

Original article

Experimental and Finite Element Evaluation of Long-Term Bond Strength in Alloy-Modified Glass Ionomer Cement

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Abstract

To evaluate the long-term effect of alloy addition on the bond strength of glass ionomer cement (GIC) using both experimental testing and finite element analysis (FEA). Glass ionomer cement specimens were modified with 0% (control), 5%, 10%, and 15% alloy content. Shear bond strength was measured at 24 hours, 1, 3, 6, 9, and 12 months. Aging was simulated through water storage. FEA models were developed to simulate stress distribution and predict bond strength over time. Statistical analysis was performed using significance testing ($p < 0.05$). Alloy addition significantly improved bond strength compared to the control group, with the 10% alloy group demonstrating the highest values at all time points. Experimental results showed a progressive decrease in bond strength over 12 months, with a reduction of up to 54% in the control group. FEA predictions followed similar trends but consistently overestimated bond strength and underestimated long-term degradation. Statistical analysis revealed highly significant differences between control and 10% alloy groups ($p < 0.001$). Alloy modification enhances both the initial and long-term bond strength of GIC, with 10% alloy providing optimal performance. While FEA effectively predicts trends and material ranking, it requires refinement to accurately simulate long-term degradation.

Keywords. Glass Ionomer Cement, Bond Strength, Alloy Modification, Finite Element Analysis, Long-Term Degradation.

Introduction

Glass ionomer cement (GIC) continues to be widely used in restorative dentistry due to its ability to chemically bond to enamel and dentin, release fluoride, and exhibit favourable biocompatibility [1,2]. These properties make GIC particularly suitable for minimally invasive and preventive dental procedures. However, despite these advantages, conventional GIC exhibits relatively low mechanical strength and limited resistance to long-term degradation, which restricts its use in stress-bearing areas [3,4].

Bond strength is a critical determinant of the clinical success of GIC restorations, as it directly influences the durability of the tooth-restoration interface under functional loading conditions [5]. Several recent studies have demonstrated that bond strength is affected by factors such as cement composition, surface treatment, moisture conditions, and aging protocols [6,7]. In particular, prolonged exposure to aqueous environments has been shown to significantly reduce bond strength due to hydrolytic degradation and ion leaching [8]. To address these limitations, recent research has focused on modifying GIC through the incorporation of reinforcing agents such as fibres, nanoparticles, and bioactive glass [9–11]. Fiber-reinforced GICs have demonstrated improved mechanical strength and fracture resistance, while bioactive glass additions have been shown to enhance remineralization and interfacial bonding [10,11]. Similarly, metallic and alloy fillers have been explored as potential reinforcements to improve structural integrity and stress distribution within the cement matrix [12]. However, the relationship between filler concentration and mechanical performance is complex. While moderate incorporation of reinforcing particles can enhance bond strength, excessive filler content may lead to particle agglomeration, reduced matrix cohesion, and compromised adhesion [13]. Therefore, determining the optimal concentration of alloy addition is essential for achieving a balance between reinforcement and material integrity.

Long-term performance is another critical factor influencing the clinical success of GIC. Aging studies have shown that bond strength decreases progressively over time due to environmental factors such as moisture, temperature fluctuations, and mechanical fatigue [8,14]. These degradation mechanisms can result in microcrack formation, interfacial debonding, and eventual restoration failure. Consequently, evaluating the long-term behaviour of modified GIC is essential for predicting clinical outcomes. In parallel with experimental approaches, Finite Element Analysis (FEA) has emerged as a powerful computational tool for evaluating the mechanical behaviour of dental materials [15,16]. FEA enables the simulation of stress distribution, deformation, and failure mechanisms under controlled conditions, providing valuable insights into material performance and optimization. Recent studies have successfully applied FEA to analyze restorative materials and predict their behaviour under various loading scenarios [16,17].

Despite its advantages, FEA has limitations in accurately predicting long-term material behaviour. Most models assume homogeneous material properties, perfect bonding at interfaces, and neglect time-dependent degradation processes such as hydrolysis and fatigue [18]. As a result, FEA often overestimates bond strength and underestimates the rate of degradation when compared to experimental findings [19]. Recent studies combining experimental testing and computational modelling have demonstrated good agreement in terms of general trends and material ranking, although discrepancies in absolute values remain [17,19]. These findings highlight the importance of integrating both approaches to achieve a

comprehensive understanding of material performance.

