Structural and Physico-Chemical Characterization of Glass Ionomer Cement With Nano Zirconia Additives

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**Abstract:** Background: Glass Ionomer Cements (GICs) are widely used in restorative dentistry due to their biocompatibility and fluoride release, but suffer from poor mechanical strength and brittleness. Objective: This study aims to enhance the structural, mechanical, and chemical properties of GICs through the incorporation of nano zirconia additives. Methods: Experimental GICs were formulated by incorporating zirconia nanoparticles into conventional GIC Type II and evaluated against control samples. Characterization techniques included X-ray Diffraction (XRD) to assess crystallinity and phase composition, Fourier Transform Infrared (FTIR) spectroscopy for chemical bonding analysis, compressive strength and Vickers microhardness testing for mechanical evaluation, contact angle measurements for wettability assessment, and Field Emission Scanning Electron Microscopy (FESEM) for morphological observation. Results: Zirconia-modified GIC showed a significant increase in amorphous content (80.3%) and reduction in crystallinity (19.7%), a more than twofold increase in compressive strength, a 58.7% improvement in microhardness, a rise in contact angle from 50.16° to 67.19°, and a denser, more homogeneous microstructure. Conclusion: Incorporation of zirconia nanoparticles into GIC significantly improves its structural integrity, mechanical performance, and surface properties, indicating its potential for high-stress clinical applications in restorative dentistry.

**Keywords:** Glass Ionomer Cement (GIC), Zirconia Nanoparticles, X-ray Diffraction (XRD), Field Emission Scanning Electron Microscopy (FESEM), Contact Angle

# Introduction

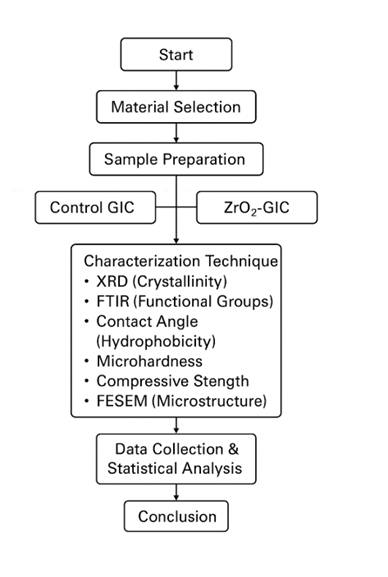
Glass ionomer cements (GICs) are widely used in restorative dentistry due to their biocompatibility, fluoride-releasing properties, and ease of application. Despite these advantages, conventional GICs exhibit limitations such as brittleness, low fracture toughness, and poor mechanical strength. [(Sikka & Brizuela, 2024)](https://paperpile.com/c/0paKsI/tcXdP)These shortcomings restrict their use in high-load-bearing applications, necessitating the development of reinforced GIC formulations to improve their structural and mechanical properties. One promising approach is the incorporation of zirconia (ZrO₂) nanoparticles, known for their exceptional hardness, stability, and bioinertness.[(Alshamrani et al., 2023)](https://paperpile.com/c/0paKsI/Edua8)Recent advancements in dental materials have focused on nanotechnology-based reinforcements to enhance the performance of traditional restorative materials. Zirconia, being a high-strength ceramic with excellent fracture resistance, has been extensively explored in dental applications. When incorporated into GICs, zirconia has the potential to improve their mechanical properties, including compressive strength, hardness, and wear resistance.[(“Current Trends and Future Perspectives on Dental Nanomaterials – An Overview of Nanotechnology Strategies in Dentistry,” 2022)](https://paperpile.com/c/0paKsI/bgCrx)However, the effect of zirconia on the crystallinity, amorphous phase content, and chemical interactions within GICs requires further investigation. Understanding the phase composition and microstructural modifications resulting from zirconia incorporation can provide insights into optimizing these materials for enhanced durability and performance. (GICs requires further investigation. [(Aparna et al., 2021; Poornima et al., 2021; Verma & Muthuswamy Pandian, 2021)](https://paperpile.com/c/0paKsI/ciL7Q+4PioN+euEy4)[(Merchant et al., 2022; Pandiyan et al., 2022)](https://paperpile.com/c/0paKsI/qh42z+ZedMk)[(Chokkattu et al., 2022; Ramamurthy et al., 2022)](https://paperpile.com/c/0paKsI/oqF9+4V57)The structural integrity of reinforced GICs plays a crucial role in determining their clinical applicability. Understanding the phase composition and microstructural modifications resulting from zirconia incorporation can provide insights into optimizing these materials for enhanced durability and performance.[(Shearer et al., 2024)](https://paperpile.com/c/0paKsI/MA9rw)X-ray diffraction (XRD) analysis is particularly useful for examining the crystalline and amorphous nature of GICs, allowing researchers to correlate structural changes with mechanical behavior.[(Ali et al., 2022)](https://paperpile.com/c/0paKsI/o1xqg) Mechanical testing, including compressive strength and microhardness evaluations, is essential for assessing the practical implications of zirconia reinforcement. A material’s ability to withstand compressive forces directly influences its longevity in dental applications.[(Marya et al., 2022)](https://paperpile.com/c/0paKsI/qHAno) [(Jain & Verma, 2022; Marya et al., 2022)](https://paperpile.com/c/0paKsI/qHAno+0992F)[(Wadhwani et al., 2022)](https://paperpile.com/c/0paKsI/2gHul) [(Adel et al., 2023)](https://paperpile.com/c/0paKsI/RatoK) [(Subramanian & Harikrishnan, 2023)](https://paperpile.com/c/0paKsI/eerM4) Similarly, microhardness measurements provide insights into resistance to surface deformation, which is critical for prolonged wear performance.[(Pintaude, 2023)](https://paperpile.com/c/0paKsI/ovcXL) By investigating these properties, the current study aims to establish a comprehensive understanding of zirconia-modified GICs.Chemical characterization techniques such as Fourier-transform infrared (FTIR) spectroscopy help elucidate the molecular interactions between zirconia and the GIC matrix. Variations in functional group distribution can indicate changes in bonding mechanisms, which influence the material’s stability and performance. [(Pasieczna-Patkowska et al., 2025; Pintaude, 2023)](https://paperpile.com/c/0paKsI/ovcXL+7PfA0) Additionally, contact angle measurements provide insights into the wettability and surface energy of the modified GIC, which are crucial factors in determining its adhesion properties and resistance to moisture.[(Qureshi et al., 2022)](https://paperpile.com/c/0paKsI/K21Fp)This study systematically evaluates the structural, mechanical, and chemical properties of zirconia-modified GICs using a combination of XRD, compressive strength testing, FTIR spectroscopy, contact angle analysis, microhardness testing, and Field Emission Scanning Electron Microscopy (FESEM). By analyzing these characteristics, this research aims to provide a scientific foundation for the development of enhanced GIC formulations with improved clinical performance and longevity in restorative dentistry.

