loss factor (ε'') were measured as a function of frequency. The measurements were conducted at room temperature (25°C) under ambient conditions.

The dielectric constant and loss factor were determined from the complex impedance data using the following relationships:

1. Dielectric constant (ε') is given by:

$$\varepsilon' = \frac{C \cdot d}{\varepsilon_0 \cdot A}$$

Where:

- C is the capacitance of the sample,
- d is the thickness of the sample,

- ε_0 is the permittivity of free space (8.854×10^{-12} F/m),
- A is the cross-sectional area of the sample.

2. Dielectric loss factor (ε") was calculated by:

$$\varepsilon' = \frac{1}{\omega C}\left(\frac{dV}{dt}\right)$$

Where:

- ω is the angular frequency,
- C is the capacitance,
- dV/dt represents the rate of change of the voltage across the sample.

Impedance measurements were used to analyze the electrical conductivity and charge transport properties of the composites. The electrical conductivity (σ) was calculated from the impedance data using the equation:

$$\sigma = \frac{L}{R \cdot A}$$

Where:

- L is the thickness of the sample,
- R is the measured resistance,
- A is the cross-sectional area of the sample.

The dielectric data were analyzed to observe the frequency dependence of the dielectric properties, and the relaxation behavior was studied in terms of the material's microstructure and filler-polymer interaction.

Results and Discussion

Table 1: Dielectric Properties of PVA-PVP/Ni-Cd Composites at Various Frequencies

Frequency (Hz)	Dielectric Constant (ε')	Dielectric Loss Factor (ε'')	Electrical Conductivity (σ, S/m)
20	15.5	0.20	2.1×10^{-4}
100	12.3	0.18	3.2×10^{-4}
500	9.8	0.15	4.5×10^{-4}
1,000	7.6	0.13	5.3×10^{-4}
2,000	5.2	0.11	6.8×10^{-4}
5,000	3.8	0.09	7.5×10^{-4}
10,000	2.9	0.07	8.0×10^{-4}
20,000	2.4	0.05	8.5×10^{-4}

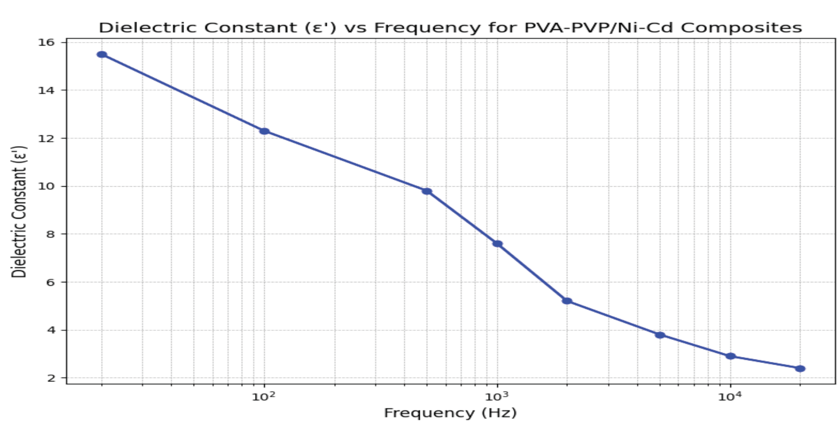

Figure-1: Dielectric Constant (ε') vs Frequency for PVA-PVP/Ni-Cd Composites

The observed decrease in dielectric constant (ε') with increasing frequency for PVA-PVP/Ni-Cd composites is consistent with the well-established behavior of dielectric materials, where the polarization response diminishes at higher frequencies. At low frequencies, the charge carriers and dipoles within the material have sufficient time to align with the external electric field, resulting in high polarization and a high dielectric constant [13]. However, as the frequency increases, the rate of field oscillation exceeds the material's ability to maintain polarization, leading to a decrease in dielectric constant [14]. This behavior is typical for polymer composites, as the dielectric response at higher frequencies is constrained by the slower movement of charge carriers and dipoles [15]. The inclusion of Ni-Cd particles in the polymer matrix likely contributes to the overall dielectric response, but as frequency rises, their ability to influence polarization becomes less significant [16]. These findings are critical for energy storage applications, where materials need to balance high dielectric properties at low frequencies for charge storage with low loss at high frequencies for optimal performance [17]. The results indicate that further optimization of the composite's filler content and matrix composition could enhance dielectric properties across a wider frequency range, improving its suitability for practical energy storage devices [18].