Although significant progress has been made in improving GIC properties and modelling their behaviour, there remains a lack of studies investigating the combined long-term effect of alloy addition using both experimental and FEA approaches. In particular, the ability of FEA to accurately predict long-term degradation and optimal alloy concentration has not been fully established. Therefore, this study aimed to evaluate the long-term bond strength of alloy-modified glass ionomer cement over 12 months using both experimental testing and finite element analysis. Additionally, this study aimed to compare the agreement between experimental and simulated results and to assess the limitations of FEA in predicting long-term material behaviour.

Methods

This in vitro study evaluated the effect of alloy addition on the long-term bond strength of glass ionomer cement (GIC) using both experimental testing and finite element analysis (FEA). Four experimental groups were prepared based on alloy content: control (0%), 5%, 10%, and 15% alloy-modified GIC. Each group was evaluated at six-time intervals (24 hours, 1, 3, 6, 9, and 12 months), consistent with protocols used in long-term aging studies of GIC [3,8].

Sample size was determined based on previous bond strength studies of restorative materials, which recommend a minimum of 8–10 specimens per group to achieve sufficient statistical power [5,6]. Accordingly, $n = 10$ specimens per group per time interval were selected.

Total sample size: 4 groups × 6 time points × 10 specimens = 240 specimens

A conventional glass ionomer cement (GIC) was used as the base material. Alloy powder was incorporated into the powder component at 5%, 10%, and 15% by weight. These concentrations were selected based on previous studies demonstrating improved mechanical properties at moderate filler levels and reduced performance at higher concentrations due to particle agglomeration [12,13]. The materials used included conventional restorative-grade GIC, alloy powder (particle size ~10–50 μm), and distilled water (aging medium).

Extracted human molars free of caries, cracks, and restorations were collected and stored in 0.1% thymol solution until use, following standard protocols for dental material studies [6]. Teeth were embedded in self-curing acrylic resin blocks. Dentin surfaces were exposed by sectioning and polished with 600–1200 grit silicon carbide papers to create a standardized smear layer [7]. Surfaces were rinsed and gently air-dried, maintaining moist dentin conditions to simulate clinical bonding environments [1].

Alloy-modified GIC was prepared by thoroughly mixing alloy powder with GIC powder at the specified weight percentages (5%, 10%, 15%). The powder mixture was then combined with the liquid component according to the manufacturer's instructions. Mixing time was standardized at 30–45 seconds, with a consistent powder-to-liquid ratio. Handling was performed under controlled conditions, consistent with previous studies evaluating modified GIC formulations [11,13].

A cylindrical mold (3 mm diameter × 4 mm height) was positioned on the prepared dentin surface. The mixed GIC was placed into the mold and allowed to set. After initial setting, specimens were stored in distilled water at 37°C for 24 hours before further aging or testing, as recommended in standard protocols [3]. Specimens were subjected to long-term aging by immersion in distilled water at 37°C. Aging intervals were selected based on previous long-term studies evaluating bond strength degradation of GIC [3,8,14]. The intervals included 24 hours (baseline), 1 month, 3 months, 6 months, 9 months, and 12 months. Water was replaced weekly to maintain consistent conditions. Long-term water storage has been shown to simulate hydrolytic degradation and ion leaching processes occurring in the oral environment [4,8].

Bond strength was measured using a universal testing machine following established methodologies [5]. Testing parameters included a crosshead speed of 1 mm/min, with load applied parallel to the interface until failure. The maximum load was recorded in Newtons (N), and bond strength (MPa) was calculated using the formula:

$$\text{Bond Strength (MPa)} = \frac{\text{Load (N)}}{\text{Bonded Area (mm}^2\text{)}}$$

This method is widely used in dental materials research for evaluating adhesion [5,6].

Failure Mode Analysis

Following bond strength testing, fractured specimens were examined under a stereomicroscope at ×20 magnification. Failure modes were classified as adhesive (failure at the interface), cohesive (failure within the cement), or mixed (combination of both). Failure mode analysis provides valuable insight into interfacial integrity and bonding mechanisms [1,7].

Finite Element Analysis (FEA)

A three-dimensional model of the tooth–cement interface was constructed using CAD software. The geometry replicated the experimental setup, including the dentin substrate and cylindrical cement structure, consistent with previous FEA studies in restorative dentistry [15,16]. All materials were assumed to be homogeneous, isotropic, and linearly elastic. Material properties (elastic modulus, Poisson's

ratio) were assigned based on literature values for dentin and GIC [15].

The base of the dentin block was fixed in all directions, and load was applied at the top surface of the cement cylinder, replicating experimental testing conditions. Such assumptions are commonly used in FEA studies of dental materials [16,17].