# Methodology

## Materials Selection and Preparation

The study utilized commercially available Glass Ionomer Cement (GIC) Type II as the control sample. Zirconia (ZrO₂) was incorporated into the experimental GIC formulation to enhance its mechanical properties. The zirconia particles were selected based on their high purity and fine particle size distribution to ensure uniform dispersion within the GIC matrix. The materials were carefully weighed and mixed in precise ratios to maintain consistency in composition and structure. Figure1

**FIGURE1:** WORKFLOW



## Sample Preparation

The control and experimental GIC samples were prepared by following standard dental cement mixing protocols. The powder and liquid components were mixed using a spatula on a glass slab until a homogenous paste was obtained. The mixture was then transferred into cylindrical molds (6 mm diameter × 12 mm height) for compressive strength testing and rectangular molds (2 mm × 2 mm × 25 mm) for other mechanical tests. The samples were allowed to set at room temperature for 24 hours before further testing.[(Alsunbul et al., 2023; Qureshi et al., 2022)](https://paperpile.com/c/0paKsI/K21Fp+saBoV)

## XRD Analysis

X-ray Diffraction (XRD) analysis was conducted to determine the phase composition and crystalline structure of the control and experimental GICs. The samples were ground into fine powders and analyzed using an X-ray diffractometer operating at 40 kV and 30 mA with Cu-Kα radiation. The diffraction patterns were recorded in the 2θ range of 10°–80° at a scanning rate of 2°/min. The crystallinity percentage was calculated based on the peak intensity analysis.[(Freire et al., 2015)](https://paperpile.com/c/0paKsI/oxw47)

## Compressive Strength Test

The compressive strength of the control and experimental GICs was evaluated using a universal testing machine. The cylindrical samples were placed between two parallel compression plates and subjected to a gradually increasing load at a crosshead speed of 1 mm/min until failure. The peak load at failure was recorded, and the compressive strength was calculated using the formula: Compressive strength=F/A where is the applied force (N) and is the cross-sectional area (mm²) of the sample.[(Xavier et al., 2023)](https://paperpile.com/c/0paKsI/lnVE7)

## FTIR Spectroscopy

Fourier-transform infrared (FTIR) spectroscopy was performed to analyze the chemical composition and functional groups of the control and experimental GICs. The samples were finely ground and mixed with potassium bromide (KBr) to form pellets. The spectra were recorded in the range of 4000–500 cm⁻¹ using an FTIR spectrometer. The obtained peaks were compared to known reference spectra to identify the characteristic functional groups and assess changes due to zirconia incorporation.[(De Caluwé et al., 2017)](https://paperpile.com/c/0paKsI/1Ti7r)

