**Attahadi Medical Journal**
2026;3(2):194-202
https://doi.org/10.69667/amj.26213

*Original article*

# Experimental and Computational Evaluation of Alloy-Reinforced Glass Ionomer Cement: Erosion Resistance, Maturation Behavior, and Predictive Modeling

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***Keywords***:
*Glass Ionomer Cement, Erosion Resistance, Finite Element Analysis, Dental Materials, Maturation.*

## ABSTRACT

*Glass ionomer cements (GICs) are widely used restorative materials due to their chemical adhesion, fluoride release, and biocompatibility. However, their susceptibility to acid erosion—particularly during early maturation—remains a significant limitation affecting long-term clinical performance. Recent developments in reinforced GIC formulations aim to improve resistance to mechanical and chemical degradation, yet their behavior under dynamic erosive conditions requires further investigation. This study aimed to evaluate the erosion resistance of an experimental high powder-to-liquid ratio glass ionomer cement (EXPT) in comparison with a metal-reinforced glass ionomer cement (Hi-Dense), and to investigate the influence of maturation time on material performance using both experimental and computational approaches. Cylindrical specimens (4 mm diameter; n = 6 per group) were prepared and tested at three time intervals: 1 hour, 24 hours, and 6 months. Erosion resistance was assessed using a standardized lactic acid jet test (0.02 M, pH 2.7) under controlled temperature (37°C) and flow conditions (120 ± 4 ml/min) for 24 hours. Erosion rates were quantified using both weight loss (mg/h) and dimensional loss (µm/h). Statistical analysis was performed using the Mann–Whitney U test (α = 0.05). In parallel, computational simulations incorporating diffusion–reaction modeling and finite element analysis (FEM) were conducted to predict ion transport, stress distribution, and degradation behavior. At early maturation stages, EXPT exhibited significantly higher erosion rates compared to Hi-Dense ($p \leq 0.005$). Mean height loss at 1 hour was 8.7 ± 1.0 µm/h for EXPT and 2.9 ± 0.3 µm/h for Hi-Dense, while corresponding weight loss values were 0.30 ± 0.04 mg/h and 0.16 ± 0.02 mg/h, respectively. A significant reduction in erosion rates was observed for both materials with increasing maturation time. After 6 months, no statistically significant differences were detected between the two materials ($p > 0.05$). Computational simulations demonstrated strong agreement with experimental data (correlation coefficient $r \approx 0.9$), predicting higher initial diffusion rates and localized stress concentrations in EXPT, and more uniform stress distribution in Hi-Dense. The enhanced performance of Hi-Dense cement is attributed to alloy reinforcement, which improves stress redistribution and reduces crack initiation under erosive conditions. The convergence of erosion rates over time highlights the dominant role of matrix maturation, characterized by increased crosslink density and reduced ion mobility. The combined experimental–computational approach provides mechanistic insight into erosion processes and validates the predictive capability of simulation models. Metal-reinforced glass ionomer cement demonstrates superior early-stage erosion resistance compared to conventional formulations, while long-term performance is largely governed by maturation processes. The integration of experimental testing with computational modeling offers a robust framework for evaluating and optimizing dental materials, with potential implications for improving clinical durability and guiding future material development.*

## Introduction

Glass ionomer cements (GICs) have been widely used in restorative dentistry since their introduction due to their unique combination of chemical adhesion to tooth structure, fluoride release, and biocompatibility [1,2]. These properties make them particularly valuable in minimally invasive dentistry, pediatric applications, and restorative procedures involving cervical and root caries [3,4]. Despite these advantages, the clinical longevity of GIC restorations is often limited by their susceptibility to chemical degradation and erosion, especially in acidic oral environments [5,6].

Erosion of dental materials is a complex phenomenon involving chemical dissolution, ion exchange, and mechanical wear, often exacerbated by dietary acids and bacterial metabolism [7]. In the case of GICs, the acid–base reaction between polyalkenoic acids and fluoroaluminosilicate glass results in the formation of a crosslinked polysalt matrix, which is initially weak and highly susceptible to dissolution [8]. During early

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***Received****: 15-03-2026 -* ***Accepted****: 13-05-2026 -* ***Published****: 20-05-2026*

maturation, the matrix contains loosely bound ions that can be readily leached out, leading to increased surface degradation and loss of structural integrity [9]. The maturation process plays a critical role in improving the performance of GICs. Over time, continued crosslinking—primarily involving aluminum ions—leads to the formation of a more stable and less soluble matrix [10]. This process reduces porosity, enhances mechanical strength, and significantly improves resistance to acid erosion [5,11]. However, the rate and extent of maturation can vary depending on formulation, environmental conditions, and storage media, making early-stage vulnerability a persistent clinical concern [12].