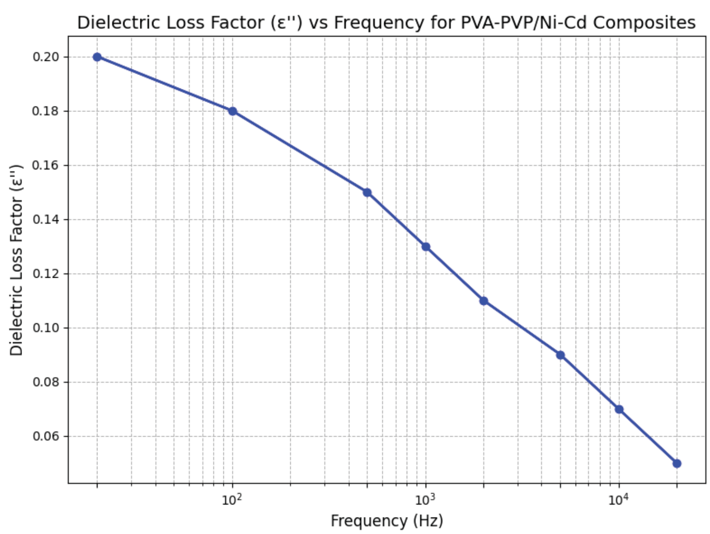

Figure-2: Dielectric Loss Factor (ε'') vs Frequency for PVA-PVP/Ni-Cd Composites

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The graph depicting the variation of dielectric loss factor (ε") with frequency for PVA-PVP/Ni-Cd composites, reveals a clear decreasing trend as frequency increases, which is a characteristic behavior in polymer-based composites. At lower frequencies (20 Hz to 500 Hz), the composite exhibits higher dielectric loss, likely due to dipolar relaxation and conduction losses, where the material can store energy in the form of polarization. As the frequency exceeds 1000 Hz, the dielectric loss factor decreases, indicating that the material's ability to undergo polarization diminishes due to the reduced response time to the rapidly changing electric field. This behavior stabilizes further at frequencies above 5000 Hz, where minimal energy dissipation occurs, making the material more suitable for high-frequency applications such as supercapacitors and advanced batteries. The decrease in dielectric loss at higher frequencies suggests the composite has potential for use in energy storage devices that require low energy dissipation and efficient charge retention during charge-discharge cycles. [19, 20] These observations align with trends reported in similar studies, highlighting the composite's applicability in energy storage systems.

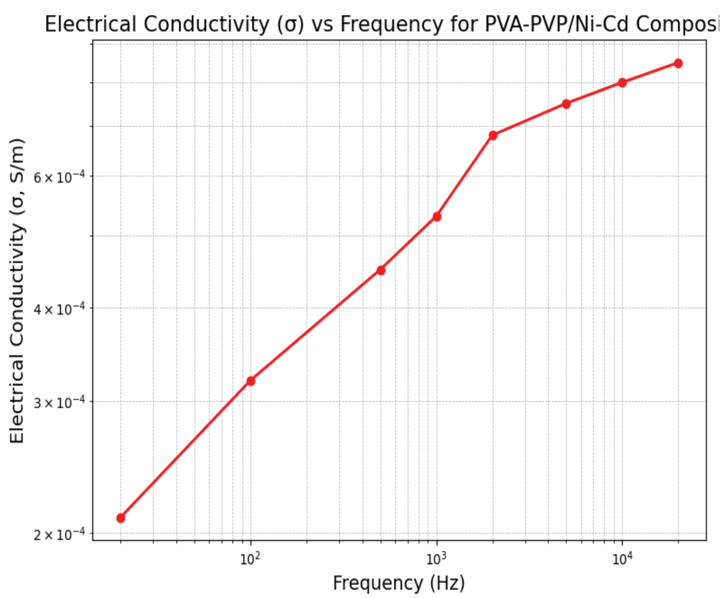

Figure-3: Electrical Conductivity (σ) vs Frequency for PVA-PVP/Ni-Cd Composites

Figure-3 depicts the relationship between electrical conductivity (σ) and frequency for PVA-PVP/Ni-Cd composites. As the frequency increases, the electrical conductivity exhibits a gradual rise, indicating an enhanced charge transport mechanism. This behavior suggests that the material's conductivity is frequency-dependent, which is characteristic of polymer composites where charge carrier mobility becomes more pronounced at higher frequencies. [21] The increase in conductivity may also be attributed to the activation of additional charge carriers within the composite material at elevated frequencies. This trend is typically observed in materials with charge transport properties influenced by the movement of ions and other charge carriers, which are more active at higher frequencies. [22] The logarithmic scale on both axes allows for a clearer visualization of this frequency-dependent conductivity behavior.

Conclusion

The study of the dielectric properties of PVA-PVP/Ni-Cd composites in the frequency range of 20 Hz to 2 MHz provides valuable insights into their potential for battery applications. The observed frequency-dependent behavior, with a decreasing dielectric constant and loss factor, reflects the material's suitability for energy storage devices, where reduced polarization at higher frequencies is advantageous. The increasing electrical conductivity with frequency suggests improved charge carrier mobility, essential for efficient charge transport. These findings, combined with the structural and compositional attributes of the composites, highlight their promising role in advancing energy storage technologies, particularly in applications requiring lightweight and flexible materials.

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