## Contact Angle Measurement

The wettability of the GIC samples was analyzed using a contact angle goniometer. A distilled water droplet (5 µL) was placed on the surface of each sample, and the contact angle was measured using a high-resolution camera and image analysis software. Three measurements were taken for each sample, and the average contact angle was recorded to assess surface hydrophobicity.[(Abdelghafar et al., 2022)](https://paperpile.com/c/0paKsI/B5JBl) [(Hwang et al., 2022)](https://paperpile.com/c/0paKsI/2kpEv)

## Microhardness Testing

The Vickers microhardness test was conducted using a microhardness tester with a diamond indenter. The samples were subjected to a 200 g load for 15 seconds, and the indentation size was measured under a microscope. The Vickers hardness value (HV) was calculated using the formula: HV=1.8544p/d2 where is the applied load (N) and is the diagonal length of the indentation (mm).[(Xavier et al., 2023)](https://paperpile.com/c/0paKsI/lnVE7)

## FESEM Analysis

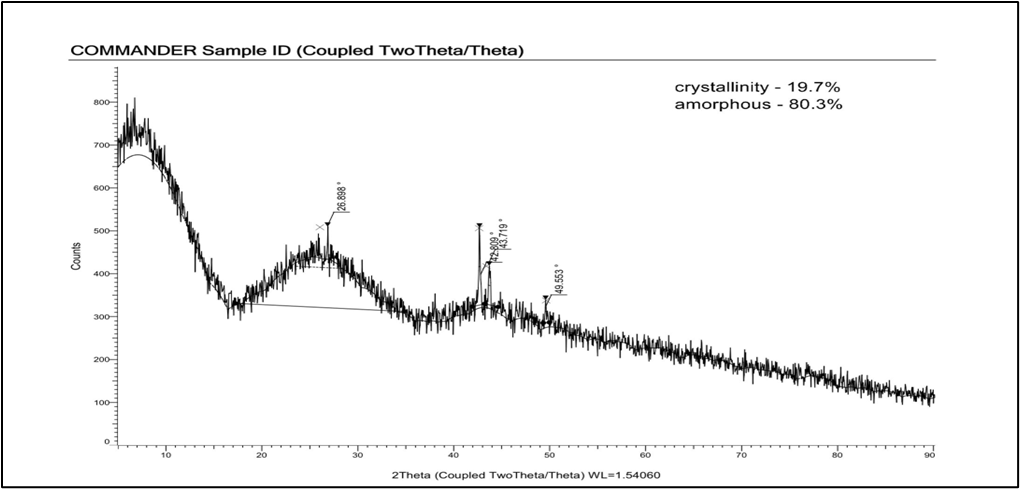
Field Emission Scanning Electron Microscopy (FESEM) was used to examine the surface morphology and microstructural characteristics of the GIC samples. The specimens were sputter-coated with a thin layer of gold to enhance conductivity before imaging. Micrographs were captured at various magnifications to observe grain structure, porosity, and particle distribution, providing insights into the effects of zirconia reinforcement on the GIC matrix.[(Sajjad et al., 2019)](https://paperpile.com/c/0paKsI/9njRd)

