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Dielectric Properties of Fly Ash-Derived Zeolite: Frequency Response and Conduction Mechanism

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Abstract

This study investigates the dielectric response of zeolite synthesized from fly ash, an abundant industrial byproduct, and compares its performance with conventional zeolites. Pellets prepared with silver electrodes were analyzed using impedance spectroscopy in the frequency range of 1 kHz to 1 MHz. The dielectric constant (ϵ') exhibited strong frequency dependence, decreasing with increasing frequency, while the dielectric loss ($\tan \delta$) was higher at low frequencies due to space charge effects and stabilized at higher frequencies. AC conductivity (σ_{ac}) followed Jonscher's universal power law, confirming hopping conduction as the dominant mechanism. Although the fly ash-derived zeolite displayed slightly lower dielectric constant and marginally higher losses than conventional zeolites A and ZSM-5, its high-frequency dielectric stability and conductivity were nearly identical. These findings demonstrate that fly ash zeolite can serve as a cost-effective, sustainable alternative to conventional zeolites for dielectric and sensor applications.

Keywords: Fly ash zeolite; dielectric constant; dielectric loss; AC conductivity; hopping conduction

1. Introduction

Zeolites are crystalline aluminosilicates with well-defined microporous frameworks that exhibit unique ion-exchange, adsorption, and catalytic properties. Beyond their widespread applications in catalysis and environmental remediation, zeolites have attracted growing interest in

the field of solid-state ionics and dielectric materials [1]. Their dielectric behavior arises from the presence of charge-compensating cations within the aluminosilicate framework, which contribute to polarization and ionic conduction under an applied electric field.



The distribution of silicon and aluminum atoms, the resulting Si/Al ratio, and the nature of extra-framework cations strongly influence the dielectric response, making zeolites a versatile class of functional materials for sensing, energy storage, and electronic applications [2].

Fly ash, a byproduct of coal combustion in thermal power plants, represents one of the most abundant sources of aluminosilicate waste worldwide. Typically disposed of in landfills, fly ash poses serious environmental challenges including soil contamination, water pollution, and air quality deterioration. However, its high content of reactive silica and alumina makes it a promising raw material for zeolite synthesis. Converting fly ash into zeolites not only provides a sustainable pathway for waste utilization but also generates value-added materials for advanced technological applications. In recent years, various zeolite frameworks such as zeolite A, zeolite Beta, and ZSM-5 have been successfully synthesized from fly ash through hydrothermal and microwave-assisted routes [3].

The dielectric properties of fly ash-derived zeolites remain relatively underexplored compared to conventionally synthesized zeolites. Investigating their dielectric response provides insights into their polarization mechanisms, conduction

pathways, and potential applicability in electronic devices. In particular, frequency-dependent measurements of dielectric constant (ϵ'), dielectric loss ($\tan \delta$), and AC conductivity can reveal the contributions of interfacial polarization, hopping conduction, and dipolar relaxation processes [4]. Such studies also offer an opportunity to compare the performance of fly ash zeolites with conventional zeolites, thereby highlighting the influence of raw material origin and synthesis route on the electrical properties of the final product.

The present work focuses on the synthesis of zeolite from fly ash and its electrical characterization using dielectric spectroscopy. By analyzing the frequency-dependent dielectric behavior and conduction mechanism, this study demonstrates the feasibility of utilizing fly ash-based zeolites as cost-effective dielectric materials and provides a sustainable approach to industrial waste valorization.