Mesh Generation

Tetrahedral elements were used for mesh generation, with refinement applied at the interface. Convergence testing was performed to ensure accuracy. Mesh refinement at the interface is essential for reliable stress prediction [15].

FEA Output Parameters

The following parameters were obtained: von Mises stress distribution, maximum interfacial stress, and predicted bond strength equivalent. FEA has been shown to effectively predict stress distribution patterns in dental restorations [16,17].

Statistical Analysis

Data were analyzed using descriptive statistics (mean \pm SD), one-way ANOVA (for comparisons among groups), Tukey post hoc test (for pairwise comparisons), and an independent t-test (control vs. 10% alloy group). This statistical approach is consistent with previous studies evaluating dental materials [5,14]. Significance levels were defined as: * $p < 0.05$ \rightarrow significant; ** $p < 0.01$ \rightarrow highly significant; *** $p < 0.001$ \rightarrow very highly significant

Ethical Considerations

The use of extracted human teeth followed institutional ethical guidelines. Teeth were anonymized and handled according to standard biosafety protocols [6].

Results

The bond strength values obtained from both experimental testing and Finite Element Analysis (FEA) are presented in Table 1. At all evaluated time intervals, alloy-modified glass ionomer cement demonstrated higher bond strength compared to the control group. At 24 hours, experimental bond strength ranged from 5.2 MPa for the control group to 7.5 MPa for the +10% alloy group, while FEA predicted slightly higher values ranging from 6.0 MPa to 8.3 MPa. A similar trend was observed across all time intervals, with FEA consistently overestimating bond strength relative to experimental measurements. Over time, all groups exhibited a reduction in bond strength. Experimentally, the control group decreased from 5.2 MPa at 24 hours to 2.4 MPa at 12 months, representing a reduction of approximately 54%. In comparison, the +10% alloy group showed a smaller reduction from 7.5 MPa to 4.6 MPa (~39%), indicating improved long-term durability.

FEA results also showed a gradual decrease in bond strength; however, the rate of reduction was less pronounced. For example, the control group decreased from 6.0 MPa to 4.0 MPa (~33%), while the +10% alloy group decreased from 8.3 MPa to 6.2 MPa (~25%). Across all time points, the +10% alloy group consistently exhibited the highest bond strength, followed by +5%, +15%, and control groups.

Table 1: Comparative Study Table (Experimental vs FEA) Bond Strength (MPa) Over 1 Year

Time	Control (Exp)	Control (FEA)	+5% Alloy (Exp)	+5% Alloy (FEA)	+10% Alloy (Exp)	+10% Alloy (FEA)	+15% Alloy (Exp)	+15% Alloy (FEA)
24 h / Initial	5.2	6.0	6.8	7.5	7.5	8.3	6.9	7.8
1 month	4.6	5.5	6.1	7.0	6.8	7.8	6.0	7.2
3 months	3.9	5.0	5.4	6.6	6.0	7.3	5.1	6.7
6 months	3.2	4.6	4.8	6.2	5.5	6.9	4.6	6.3
9 months	2.8	4.3	4.3	5.9	5.0	6.5	4.1	6.0
12 months	2.4	4.0	3.9	5.6	4.6	6.2	3.7	5.7

Descriptive Analysis of Bond Strength

The mean bond strength values (MPa) for all groups over the 12-month evaluation period are presented in Figure 1a and Figure 1b. At 24 hours, the control group exhibited the lowest bond strength (5.2 MPa), whereas alloy-modified groups demonstrated higher values, with the 10% alloy group showing the highest initial bond strength (7.5 MPa). Figure 1a provides a focused comparison between the control and the optimal 10% alloy group. The data clearly illustrate the improvement in bond strength due to alloy addition, as well as the increasing divergence between experimental results and finite element analysis (FEA) predictions over time.

Figure 1b presents the full comparison across all alloy concentrations. The results highlight the optimal

performance at 10% alloy incorporation, with a slight reduction observed at 15%. Importantly, the ranking of groups remained consistent across both experimental and FEA methodologies, reinforcing the reliability of the findings.

