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Effect of Alumina Reinforcement on the Physical and Electrical Properties of Kaolin-Glass Ceramic Insulators

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Abstract

This work provides a comprehensive investigation into the influence of alumina (Al_2O_3) reinforcement on kaolin–glass ceramic composites, focusing on their physical and electrical properties. A series of samples with fixed kaolin–glass ratios (50:50) and varying alumina contents (0–20 wt%) were sintered at 900, 1000, and 1100 °C. The results revealed that the addition of alumina significantly enhanced densification and dielectric behavior, with 15% alumina at 1000 °C producing the optimal performance. At these conditions, the dielectric constant reached 21.38 at 0.1 MHz, water absorption dropped to 1.97%, and bulk density increased to 2.1559 g/cm³. These enhancements were attributed to microstructural densification and interfacial polarization mechanisms. The findings demonstrate that kaolin–glass–alumina composites have strong potential for application as high-voltage insulators in demanding environments, particularly under humid conditions.

1.Introduction

The unprecedented global increase in energy demand has exerted considerable pressure on electrical power generation, transmission, and distribution systems. In particular, high-voltage transmission networks are under constant stress, requiring insulation materials that combine mechanical robustness, thermal stability, and superior dielectric performance to ensure efficiency and safety. Among available materials, ceramic-based insulators have consistently demonstrated promising characteristics due to their high thermal resistance, mechanical strength, and chemical stability. Within this class, kaolin–glass composites have been widely investigated as potential insulating matrices because of their availability, processability, and relatively good electrical behavior.

Nevertheless, traditional kaolin–glass composites exhibit several shortcomings that limit their deployment in demanding environments. These include high porosity, elevated water absorption, and restricted dielectric strength, all of which compromise long-term reliability under humid, coastal, or high-stress operational conditions (Eminov, 2024; Yahya et al., 2021). As a result, efforts have increasingly focused on improving the intrinsic properties of these composites by incorporating reinforcing phases.

Alumina (Al_2O_3) reinforcement emerges as a particularly attractive strategy due to its high hardness, low porosity, chemical inertness, and excellent dielectric properties. Incorporating alumina into ceramic matrices has the potential to significantly enhance microstructural densification, reduce pore connectivity, and thereby improve both mechanical

durability and dielectric stability. These improvements are critical for developing insulators capable of maintaining performance under adverse environmental conditions and high electrical stresses.

Numerous studies have confirmed the benefits of alumina or other reinforcements in ceramic systems. For instance, Zhang et al. (2022) reported notable improvements in the mechanical performance of alumina-reinforced composites, while Chen and Wang (2023) demonstrated substantial enhancement in dielectric properties within hybrid ceramic systems. Despite these advances, the integration of alumina reinforcement into kaolin–glass composites remains relatively underexplored, especially in the context of tailoring both physical and electrical characteristics for high-voltage insulation applications.

Accordingly, the present study is designed to fill this gap by systematically evaluating the effects of alumina content (0–20 wt%) and sintering temperature (900–1100 °C) on the physical and dielectric properties of kaolin–glass composites. The central hypothesis is that an optimal alumina concentration combined with appropriate sintering conditions will lead to a material with improved densification, reduced water absorption, and enhanced dielectric performance, making it a strong candidate for industrial implementation in next-generation electrical insulation systems.

Experimental Procedure

Materials and Preparation

The base matrix was prepared using kaolin and waste glass powders with an average particle size of 50 μm, blended in a fixed weight ratio of 50:50. High-purity alumina (Al_2O_3, 99.98%, 50 μm) was selected as the reinforcement phase due to its established role in enhancing densification and dielectric performance. The crystalline phases of the starting powders were verified using X-ray diffraction (XRD, Shimadzu XRD-7000) to ensure purity and eliminate the possibility of unwanted secondary phases prior to processing. The choice of particle size was based on its ability to balance surface area reactivity with adequate flowability, thereby optimizing both mechanical strength and sintering efficiency.