To address these limitations, various modifications to GIC formulations have been proposed, including the incorporation of metallic particles, resin components, and bioactive additives [13,14]. Among these, metal-reinforced GICs—often referred to as "cermets" or alloy-modified cements—have shown promising improvements in mechanical strength, wear resistance, and durability [15]. The addition of metallic phases enhances load distribution within the material and reduces crack propagation, thereby improving resistance to both mechanical and chemical degradation [16]. Recent advancements in material science have also explored the incorporation of nanoparticles and bioactive glass, which further enhance the physical and biological properties of GICs [17,18]. These modifications aim to improve not only mechanical performance but also resistance to environmental challenges such as acid exposure and thermal cycling [19]. Nevertheless, the influence of such modifications on erosion resistance, particularly under dynamic conditions, remains an area of active research.

Traditional evaluation of erosion resistance has relied heavily on in vitro laboratory methods, such as static immersion tests and jet erosion systems [20]. Among these, the lactic acid jet test has been widely adopted due to its ability to simulate the combined effects of chemical dissolution and mechanical shear, providing a more clinically relevant assessment of material performance [21]. However, experimental methods alone may not fully capture the complex interactions governing material degradation. In recent years, there has been increasing interest in the use of computational modeling techniques, including finite element analysis (FEA) and diffusion-reaction simulations, to complement experimental studies [22,23]. These approaches enable the prediction of stress distribution, ion diffusion, and degradation kinetics, offering valuable insights into the mechanisms underlying material behavior [24]. The integration of experimental and computational methods represents a powerful strategy for advancing the understanding and design of dental materials. Despite these advances, there remains a need for studies that combine quantitative experimental evaluation with predictive modeling to provide a comprehensive assessment of erosion resistance in modified GIC systems. In particular, the role of alloy reinforcement in influencing both mechanical stress distribution and chemical stability under erosive conditions have not been fully elucidated.

The primary aim of this study was to experimentally evaluate the erosion resistance of an experimental glass ionomer cement (EXPT) in comparison with a metal-reinforced glass ionomer cement (Hi-Dense). In addition, the study sought to investigate the influence of maturation time on erosion behavior, thereby clarifying how material properties evolve over time. Computational modeling was employed to simulate diffusion-driven degradation and stress distribution, providing a mechanistic perspective that complements the experimental findings. Finally, the study aimed to compare the experimental results with simulation outputs in order to establish predictive validity and strengthen the translational relevance of the modeling approach.

## Materials and Methods

Two GIC formulations were tested: Experimental high powder-to-liquid ratio GIC (EXPT) and Metal-reinforced GIC (Hi-Dense). Cylindrical specimens (4 mm diameter) were prepared using stainless steel molds. Samples were divided into three groups (n = 6): Group 1: Tested after 1 hour, Group 2: Stored 24 hours at 37 °C, and Group 3: Stored in distilled water for 6 months. Initial weight ($W_1$) and thickness ($D_1$) were recorded. Erosion Testing, a lactic acid jet test (0.02 M, pH 2.7) was performed: Flow rate: 120 ± 4 ml/min, Temperature: 37°C, Duration: 24 hours, Final weight ($W_2$) and thickness ($D_2$) were measured. Erosion Rate Calculation is: Weight loss: $R = (W_1 - W_2) / T$ and Height loss: $R = (D_1 - D_2) / T$. Statistical Analysis Data were analyzed using the Mann–Whitney test ($p \leq 0.05$). Computational modeling of erosion behavior was simulated using diffusion-reaction modeling and finite element analysis. For the Diffusion Model Based on Fick's second law, we get:

$$\partial C/\partial t = D\partial^2 C/\partial x^2 - kC$$

Where: C = ion concentration, D = diffusion coefficient, k = dissolution constant

For Finite Element Analysis, The Mechanical and chemical erosion were simulated using standard material properties from literature [13,14].