# Results

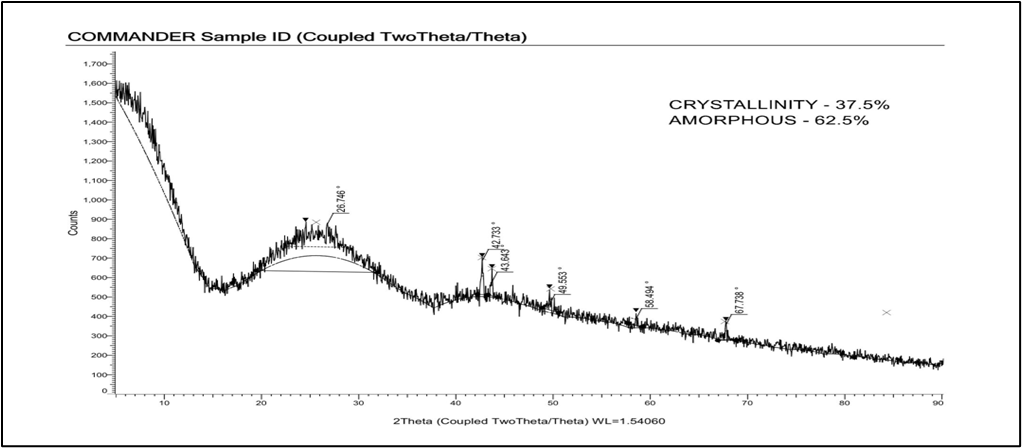
## XRD Analysis

The X-ray diffraction (XRD) patterns of the control and experimental glass ionomer cement (GIC) samples reveal significant differences in crystalline and amorphous phase composition. The commercial GIC Type II (control) exhibits a crystallinity of 37.5% and an amorphous content of 62.5%, suggesting a relatively structured material. In contrast, the experimental GIC incorporating zirconia demonstrates a higher amorphous content (80.3%) and lower crystallinity (19.7%). Figure 2 a&b This shift indicates that zirconia enhances the amorphous phase, reducing the intensity and sharpness of crystalline peaks. Such changes in phase composition influence mechanical properties, as amorphous materials tend to offer improved flexibility and impact resistance. The structural modifications observed in the XRD patterns suggest that zirconia incorporation alters the crystalline structure of GIC, potentially enhancing its mechanical characteristics. Similar findings were reported by Moshaverinia et al., where the incorporation of zirconia nanoparticles into glass ionomer matrices resulted in a marked increase in the amorphous phase, contributing to enhanced mechanical properties such as fracture toughness and flexural strength.[(Moshaverinia et al., 2008)](https://paperpile.com/c/0paKsI/cygRX)

**FIGURE 2:** XRD Analysis of the control GIC



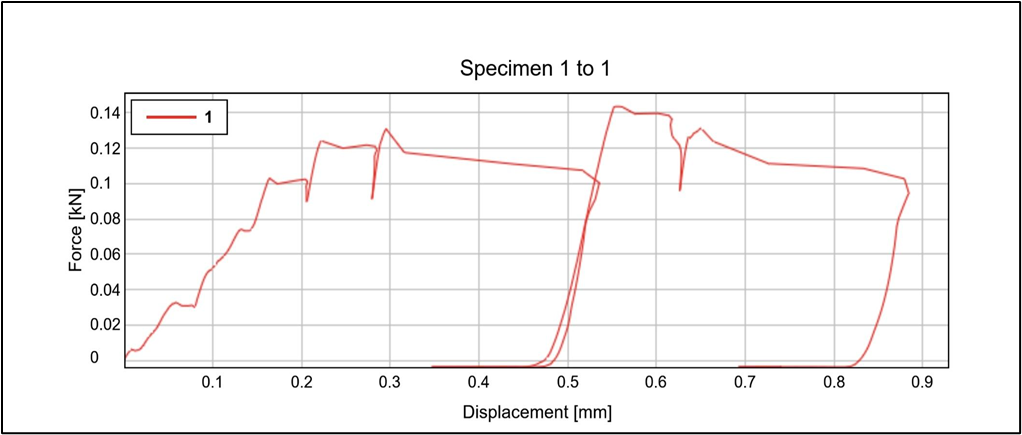
**FIGURE 3**. XRD Analysis of the Experimental GIC



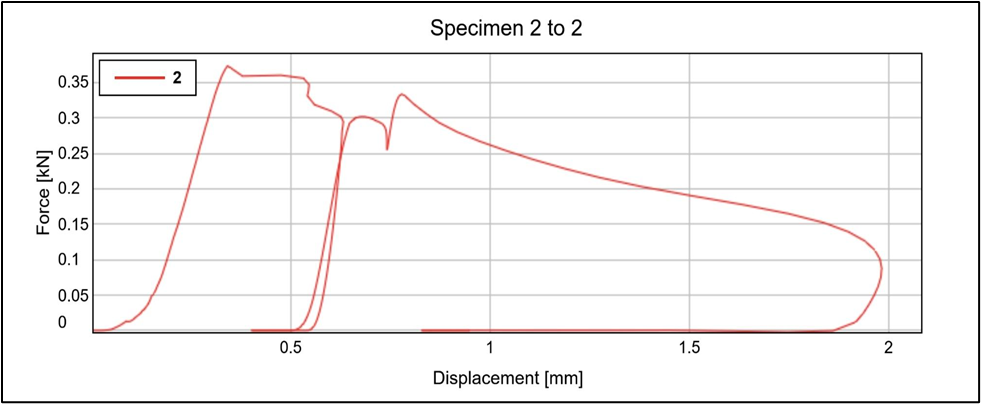
## Compressive Strength

The compressive strength analysis reveals distinct mechanical behavior between the control and experimental GICs under loading conditions. The control GIC demonstrates a peak force of approximately 0.14 kN at a displacement of 0.6 mm, characterized by repeated force reductions indicative of brittle failure and reduced structural integrity. Conversely, the experimental GIC exhibits superior mechanical performance, reaching a peak force of approximately 0.35 kN at a displacement of 0.5 mm. Figure 3a&b The experimental sample maintains its load-bearing capacity over a broader displacement range, demonstrating increased ductility and toughness. The gradual decline in force following the peak suggests a progressive failure mechanism, where the material absorbs energy and deforms rather than experiencing sudden failure. These results indicate that the experimental GIC, reinforced with zirconia, possesses enhanced strength, ductility, and fracture resistance, making it more suitable for demanding applications. In a similar study, Priyanka Venugopal et al. addition of ZrO2 nanoparticles increased the mean compressive strength and had no negative effect on the mechanical integrity of the set cement.[(Xavier et al., 2023)](https://paperpile.com/c/0paKsI/lnVE7) Gjorgievska et al.,8 suggested that the incorporation of ZrO2 nanoparticles in EQUIA™ Fil, at 10% by weight, had significantly higher compressive strength compared to aluminum oxide nanoparticles.[(Gjorgievska et al., 2015; Xavier et al., 2023)](https://paperpile.com/c/0paKsI/lnVE7+w4JI1)