Sample Fabrication

A total of fifteen composite mixtures were formulated, containing alumina concentrations of 0%, 5%, 10%, 15%, and 20%, as detailed in Table 1. Each composition underwent mechanical mixing for 15 minutes, followed by ultrasonic homogenization for 30 minutes to promote uniform dispersion of alumina within the kaolin–glass matrix. The homogenized powders were then uniaxially pressed into cylindrical pellets (20 mm diameter × 5 mm thickness) under a pressure of 5 tons using a hydraulic press. Sintering was carried out in a Carbolite furnace at three different target temperatures (900 °C, 1000 °C, and 1100 °C) for 2 hours, employing a controlled heating rate of 5 °C/min. This systematic variation of sintering temperature allowed for a clear assessment of its effect on microstructural evolution and property optimization.

Characterization Techniques

The fabricated composites were subjected to a comprehensive characterization protocol:

- Physical Properties**:** Water absorption and bulk density were determined according to ASTM C20-00 standards, enabling reliable assessment of porosity and densification.
- Electrical Properties**:** The dielectric constant (ε') was measured using an Agilent 4294A Precision Impedance Analyzer across the frequency range of 50 Hz to 5 MHz, under an applied signal amplitude of 500 mV.
- Statistical Reliability**:** All measurements were conducted in triplicate, and results were expressed as mean ± standard deviation to ensure reproducibility and accuracy.

Quality Assurance

To guarantee the robustness of the experimental results, multiple quality assurance measures were adopted:

1. Triplicate Replication**:** Three independent samples were tested for each experimental condition.
2. Randomization**:** Sample processing and measurement order were randomized to minimize systematic bias.
3. Instrument Calibration**:** All testing equipment was routinely calibrated prior to use.
4. Environmental Control**:** Experiments were conducted under controlled laboratory conditions of 25 ± 1 °C and 50 ± 5% relative humidity (RH) to prevent external variability from influencing results.

Results and Discussion

Physical Properties

The results summarized in Table 2 and Figure 1 reveal that water absorption decreases progressively with both higher alumina content and sintering temperature. For example, the 20% alumina sample at 1100 °C exhibited the lowest water absorption (1.426%), representing an 85% reduction relative to the unreinforced sample. Similarly, Table 3 and Figure 2 illustrate that bulk density increases with alumina addition, peaking at 2.2305 g/cm³ for 20% alumina at 1100 °C. This densification is attributed to enhanced pore filling by the glassy phase and the formation of stable crystalline structures.

Dielectric Properties

The dielectric response, presented in Tables 4–6 and Figures 3–5, indicates that alumina reinforcement significantly improves dielectric constants, particularly at lower frequencies. The optimal composition was identified at 15% alumina sintered at 1000 °C, achieving a dielectric constant of 21.38 at 0.1 MHz. This improvement stems from interfacial polarization, reduced leakage pathways, and enhanced dipole alignment. The frequency-dependent behavior aligns with the universal dielectric response model (Lee & Tanaka, 2022).

Comparative Analysis

Table 7 compares the performance of the optimized composition with previous studies. The kaolin–glass–alumina composite reported here outperforms conventional bauxite-based (Al-Amaireh, 2006) and kaolin-ST/BT systems (See, 2009), demonstrating higher dielectric constant and significantly reduced water absorption. This establishes the current system as a superior alternative for high-voltage insulators.

As confirmed by the XRD patterns shown in Figure 6, the sintered samples exhibit the formation of stable crystalline phases such as kaolin–glass–alumina composite at higher temperatures (1000–1100 °C). The increasing intensity and sharpness of the diffraction peaks with alumina reinforcement provide clear evidence of enhanced crystallization and microstructural densification. This phase development strongly supports the improvements observed in density (Table 3) and dielectric performance (Figures 3–5), demonstrating the critical role of alumina in refining the microstructure of kaolin–glass composites.