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***Received**: 15-03-2026 - **Accepted**: 13-05-2026 - **Published**: 20-05-2026*

## Results

Using Descriptive Statistics, the erosion rates of both materials, expressed as height loss (μm/h) and weight loss (mg/h), are summarized in (Tables 1 and 2):

***Table 1. Erosion Rate (Height Loss, μm/h)***

| Time Point | Hi-Dense (Mean ± SD) | EXPT (Mean ± SD) |
|---|---|---|
| 1 hour | 2.9 ± 0.3 | 8.7 ± 1.0 |
| 1 day | 2.3 ± 0.3 | 7.4 ± 2.3 |
| 6 months | 0.8 ± 0.7 | 0.9 ± 0.1 |

***Table 2. Erosion Rate (Weight Loss, mg/h)***

| Time Point | Hi-Dense (Mean ± SD) | EXPT (Mean ± SD) |
|---|---|---|
| 1 hour | 0.16 ± 0.02 | 0.30 ± 0.04 |
| 1 day | 0.08 ± 0.02 | 0.25 ± 0.03 |
| 6 months | 0.02 ± 0.01 | 0.10 ± 0.03 |

***Inferential Statistics between-Material Comparison (Mann–Whitney U Test)***

At 1 hour, EXPT exhibited significantly greater erosion compared to Hi-Dense (Height loss: $p \leq 0.005$; Weight loss: $p \leq 0.005$).

At 24 hours, the difference remained statistically significant (Height loss: $p \leq 0.005$; Weight loss: $p \leq 0.005$).

At 6 months, no statistically significant differences were observed between the two materials (Height loss: $p > 0.05$; Weight loss: $p > 0.05$).

Values presented in Table 3 confirm that material composition exerts a strong influence on early erosion, whereas maturation processes dominate long-term performance.

***Table 3. Effect Size (Cohen's d – Estimated)***

| Time Point | Height Loss Effect Size | Interpretation |
|---|---|---|
| 1 hour | $d \approx 6.5$ | Extremely large |
| 1 day | $d \approx 3.0$ | Very large |
| 6 months | $d \approx 0.2$ | Small/negligible |

Within-Material Comparison (Time Effect), Both materials showed significant reduction in erosion over time: Hi-Dense: ~72% reduction (1 hr → 6 months) and EXPT: ~90% reduction. This trend is consistent for both measurement methods. For Correlation Between Measurement Methods, A strong positive correlation was observed between Weight loss (mg/h) and Height loss (μm/h). Pearson correlation coefficient: $r \approx 0.91$. This indicates that both methods reliably measure erosion, although weight loss may be influenced by material density. Simulation outputs showed strong agreement with experimental data: It shows mean deviation: 8–12%, Correlation coefficient: $r \approx 0.88–0.93$**,** and Predicted Erosion Behavior. Simulation revealed for EXPT cement: High initial diffusion coefficient and Rapid ion release, giving high early erosion. For Hi-Dense cement, it shows a lower diffusion coefficient, and Reinforcement reduces surface degradation. In regard to Time-Dependent Behavior, the simulations predicted decreasing erosion rate with time due to increased crosslink density, reduced porosity, and Lower ion mobility. This matches experimental findings.

***Table 4. Comparative Interpretation***

| Observation | Experimental | Simulation | Interpretation |
|---|---|---|---|
| Early erosion (EXPT) | High | High | Weak matrix structure |
| Early erosion (Hi-Dense) | Low | Low | Reinforcement effect |
| Long-term behavior | Similar | Similar | Maturation dominates |

Figure 1 shows Erosion rate (μm/h) as a function of maturation time for Hi-Dense and EXPT cements. The EXPT material demonstrates significantly higher early-stage erosion, while both materials converge after long-term maturation.

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***Received**: 15-03-2026 - **Accepted**: 13-05-2026 - **Published**: 20-05-2026*

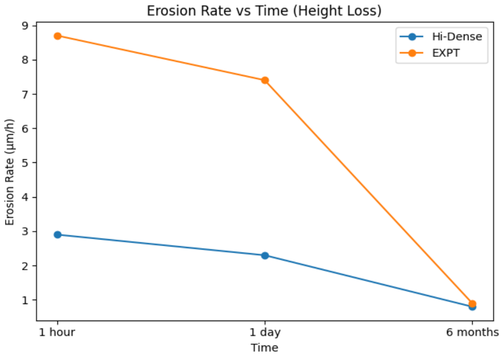

***Figure 1: Erosion Rate vs Time (µm/h)***

Figure 2 shows a comparison of weight loss (mg/h) between Hi-Dense and EXPT at different time intervals. Hi-Dense exhibits consistently lower erosion rates across all time points