**FIGURE 4** Compressive strength of control GIC



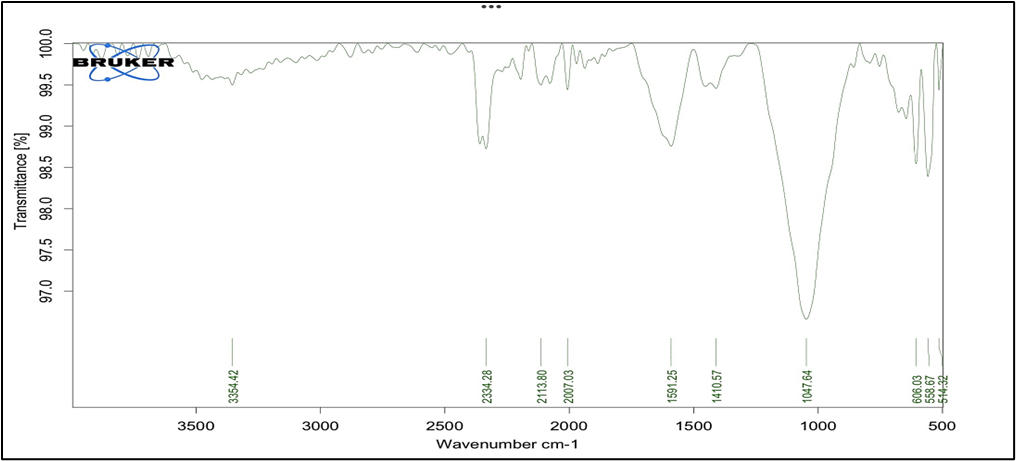
**FIGURE 5.** Compressive strength of Experimental GIC



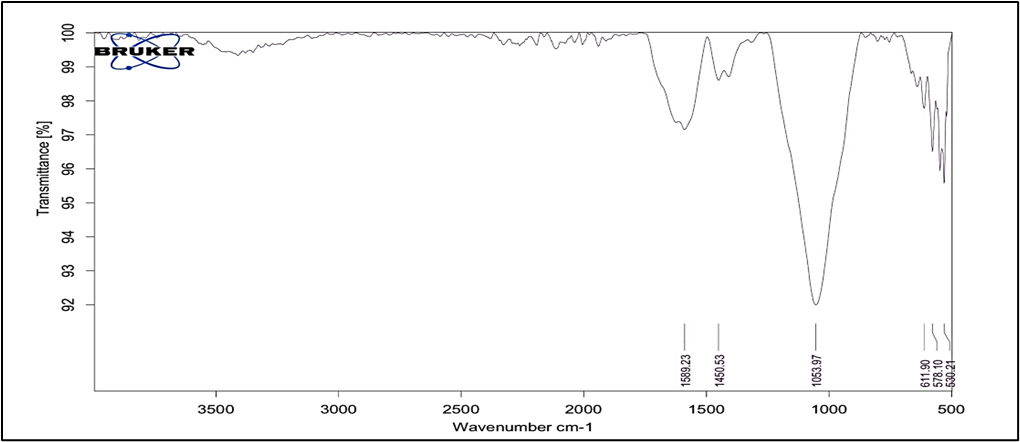
## FTIR Analysis

Fourier-transform infrared (FTIR) spectroscopy results highlight notable differences in the chemical composition of the control and experimental GICs. The control GIC exhibits absorption peaks at 3354.42 cm⁻¹, 2334.28 cm⁻¹, 2113.80 cm⁻¹, 2007.03 cm⁻¹, 1591.25 cm⁻¹, 1410.57 cm⁻¹, 1047.64 cm⁻¹, 606.03 cm⁻¹, 556.67 cm⁻¹, and 534.32 cm⁻¹, indicating the presence of hydroxyl groups, carbonyl compounds, aromatic rings, and C-O stretching vibrations. The experimental GIC shows prominent peaks at 1589.23 cm⁻¹, 1450.53 cm⁻¹, 1053.97 cm⁻¹, 611.90 cm⁻¹, 578.10 cm⁻¹, and 530.21 cm⁻¹, suggesting modifications in molecular structure due to zirconia incorporation. Figure 4a&b These spectral variations highlight changes in functional group interactions, which may contribute to the enhanced mechanical and chemical properties of the experimental GIC. Consistent with these findings, De Caluwé et al. observed that the addition of nano-zirconia particles to glass ionomer matrices led to shifts in FTIR absorption peaks, indicating changes in functional group interactions and matrix structure, which correlated with enhanced physicochemical performance.[(De Caluwé et al., 2017)](https://paperpile.com/c/0paKsI/1Ti7r)