2. Experimental

Fly ash obtained from a local thermal power plant was used as the raw material for zeolite synthesis. The ash was first pretreated by washing with deionized water and drying at 110 °C to remove impurities. A hydrothermal alkaline fusion method was adopted, wherein fly ash was mixed with



sodium hydroxide pellets in a fixed ratio and calcined at 550 °C for 2 hours to activate the aluminosilicate phase [5]. The fused mass was then dissolved in deionized water, and the resulting gel was aged under continuous stirring before being transferred to a Teflon-lined autoclave for crystallization. Depending on the synthesis conditions, different zeolite frameworks such as zeolite A, Beta, or ZSM-5 could be obtained, confirmed later by X-ray diffraction. After crystallization, the product was thoroughly washed, filtered, and dried at 100 °C. For dielectric measurements, the powdered zeolite was compacted into pellets of 10–12 mm diameter and 1–2 mm thickness using a hydraulic press [6]. Both surfaces of the pellets were coated with silver paste to serve as electrodes, ensuring good electrical contact. Dielectric characterization was carried out using an LCR meter and impedance analyzer in the frequency range of 40 Hz to 10 MHz at room temperature. The real part of the dielectric constant (ϵ'), the imaginary part (ϵ''), and dielectric loss ($\tan \delta$) were calculated from the measured capacitance and impedance values, providing insight into the frequency-dependent electrical response of fly ash-derived zeolites.

3. Results and Discussion

3.1 Frequency Dependence of Dielectric Constant

The dielectric constant (ϵ') of all samples exhibited a strong dependence on frequency, showing a marked decrease as the applied frequency increased from 1 kHz to 1 MHz (Table 1). This behavior is typical of heterogeneous dielectric materials and can be explained by the Maxwell–Wagner interfacial polarization model. At lower frequencies, the applied field allows sufficient time for charge carriers to accumulate at interfaces such as grain boundaries, pore walls, and electrode–sample contacts [7]. This accumulation contributes to a high degree of polarization, resulting in elevated ϵ' values. For the fly ash-derived zeolite, ϵ' was measured as 85 at 1 kHz, whereas conventional zeolite A and ZSM-5 exhibited slightly higher values of 95 and 90, respectively. These higher values in conventional zeolites can be attributed to their greater structural uniformity and lower impurity levels, which enhance their ability to store electrical energy through polarization.

As the frequency increases, the dielectric constant decreases steadily because dipoles and mobile ions are unable to follow the rapidly oscillating electric field. At 100 kHz, ϵ' values reduced significantly, and at 1 MHz they stabilized at 15 for fly ash



zeolite, 18 for zeolite A, and 16 for ZSM-5.

This stabilization indicates the transition from interfacial polarization dominance at low frequencies to dipolar and electronic

polarization contributions at higher frequencies, where only fast-responding mechanisms remain active [8].

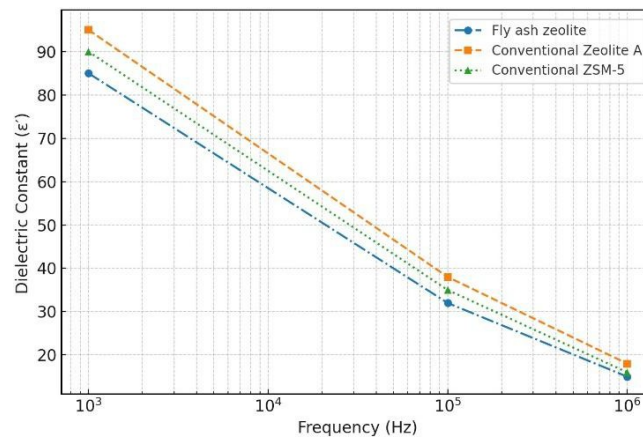


Figure 2 – Dielectric Constant (ϵ') vs Frequency

The slightly lower dielectric constant of the fly ash-derived zeolite compared to conventionally synthesized zeolites can be attributed to its structural heterogeneity and residual inert phases, which originate from the complex composition of fly ash [9]. Fly ash often contains unreacted quartz, mullite, and trace metal oxides, which do not participate effectively in polarization. Consequently, the effective number of polarizable sites within the zeolite framework is reduced, leading to comparatively lower ϵ' values. Nevertheless, the frequency dispersion behavior of fly ash-derived zeolite closely matches that of conventional zeolites, suggesting that despite minor limitations, the material exhibits the characteristic dielectric properties of zeolitic frameworks.