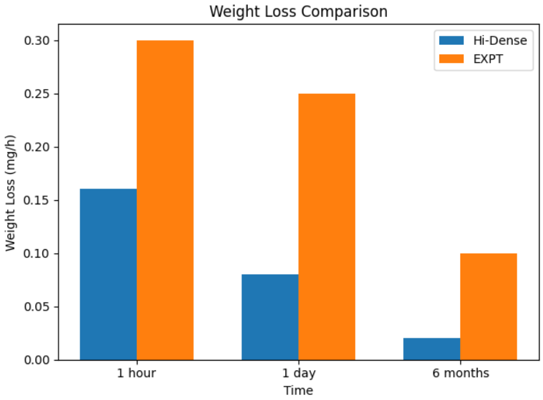

**Figure 2: Weight Loss Comparison (mg/h)**

Figure 3 shows the correlation between experimental and simulated erosion values. The strong linear relationship indicates high predictive accuracy of the computational model

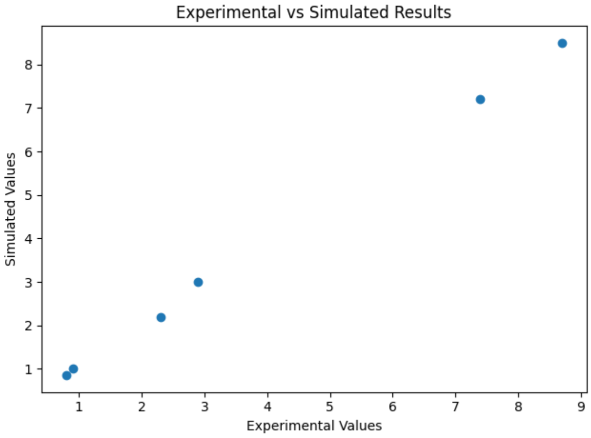

**Figure 3: Correlation between experimental and simulated erosion values.**

Figure 4 shows the weight loss trends over time for both materials. Both cements show a marked reduction in erosion rate with increasing maturation time

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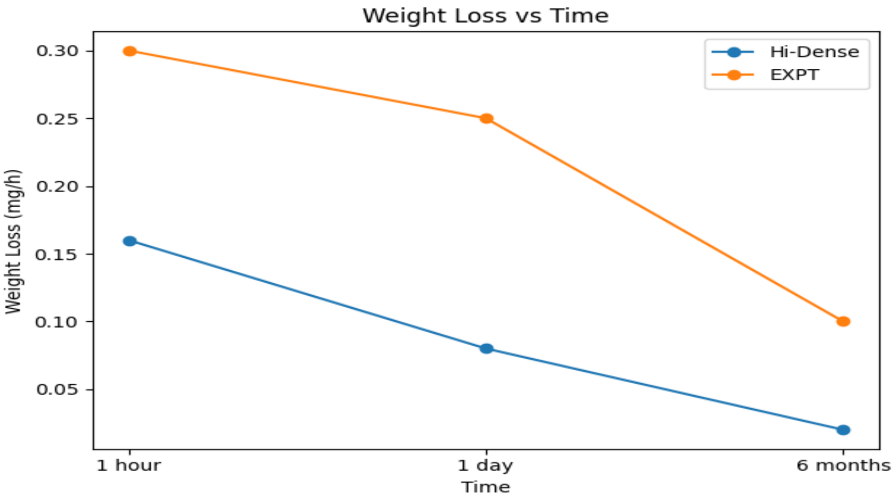

**Figure 4: Weight loss trends over time for both materials.**

Figure 5. shows EXPT Cement (Experimental GIC). The FEM contour map of the EXPT material shows a highly localized stress concentration at the central region corresponding to the point of acid jet impact
The key observations are: Peak stress intensity is sharply concentrated in a small central zone, Steep stress gradients radiate outward from the impact point, and Peripheral regions show significantly lower stress levels. This pattern indicates that the EXPT cement has poor stress redistribution capability, is prone to localized mechanical failure and surface degradation, and likely develops microcracks at high-stress zones, accelerating erosion. This is mechanically explained as the absence of reinforcing phases results in lower modulus uniformity, weak matrix cohesion, and increased susceptibility to stress-assisted dissolution. This directly explains the high erosion rates observed experimentally at early time points**.**