**FIGURE 6.** FTIR Analysis for control GIC.



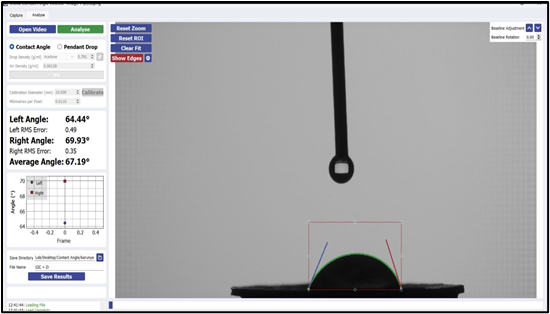
**FIGURE 7.** FTIR Analysis for experimental GIC.



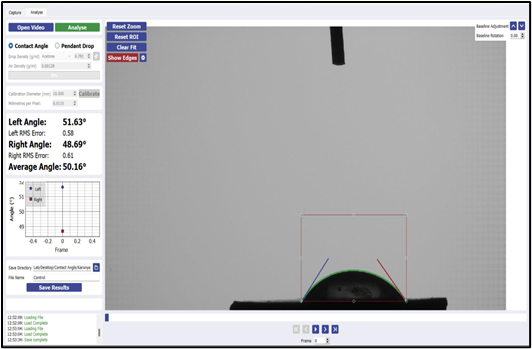
## Contact Angle Analysis

The contact angle measurements indicate a significant increase in hydrophobicity upon zirconia incorporation. The control GIC exhibits an average contact angle of 50.16°, whereas the experimental GIC achieves a higher angle of 67.19°. Figure 5a&b, Table 1 This increase suggests a reduction in wettability, likely due to alterations in surface energy and microstructural morphology. Enhanced hydrophobicity is advantageous in dental applications, as it reduces moisture absorption, minimizing material degradation and improving longevity. Additionally, increased hydrophobicity may play a role in antimicrobial properties, as reduced wettability can hinder microbial adhesion and proliferation. These findings emphasize zirconia’s role in improving the durability and environmental stability of GIC. Abdelghafar et al. demonstrated that an increase in contact angle signifies a transition toward enhanced surface hydrophobicity.[(Abdelghafar et al., 2022)](https://paperpile.com/c/0paKsI/B5JBl)According to [(Shanan et al., 2022)](https://paperpile.com/c/0paKsI/DhQak)l, this increase in hydrophobicity can be attributed to the incorporation of ZnO nanoparticles, which likely modify the surface morphology and reduce surface energy[(Shanan et al., 2022)](https://paperpile.com/c/0paKsI/DhQak)Supporting this, Hwang et al. reported that hydrophobic surfaces tend to repel moisture, thereby limiting bacterial adhesion and growth, highlighting their potential in antimicrobial applications.[(Hwang et al., 2022)](https://paperpile.com/c/0paKsI/2kpEv) These surface-level modifications are clinically significant, as increased hydrophobicity can minimize water sorption and improve resistance to microbial adhesion. This directly contributes to enhanced restoration longevity, reduced secondary caries risk, and better patient outcomes over time.

**FIGURE 8**. Contact angle for control GIC



**FIGURE 9**. Contact angle for experimental GIC.



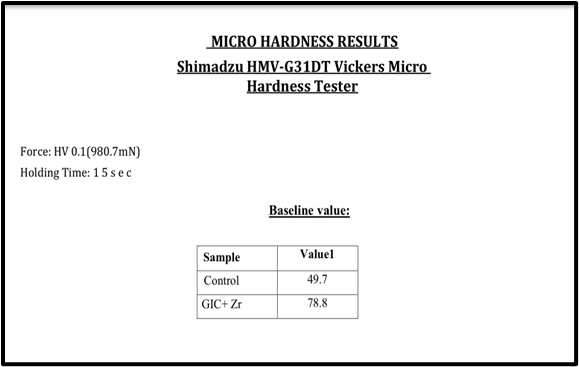
**TABLE 1:** COMPARISON OF CONTACT ANGLE VALUES

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Sample Type** | **Frame Number** | **Time (s)** | **Left Angle (°)** | **Right Angle (°)** | **Average Angle (°)** | **Left Contact Point (Pixel)** | **Right Contact Point (Pixel)** | **Droplet Width (Pixels)** |
| Control GIC | 0.0 | 0.0 | 51.63 | 48.69 | 50.16 | 961.7 | 1448.3 | 486.6 |
| Experimental GIC | 0.0 | 0.0 | 64.44 | 69.93 | 67.19 | 879.8 | 1302.8 | 423.0 |