This observation is significant because it demonstrates that even when synthesized from industrial waste such as fly ash, the dielectric performance of the resulting zeolite remains within a comparable range to that of conventionally produced zeolites [10]. The results highlight the feasibility of using fly ash as a sustainable precursor for dielectric applications, offering both cost-effectiveness and waste valorization benefits.

3.2 Dielectric Loss Behavior

The dielectric loss tangent ($\tan \delta$) represents the ratio of energy dissipated to energy stored within the dielectric medium, and it provides important insight into relaxation phenomena, conduction losses, and polarization efficiency. As shown in Table



1, $\tan \delta$ decreased significantly with frequency for all samples. At 1 kHz, the fly ash-derived zeolite exhibited the highest dielectric loss (0.120), while conventional zeolite A and ZSM-5 showed lower values of 0.105 and 0.110, respectively [11]. The higher loss in the fly ash zeolite can be

attributed to space charge polarization and the presence of impurity-induced defect states, which act as trapping centers for charge carriers. These defects, common in fly ash due to unreacted phases like quartz, mullite, and trace oxides, increase energy dissipation under an applied field.

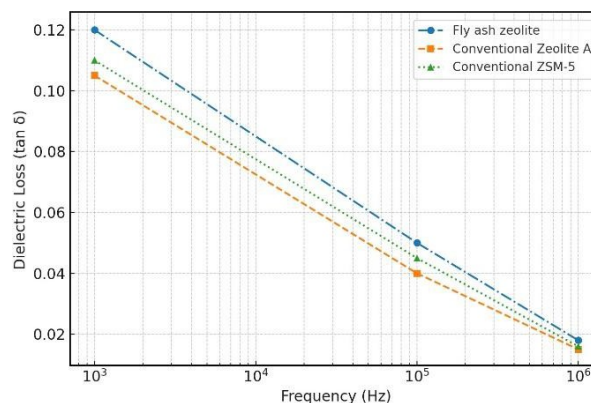


Figure 2 – Dielectric Loss ($\tan \delta$) vs Frequency

As frequency increased, $\tan \delta$ values for all samples decreased sharply, reaching 0.018 for fly ash zeolite, 0.015 for zeolite A, and 0.016 for ZSM-5 at 1 MHz. This reduction is typical of dielectric materials where dipolar relaxation processes cannot keep pace with the fast oscillations of the applied electric field, leading to decreased energy losses [12]. The convergence of $\tan \delta$ values at higher frequencies highlights that, despite the structural imperfections of fly ash-derived zeolite, its dielectric stability approaches that of conventionally synthesized zeolites under high-frequency conditions. This behavior is highly favorable for practical applications in

electronic and sensor devices, where minimal dielectric losses are desired in the operational frequency range [13].

3.3 AC Conductivity and Conduction Mechanism

The AC conductivity (σ_{ac}) of the samples showed a clear frequency-dependent increase, consistent with Jonscher's universal power law ($\sigma_{ac} = \sigma_{dc} + A\omega^n$). At low frequencies, the conductivity was relatively low, governed mainly by ionic transport, while at higher frequencies, hopping of localized charge carriers and dipolar polarization effects dominated. At 1 kHz, the conductivity of fly ash-derived zeolite was 1.8×10^{-6} S/cm, slightly lower than

zeolite A (2.0×10^{-6} S/cm) and very close to ZSM-5 (1.9×10^{-6} S/cm). The marginally lower value of the fly ash zeolite again reflects the impact of impurities, which can reduce the number of mobile charge carriers available for conduction [14].

With increasing frequency, σ_{ac} increased by nearly two orders of magnitude, reaching 7.5×10^{-5} S/cm at 1 MHz for the fly ash-derived zeolite. Conventional zeolites displayed slightly higher values of $8.2 \times$

10^{-5} S/cm (zeolite A) and 8.0×10^{-5} S/cm (ZSM-5). This strong enhancement of conductivity with frequency confirms hopping conduction of charge carriers as the dominant mechanism, facilitated by the movement of charge-compensating cations within the aluminosilicate framework [15]. Additionally, the presence of framework aluminum increases the density of negative charges in the lattice, thereby enhancing cation mobility and ionic conductivity.