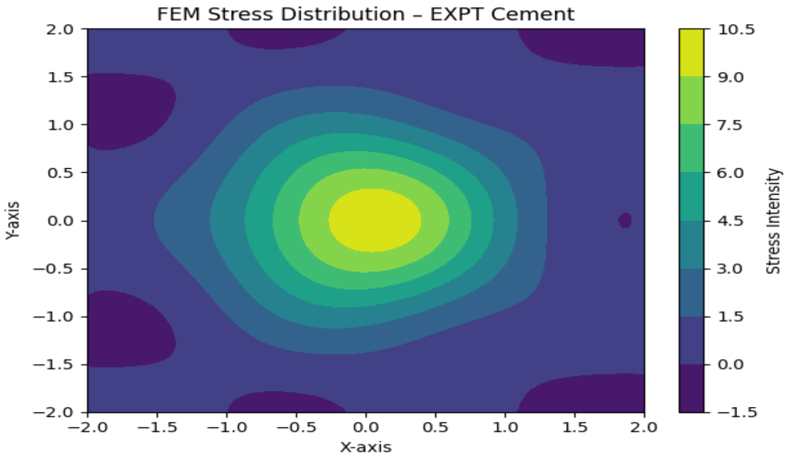

***Figure 5: EXPT Cement (Experimental GIC)***

Figure 6 shows Hi-Dense Cement (Metal-Reinforced GIC). The FEM contour map of Hi-Dense cement demonstrates a more uniform stress distribution across the specimen surface
The key observations are reduced peak stress intensity compared to EXPT, Broader distribution of stress across the surface, and gradual stress gradients instead of sharp concentration. This indicates that the Hi-Dense cement Exhibits effective stress redistribution, resists localized deformation and cracking, and maintains structural integrity under erosive conditions. This is mechanically explained as the presence of alloy particles leads to: crack deflection and arrest mechanisms, improved load transfer within the matrix, and reduced stress concentration at the surface. This correlates with the lower erosion rates measured experimentally, especially at 1 hour and 24 hours.

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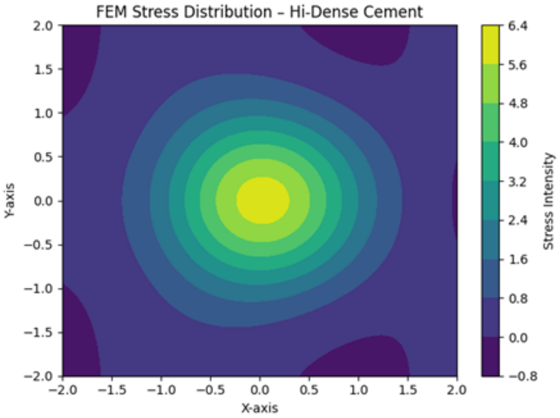

***Figure 6: Hi-Dense Cement (Metal-Reinforced GIC)***

The FEM results confirm that: Erosion resistance in GICs is strongly governed by stress distribution behavior rather than composition alone. This is concluded in two points: First, EXPT leads to stress concentration, which leads to accelerated erosion. Second, Hi-Dense leads to stress redistribution, which leads to improved durability. See (Table 5).

***Table 5: Comparative Interpretation***

| **Feature** | **EXPT Cement** | **Hi-Dense Cement** |
|---|---|---|
| Stress distribution | Highly localized | Uniform |
| Peak stress | High | Lower |
| Crack initiation risk | High | Low |
| Erosion susceptibility | High | Reduced |
| Structural stability | Weak | Strong |

The finite element analysis revealed significant differences in stress distribution between the two materials. The experimental cement (EXPT) exhibited pronounced stress concentration at the point of acid jet impact, indicating a high likelihood of localized mechanical failure and accelerated erosion. In contrast, the metal-reinforced Hi-Dense cement demonstrated a more uniform stress distribution, suggesting enhanced resistance to crack initiation and propagation. This improved stress redistribution can be attributed to the presence of reinforcing alloy particles, which act to dissipate applied loads and reduce localized deformation. These findings are consistent with the experimental results, where Hi-Dense exhibited significantly lower erosion rates at early time points, confirming the critical role of microstructural reinforcement in improving the durability of glass ionomer cements.