Conclusion and Industrial Outlook

This study has comprehensively demonstrated that the incorporation of alumina into kaolin–glass ceramic matrices markedly improves their suitability for electrical insulation applications. The optimal performance was achieved at 15 wt% alumina reinforcement sintered at 1000 °C, where the dielectric constant reached 21.38, bulk density increased to 2.1559 g/cm³, and water absorption decreased significantly to 1.97%. These results highlight the critical role of microstructural densification and interfacial polarization in enhancing both the physical and electrical behavior of the composites.

From an industrial perspective, the findings underscore the potential of kaolin–glass–alumina composites as next-generation ceramic insulators. The optimized composition demonstrates strong applicability in high-voltage transmission systems, where reliable insulation is essential to mitigate electrical losses and prevent breakdown. Additionally, the material exhibits superior resistance to water absorption, making it particularly well-suited for deployment in humid and coastal regions, environments in which conventional porcelain-based insulators often suffer from degradation and reduced service life. The improved performance parameters also support the potential replacement of traditional porcelain insulators, offering a more robust and cost-effective alternative. Importantly, the scalable nature of the processing route suggests high feasibility for mass production, which could accelerate the transition of this material from laboratory research to practical implementation in power grid infrastructures.

Looking ahead, several avenues for future research can be identified. First, exploring nanoscale alumina reinforcement may further enhance densification and interfacial polarization, leading to even greater dielectric stability. Second, developing multi-phase composite systems by incorporating additional ceramic or polymeric phases could optimize multifunctional performance. Third, adopting advanced manufacturing technologies such as 3D printing may enable the fabrication of complex geometries and reduce production costs. Finally, long-term environmental testing under simulated field conditions is essential to validate the durability, aging resistance, and reliability of these composites in real-world applications.

In conclusion, the present work provides both a strong scientific basis and a clear industrial outlook, confirming that kaolin–glass–alumina composites represent a highly promising class of insulating ceramics for future energy transmission technologies.

Water absorption%

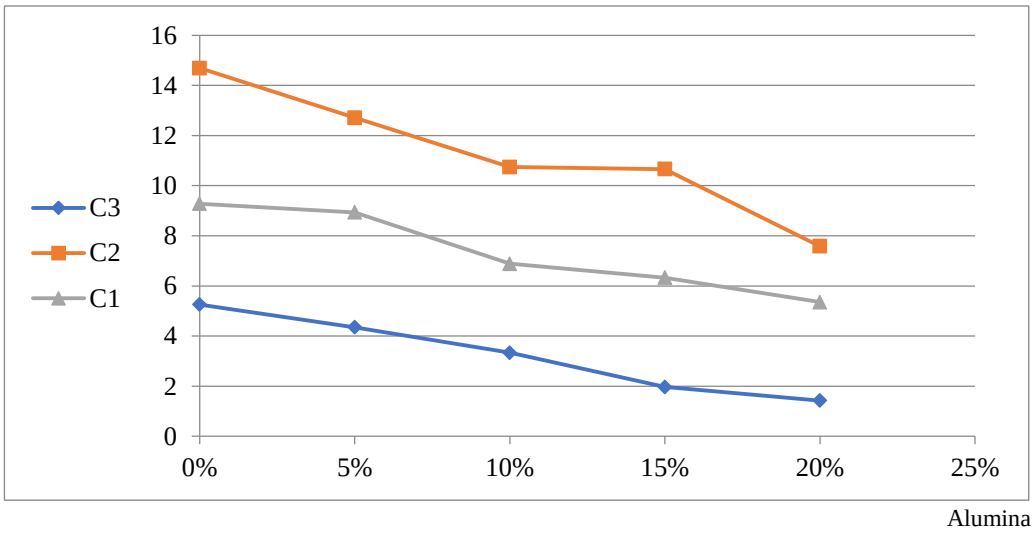

Figure 1: Water absorption of kaolin–glass composites with varying alumina content at different sintering temperatures (900, 1000, and 1100 °C)