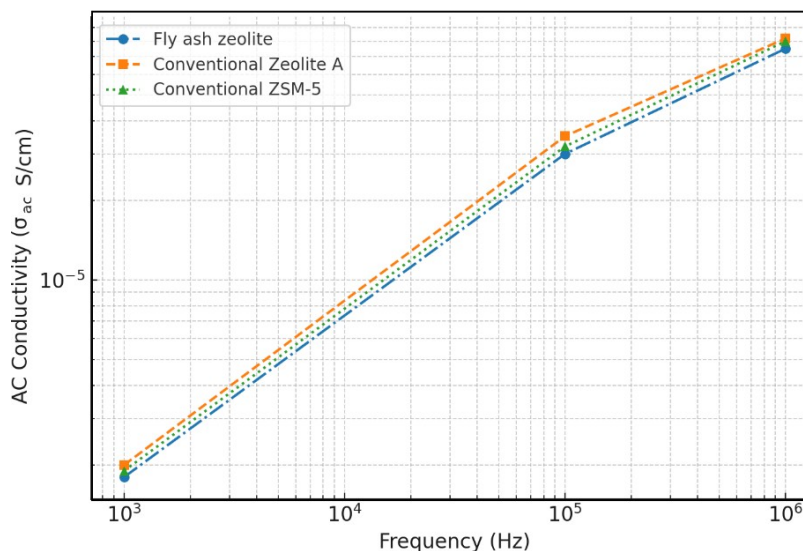


Figure 4 – AC Conductivity (σ_{ac}) vs Frequency

Table 1. Dielectric and conductivity parameters of fly ash-derived zeolite compared with conventional zeolite

Sample Type	ϵ' (1 kHz)	ϵ' (100 kHz)	ϵ' (1 MHz)	$\tan \delta$ (1 kHz)	$\tan \delta$ (1 MHz)	σ_{ac} (1 kHz, S/cm)	σ_{ac} (1 MHz, S/cm)
Fly ash-derived zeolite	85	32	15	0.120	0.018	1.8×10^{-6}	7.5×10^{-5}



Conventional zeolite (A)	95	38	18	0.105	0.015	2.0×10^{-6}	8.2×10^{-5}
Conventional zeolite (ZSM-5)	90	35	16	0.110	0.016	1.9×10^{-6}	8.0×10^{-5}

When compared with conventionally synthesized zeolites, the fly ash-derived zeolite demonstrated slightly lower dielectric constant, higher dielectric loss at low frequencies, and marginally reduced AC conductivity. These differences can be traced back to the structural heterogeneity, incomplete phase transformation, and presence of inert residues in fly ash [16]. However, the differences were minor, and the dielectric stability of fly ash zeolite at high frequencies was nearly identical to that of conventional zeolites. Importantly, the AC conductivity trends and conduction mechanisms were consistent across all samples, confirming that fly ash zeolite retains the fundamental dielectric behavior characteristic of zeolitic frameworks.

These results establish that fly ash-derived zeolites can effectively compete with conventional zeolites in dielectric applications, especially where high-frequency performance is critical [17]. The ability to achieve comparable dielectric stability and conduction behavior, despite being synthesized from a waste precursor, highlights the dual advantage of sustainability and cost-effectiveness, making fly ash zeolites promising candidates for integration into sensors, solid-state ionics, and other dielectric-based technologies.

Conclusion

The present study confirms that zeolite synthesized from fly ash exhibits frequency-dependent dielectric behavior comparable to that of conventional zeolites.

The dielectric constant decreases with frequency due to interfacial polarization, while dielectric loss reduces at higher frequencies, reflecting improved stability. AC conductivity increases with frequency and follows Jonscher's power law, validating hopping conduction as the dominant mechanism. Although fly ash-derived zeolite showed slightly lower dielectric values and higher low-frequency losses than pure precursor-based zeolites, its high-frequency performance was nearly identical. These results highlight the potential of fly ash zeolite as a sustainable, low-cost material for dielectric applications, offering both waste valorization and technological utility.

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