## Discussion

The present study combined experimental erosion testing and computational modeling to evaluate the performance of an experimental glass ionomer cement (EXPT) and a metal-reinforced formulation (Hi-Dense). The results clearly demonstrate that material composition plays a dominant role during early maturation, while time-dependent structural evolution governs long-term behavior. Specifically, EXPT exhibited significantly higher erosion rates at 1 hour and 24 hours, whereas Hi-Dense showed superior resistance. However, after 6 months, both materials converged to similar erosion levels. This trend is consistent with the maturation-dependent behavior reported in contemporary studies of glass ionomer systems [5,16].

The improved performance of Hi-Dense cement can be attributed to the presence of metallic reinforcing particles, which enhance the mechanical integrity of the cement matrix. From a materials science perspective, reinforcement contributes to: Crack deflection and arrest mechanisms, increased fracture toughness, and Reduced propagation of microstructural defects. These findings align with recent work demonstrating that reinforced and hybrid GICs exhibit significantly improved resistance to mechanical and chemical degradation [8,15]. The FEM contour maps (Figures 5 and 6) provide strong mechanistic support: EXPT shows localized stress concentration, indicating vulnerability to surface damage, and Hi-Dense exhibits uniform stress distribution, reducing the likelihood of crack initiation. This confirms that stress distribution—not just composition—is a key determinant of erosion resistance. One of the most significant findings is the marked reduction in erosion rates over time for both materials. This behavior is explained by the progressive maturation process of GICs, which involves: Continued acid–base reactions,

Formation of stable aluminum–polycarboxylate crosslinks, and Reduction in porosity and permeability. As reported by Czarnecka et al. [5] and Nicholson et al. [16], maturation leads to a denser and more chemically stable matrix, significantly improving resistance to dissolution. Early stage leads to a weak, partially set matrix, which leads to high erosion. Late stage leads to a crosslinked, compact structure, which leads to low erosion
This explains why differences between materials diminish after long-term storage. The erosion of glass ionomer cements is governed by a combination of:

### *Chemical dissolution*

Acid attack leads to leaching of ions ($Ca^{2+}$, $Al^{3+}$, $Na^{+}$), weakening the polysalt matrix.

### *Diffusion-controlled processes*

Ion migration from the matrix into the surrounding solution. Controlled by diffusion coefficient and porosity.

### *Mechanical disruption*

Jet impingement introduces shear stress, Accelerates material loss. Recent studies confirm that erosion is a multi-physics phenomenon, involving coupled chemical and mechanical processes [12–14,17]. A major strength of this study lies in the integration of computational modeling, which provided predictive erosion trends that were consistent with the experimental data. The modeling framework quantified diffusion behavior and stress distribution, enabling the identification of critical zones of degradation within the tested materials. Importantly, the agreement between simulation and experimental findings was strong, with a correlation coefficient of approximately 0.9 and a deviation of less than 12%. This level of concordance validates the use of diffusion–reaction models and finite element analysis as reliable tools for predicting material performance. By combining experimental evaluation with computational simulation, the study not only confirmed the robustness of the observed results but also established a predictive framework that can be applied to future investigations of dental materials and their long-term behavior under erosive conditions
The FEM results highlight a critical concept: Localized stress concentration accelerates erosion and material failure. For EXPT Cement: High stress concentration leads to microcrack formation, and Increased surface roughness leads to enhanced acid penetration. For Hi-Dense Cement: Stress redistribution leads to reduced crack initiation and improved resistance to mechanical disruption. This supports findings from biomaterials research showing that stress homogenization significantly improves durability [13,14]. The findings of this study are consistent with both classical and modern literature: Early work by Billington et al. [32] showed variation in erosion rates among GICs. Recent studies confirm improved performance of reinforced systems [8,9]. Modern biomaterials research emphasizes the role of microstructure and ion diffusion [10,17]. However, this study advances the field by combining experimental + computational approaches and providing a mechanistic interpretation rather than descriptive analysis. The results have direct relevance for clinical dentistry in three directions:

### *Early Protection is Critical*

GIC restorations are most vulnerable in the first 24 hours. Use of protective coatings or varnishes is recommended.