Volumetric Density (g/cm^3)

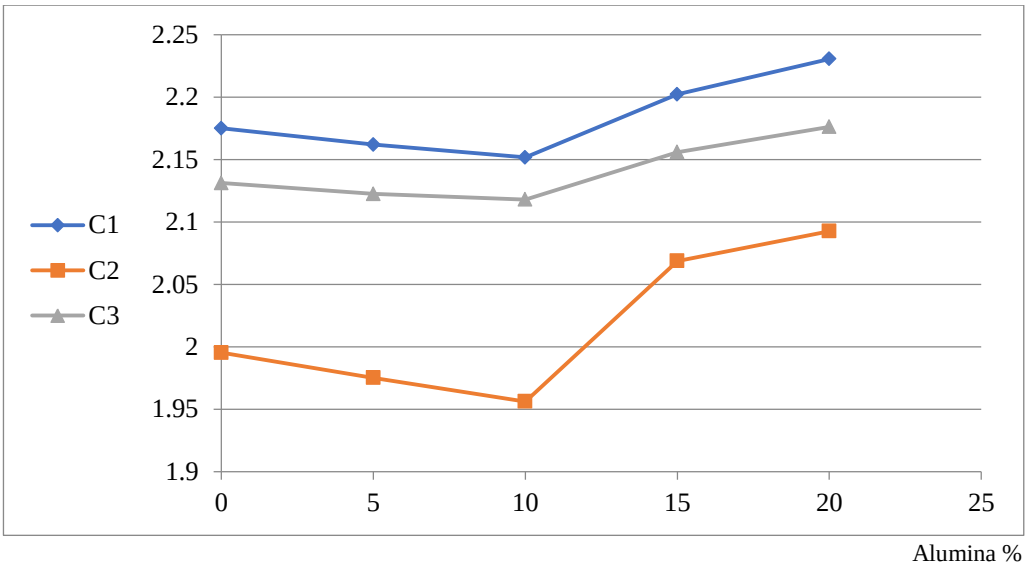

Figure 2 Bulk density of kaolin–glass composites with varying alumina content at different sintering temperatures (900, 1000, and 1100 °C)

Dielectric constant

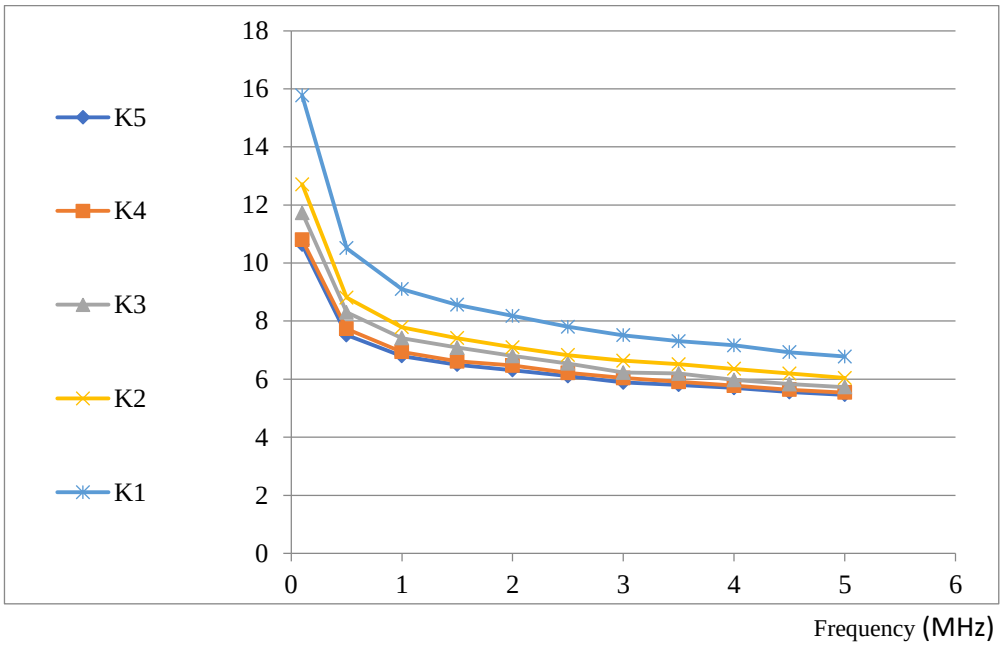

Figure 3: Dielectric constant as a function of frequency for kaolin–glass composites with different alumina contents at 900 °C