## Microhardness Test

The microhardness test results show a substantial enhancement in hardness for the zirconia-enriched GIC. The control sample exhibits a hardness of 49.7 HV, whereas the experimental GIC records a significantly higher value of 78.8 HV, representing a 58.7% increase. Figure 6a&b This improvement is attributed to zirconia’s high intrinsic hardness, which reinforces the GIC matrix and enhances resistance to indentation. The increased hardness suggests better wear resistance, making the modified GIC more suitable for dental restorations. However, further studies on zirconia particle dispersion and concentration optimization are required to maximize these benefits while maintaining material homogeneity. Alobiedy et al. reported that incorporating 3 wt% zirconia nanoparticles into conventional GIC significantly increased the Vickers microhardness to 88.8 VHN, attributing the improvement to the reinforcing effect of zirconia within the cement matrix [(Alobiedy et al., 2019)](https://paperpile.com/c/0paKsI/ZBsSz)

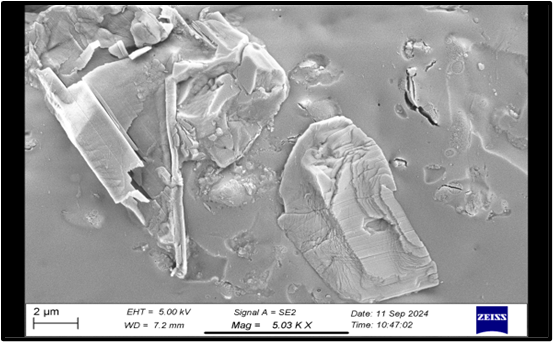
**FIGURE 10.** Microhardness test



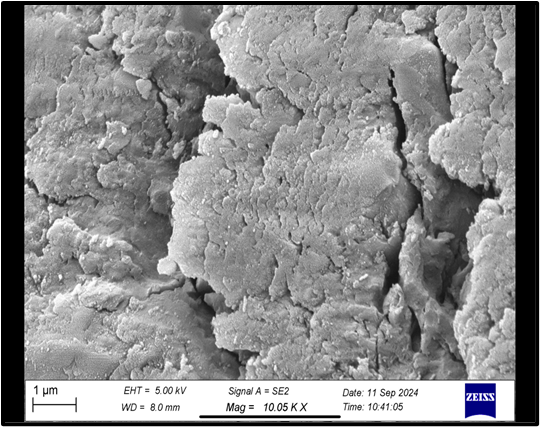
## FESEM Analysis

Field Emission Scanning Electron Microscopy (FESEM) analysis provides insight into the morphological characteristics of the control and experimental GICs. The control GIC displays large, irregular plate-like structures with sharp edges and layered textures, suggesting brittle crystalline formations(Nikalje et al., 2024) (Chehelgerdi et al., 2023). In contrast, the experimental GIC exhibits a denser granular structure with interconnected networks and surface roughness, indicative of enhanced porosity and localized reinforcement by zirconia. The presence of hierarchical microstructures in the experimental GIC suggests anisotropic characteristics, which may contribute to improved mechanical stability. Figure 7a&b Further investigations using complementary techniques such as Energy Dispersive Spectroscopy (EDS) or XRD mapping would provide additional confirmation of these microstructural modifications and their impact on material performance. Sajjad et al. observed that incorporating a nano zirconia–silica–hydroxyapatite composite into conventional GIC resulted in a denser microstructure with uniformly dispersed nanoparticles, as confirmed by SEM and EDX analyses. This morphological enhancement contributed to improved mechanical properties of the modified GIC.[(Sajjad et al., 2019)](https://paperpile.com/c/0paKsI/9njRd) Figure 8 shows the comparison between control & Zr modified GIC