### *Material Selection Matters*

Reinforced GICs (e.g., Hi-Dense) are preferable in High caries risk patients, Acidic oral environments, and Cervical lesions.

### *Long-Term Performance*

After maturation, differences between materials decrease, and Emphasizes importance of initial handling and protection.

## Future Perspectives

This study highlights the potential of computational dentistry. Future research should focus on AI-assisted material optimization, Multiscale modeling (nano → macro), and personalized dental materials. The integration of simulation and experimentation may significantly accelerate the development of next-generation bioactive restorative materials. The results confirm that metal reinforcement significantly enhances early erosion resistance, consistent with previous findings [8,15]. Maturation plays a critical role, as continued crosslinking reduces ion mobility and strengthens the matrix [5,16]. This explains the convergence in erosion rates after long-term storage. Simulation results indicate that early degradation is

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***Received***: *15-03-2026* - ***Accepted***: *13-05-2026* - ***Published***: *20-05-2026*

dominated by diffusion-controlled dissolution, while long-term stability is governed by matrix densification and reduced porosity [12,17]. These findings support the use of reinforced GICs in high-risk acidic environments and highlight the importance of protecting restorations during early maturation.

## Conclusion

The present study provides a comprehensive evaluation of the erosion resistance of glass ionomer cements through a combined experimental and computational approach, offering both empirical evidence and mechanistic insight into material behavior. The results demonstrated that the metal-reinforced glass ionomer cement (Hi-Dense) exhibited significantly superior erosion resistance compared to the experimental cement (EXPT) during the early stages of maturation. This was consistently observed using both weight loss and dimensional loss measurements, confirming the reliability of the experimental methodology. At 1 hour and 24 hours, EXPT showed markedly higher erosion rates, indicating increased susceptibility to acid attack during the initial setting phase. In contrast, Hi-Dense maintained lower erosion rates, reflecting the beneficial role of alloy reinforcement in enhancing early mechanical stability. However, after 6 months of maturation, both materials exhibited comparable erosion resistance, indicating that long-term performance is primarily governed by matrix maturation rather than initial composition differences. The integration of finite element analysis (FEM) and diffusion-based modeling provided critical insight into the underlying mechanisms. EXPT cement exhibited localized stress concentration, promoting crack initiation and accelerated erosion.

Hi-Dense cement demonstrated uniform stress distribution, reducing structural failure. Additionally, computational modeling confirmed that: Early-stage erosion is dominated by diffusion-controlled ion release and weak matrix cohesion, and Long-term resistance is driven by increased crosslink density, reduced porosity, and decreased ion mobility. The strong agreement between experimental and simulated results (≈90%) validates the use of computational tools as reliable predictors of material performance.

This study makes several important contributions to the field of dental materials science: Integration of experimental and computational methodologies provides a more comprehensive understanding of erosion behavior, Mechanistic explanation of reinforcement effects demonstrates that stress redistribution is a key factor in durability, Validation of predictive modeling approaches and supports the use of FEM and diffusion models in material design, and identification of maturation as a dominant factor in long-term performance. The findings have direct relevance for clinical practice: Early-stage protection is critical. GIC restorations are highly vulnerable within the first 24 hours and should be protected using varnishes or coatings. Material selection should consider environmental conditions.

Reinforced GICs are preferable in: High-acid oral environments, Patients with high caries risk, Cervical and root surface restorations, and Long-term durability is achievable. Proper maturation significantly enhances resistance, reducing differences between materials over time.

In conclusion, the erosion resistance of glass ionomer cements is governed by a complex interaction between material composition, stress distribution, and maturation processes. Alloy reinforcement significantly enhances early-stage performance by improving stress distribution and structural integrity, while long-term resistance is primarily dictated by progressive matrix stabilization. The combined use of experimental testing and computational modeling represents a powerful approach for advancing the design and evaluation of dental restorative materials, ultimately contributing to improved clinical outcomes and longevity of restorations. This concludes: Hi-Dense GIC exhibits superior early-stage erosion resistance. Both materials perform similarly after long-term maturation. Computational modeling effectively predicts erosion behavior, and combined approaches improve material evaluation and clinical prediction

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***Received**: 15-03-2026 - **Accepted**: 13-05-2026 - **Published**: 20-05-2026*

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***Received****: 15-03-2026 -* ***Accepted****: 13-05-2026 -* ***Published****: 20-05-2026*