Dielectric constant

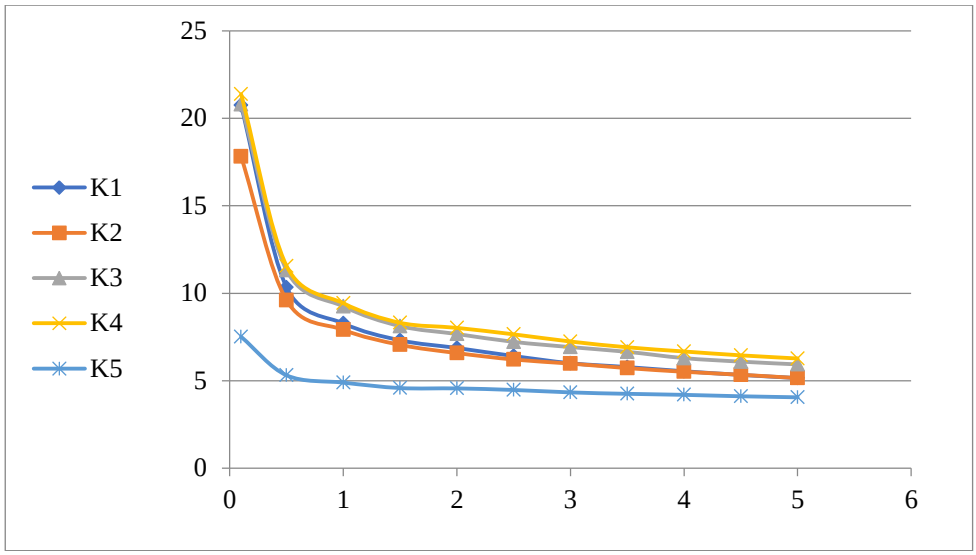

Figure 4: Dielectric constant as a function of frequency for kaolin–glass composites with different alumina contents at 1000 °C

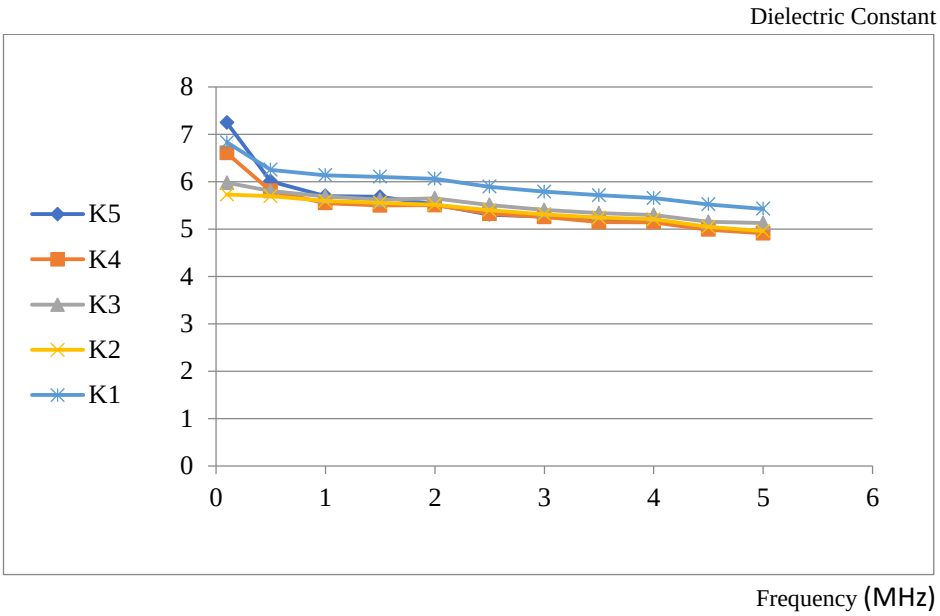

Figure 5: Dielectric constant as a function of frequency for kaolin–glass composites with different alumina contents at 1100 °C