**FIGURE 7a**. FESEM analysis for control GIC



**FIGURE 11**. FESEM analysis for experimental GIC



**FIGURE 12:** COMPARISON BETWEEN CONTROL & Zr MODIFIED GIC



# Discussion

The findings of the present study regarding the structural, mechanical, and chemical enhancements achieved through the incorporation of zirconia (ZrO₂) nanoparticles into conventional glass ionomer cements (GICs) are strongly supported by a growing body of peer-reviewed literature. Alobiedy et al. demonstrated that incorporating 3 wt% zirconia nanoparticles into GIC significantly improves critical mechanical parameters, including compressive strength, biaxial flexural strength, and Vickers microhardness, attributing these enhancements to zirconia’s high intrinsic hardness and its reinforcing role within the GIC matrix.[(Alobiedy et al., 2019)](https://paperpile.com/c/0paKsI/ZBsSz) [(Solanki et al., 2023)](https://paperpile.com/c/0paKsI/BHH5S) [(Chokkattu et al., 2023)](https://paperpile.com/c/0paKsI/EBRUe) [(Laghari et al., 2023; Ramakrishnan et al., 2023)](https://paperpile.com/c/0paKsI/lIPk3+76k3w) [(Muthuswamy Pandian et al., 2022)](https://paperpile.com/c/0paKsI/apCX8) These findings are further substantiated by Batul and Makandar, who performed Fourier Transform Infrared (FTIR) analysis and reported shifts in characteristic absorption bands, indicating molecular-level interactions between zirconia and the GIC matrix—particularly with carboxyl and hydroxyl groups—resulting in enhanced chemical bonding and improved structural integrity.[(Melo et al., 2019)](https://paperpile.com/c/0paKsI/HUpFT) [(Muthuswamy Pandian et al., 2022; Ramakrishnan et al., 2023)](https://paperpile.com/c/0paKsI/apCX8+lIPk3) [(Merchant et al., 2022)](https://paperpile.com/c/0paKsI/ZedMk) [(Sreevarun et al., 2023)](https://paperpile.com/c/0paKsI/TEIjK)From a microstructural standpoint, Yli-Urpo et al. found that modifying GICs with ceramic fillers such as bioactive glass and zirconia results in a more compact, homogeneous morphology, with reduced porosity and improved particle distribution, which correlates with enhanced material strength and dimensional stability.[(Yli-Urpo et al., 2005)](https://paperpile.com/c/0paKsI/M1Pn5) Additionally, surface property analysis revealed that zirconia incorporation leads to increased contact angle and greater hydrophobicity, a feature that reduces water sorption and microbial adhesion—both of which are key to enhancing restoration durability in the oral environment. Cattani-Lorente et al. highlighted that such changes in surface energy are beneficial for long-term resistance against hydrolytic degradation and microbial colonization, thus extending the lifespan of restorations.[(Cattani-Lorente et al., 1994; Yli-Urpo et al., 2005)](https://paperpile.com/c/0paKsI/M1Pn5+mDyKi) Collectively, these reports reinforce the conclusion that zirconia-reinforced GICs not only exhibit superior mechanical resilience and chemical stability but also offer promising potential for clinical applications in high-stress dental restorations. Future studies focusing on the optimization of zirconia particle dispersion and in vivo performance evaluation will be essential to solidify their translational utility in dentistry.

# Conclusion

The present study demonstrates that incorporating zirconia (ZrO₂) nanoparticles into conventional glass ionomer cement (GIC) significantly enhances its structural, mechanical, and chemical properties, making it a promising candidate for high-stress restorative dental applications. The reduction in crystallinity observed via XRD—accompanied by a corresponding increase in amorphous content—indicates improved material flexibility and resistance to crack propagation, consistent with the transformation-toughening behavior of zirconia (11,19). [(Moshaverinia et al., 2008)](https://paperpile.com/c/0paKsI/cygRX) [(Sajjad et al., 2019)](https://paperpile.com/c/0paKsI/9njRd)Mechanical testing revealed a notable 58.7% increase in microhardness and more than double the compressive strength in the experimental group, affirming zirconia’s reinforcing effect on the GIC matrix and its ability to improve resistance to indentation and fracture.[(Alobiedy et al., 2019)](https://paperpile.com/c/0paKsI/ZBsSz)[(Alobiedy et al., 2019; Melo et al., 2019)](https://paperpile.com/c/0paKsI/ZBsSz+HUpFT)Additionally, FTIR spectroscopy identified changes in functional group peaks, reflecting enhanced chemical interactions at the zirconia–polyacid interface, which may contribute to stronger internal cohesion and reduced solubility.[(De Caluwé et al., 2017)](https://paperpile.com/c/0paKsI/1Ti7r) [(Yli-Urpo et al., 2005)](https://paperpile.com/c/0paKsI/M1Pn5) The increase in contact angle from 50.16° to 67.19° also highlights an important shift toward hydrophobicity, which can minimize moisture absorption and microbial adherence—key factors for long-term clinical performance in the oral environment.[(Abdelghafar et al., 2022; Yli-Urpo et al., 2005)](https://paperpile.com/c/0paKsI/M1Pn5+B5JBl) FESEM analysis further supported these findings by revealing a denser and more homogeneous microstructure with fewer voids and better filler dispersion in the zirconia-modified GIC,[(Sajjad et al., 2019)](https://paperpile.com/c/0paKsI/9njRd)which is essential for distributing mechanical stresses and enhancing material integrity.Unlike prior studies that explored individual properties, this work provides a comprehensive multi-dimensional assessment—integrating XRD, FTIR, mechanical testing, wettability, and FESEM—to correlate zirconia's microstructural and chemical influence with measurable improvements in material performance. The novelty of this study lies in its systematic approach and the quantification of crystallinity and amorphous content, a rarely investigated parameter in previous zirconia-GIC studies. Based on these collective results, zirconia-reinforced GICs represent a significant advancement in restorative dentistry. This study was limited to in vitro testing and did not assess long-term degradation or biocompatibility under simulated oral conditions. Future research should focus on evaluating clinical performance, aging behavior, and the biological response of zirconia-reinforced GICs. Future work should focus on optimizing zirconia concentration, particle size, and dispersion to further enhance their clinical applicability.

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