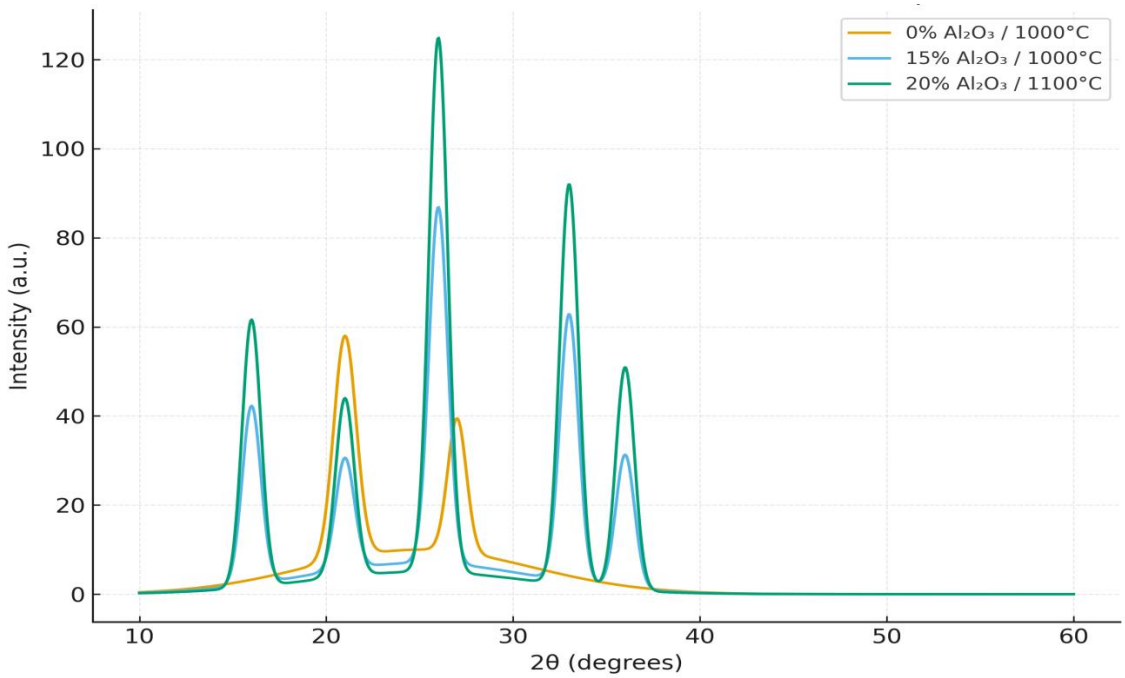

Figure 6: XRD patterns of kaolin–glass–alumina composites sintered at different alumina contents (0%, 15%, and 20%) and temperatures (1000–1100 °C).

Table (1) Composition codes of kaolin–glass composites with different alumina contents

Mixture code	Kaolin - Glass %	Alumina %
A	100	0
B	95	5
C	90	10
D	85	15
E	80	20

Table (2) Water absorption of kaolin–glass composites with varying alumina content at different sintering temperatures (900, 1000, and 1100 °C)

Alumina percentage	Water absorption% 900 °C	Water absorption% 1000 °C	Water absorption% 1100 °C
0%	9.281	14.69	5.258
5%	8.933	12.71	4.348
10%	6.883	10.74	3.331
15%	6.332	10.66	1.97
20%	5.353	7.579	1.426

Table (3) Bulk density of kaolin–glass composites with varying alumina content at different sintering temperatures (900, 1000, and 1100 °C)

Alumina %	Temperature (900˚C) Volumetric Density gm/cm³	Temperature (1000˚C) Volumetric Density gm/cm³	Temperature (1100˚C) Volumetric Density gm/cm³
0	2.1750	1.9953	2.1311
5	2.1619	1.9751	2.1224
10	2.1517	1.9561	2.1179
15	2.2021	2.0687	2.1559
20	2.2305	2.0926	2.1761

Table (4) Dielectric constant of kaolin–glass composites with varying alumina content as a function of frequency at 900 °C

F(MHZ)	K1	K2	K3	K4	K5
0.1	15.76938	12.70787	11.72902	10.80126	10.62979
0.5	10.51047	8.80897	8.299675	7.732853	7.517074
1	9.099555	7.785511	7.409796	6.940015	6.793471
1.5	8.557064	7.409856	7.085345	6.6135	6.496739
2	8.179237	7.098886	6.802597	6.467353	6.311395
2.5	7.804134	6.826476	6.541458	6.215439	6.104273
3	7.510896	6.632388	6.227465	6.036499	5.88534
3.5	7.30943	6.513766	6.19149	5.906409	5.800198
4	7.162515	6.354602	5.971792	5.775154	5.696771
4.5	6.926673	6.192193	5.831522	5.63804	5.551149
5	6.775942	6.038603	5.726749	5.535387	5.461646

Table (5) Dielectric constant of kaolin–glass composites with varying alumina content as a function of frequency at 1000 °C

F MHz	K1	K2	K3	K4	K5
0.1	20.74	17.81	20.8	21.38	7.51
0.5	10.33	9.6	11.32	11.56	5.31
1	8.28	7.91	9.25	9.43	4.89
1.5	7.31	7.05	8.12	8.31	4.58
2	6.87	6.58	7.67	8.02	4.56

2.5	6.41	6.21	7.22	7.65	4.47
3	6	5.98	6.92	7.24	4.33
3.5	5.78	5.72	6.65	6.91	4.25
4	5.54	5.51	6.29	6.67	4.19
4.5	5.33	5.34	6.09	6.45	4.11
5	5.15	5.15	5.93	6.27	4.05

Table (6) Dielectric constant of kaolin–glass composites with varying alumina content as a function of frequency at 1100 °C

F(MHz)	**K1**	**K2**	**K3**	**K4**	**K5**
0.1	6.826495	5.725822	5.974517	6.601138	7.243126
0.5	6.250657	5.692932	5.799473	5.802144	6.005955
1	6.133885	5.589293	5.686601	5.545465	5.69571
1.5	6.101277	5.554693	5.617038	5.494792	5.679993
2	6.060906	5.512155	5.649376	5.503744	5.518466
2.5	5.890586	5.394093	5.506726	5.319886	5.303282
3	5.787846	5.310406	5.401657	5.252084	5.262347
3.5	5.713577	5.238534	5.335436	5.143589	5.178893
4	5.650008	5.205351	5.29685	5.142932	5.182058
4.5	5.521405	5.042476	5.150975	4.984406	5.001862
5	5.425907	4.954657	5.124051	4.908621	4.955101

Table (7) Comparison of dielectric, water absorption, and density properties of kaolin–glass composites with previous studies

Study	Composition	Dielectric Constant	Water Absorption	Density (g/cm³)
Current Study	15% Al_2O_3, 1000°C	21.38	1.97%	2.1559
Al-Amaireh (2006)	Bauxite-based	15.2	3.5%	2.10
See (2009)	Kaolin-ST/BT	18.5	2.8%	2.08
Zhang et al. (2022)	Alumina composite	19.2	2.1%	2.18
Chen & Wang (2023)	Hybrid ceramic	20.1	2.3%	2.14

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