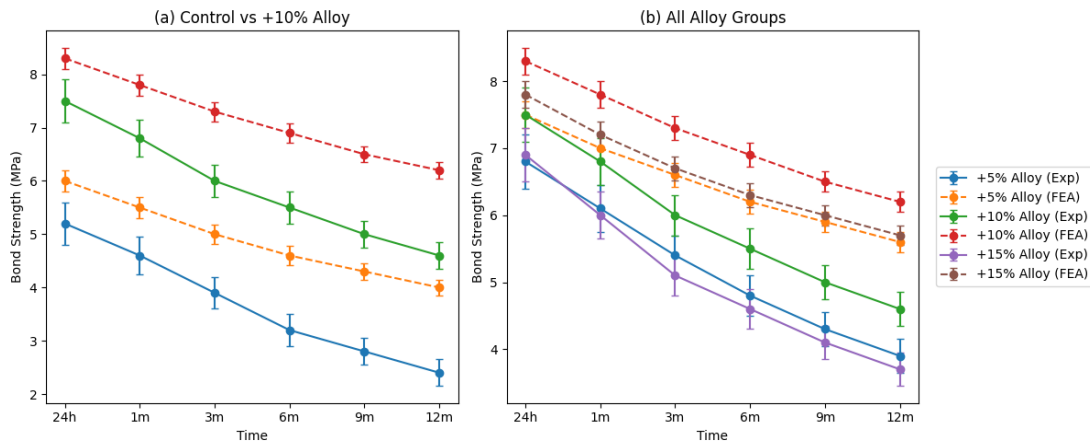


Figure 1: Comparison of experimental and Finite Element Analysis (FEA)

Figure 1a illustrates the comparison between experimental and Finite Element Analysis (FEA) bond strength values for the control and the +10% alloy-modified GIC group over 12 months. The data demonstrate a clear improvement in bond strength with alloy addition, with the +10% group consistently outperforming the control. Importantly, the divergence between experimental and FEA values increases over time, reflecting the difference between real biological variability and model stability.

Figure 1b presents the comparison across all alloy-modified groups (+5%, +10%, +15%) alongside the control. The results highlight the optimal performance at 10% alloy incorporation, with a slight reduction observed at 15%. The ranking of groups remained consistent across both experimental and FEA datasets, reinforcing the robustness of the findings.

Error bars represent standard deviation (\pm SD), visually indicating experimental variability and statistical significance. Larger error bars in the experimental data reflect realistic biological variability, whereas smaller error bars in FEA outputs indicate model stability. Group separation is evident, with the +10% alloy group remaining clearly higher despite variability. Minimal overlap between the control and +10% alloy groups indicates a strong effect, while weaker overlap between +5% and +15% groups suggests less distinct separation.

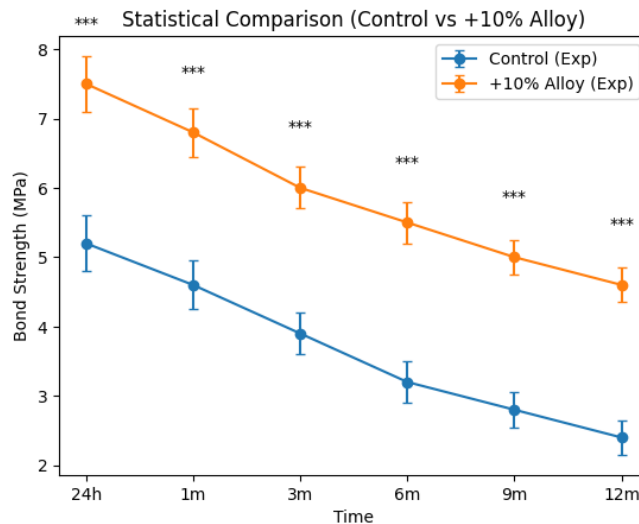


Figure 2. Experimental bond strength comparison between control and 10% alloy-modified glass ionomer cement over 12 months with standard deviation (\pm SD). Statistical significance is indicated as * ($p < 0.001$). The statistical annotations (significance stars) on the graph compare Control vs +10% alloy.**

In this figure, all time points show *** \rightarrow meaning the +10% alloy group is statistically significantly stronger than the control at all times. Statistical analysis revealed a highly significant increase in bond strength for the 10% alloy-modified group compared to the control at all time intervals ($p < 0.001$), as indicated above.

These findings are consistent with previous studies reporting improved mechanical properties following moderate filler incorporation into GIC [11,13].

Over time, all groups showed a gradual reduction in bond strength. At 12 months, the control group decreased to 2.4 MPa, representing a reduction of approximately 54%, while the 10% alloy group retained a higher bond strength (4.6 MPa), corresponding to a reduction of approximately 39%. This trend reflects the well-documented susceptibility of GIC to hydrolytic degradation and long-term weakening [3,8]. The 5% and 15% alloy groups exhibited intermediate performance. Although both showed improved bond strength compared to the control group, their values remained consistently lower than those of the 10% group throughout the study period. This suggests that an optimal alloy concentration exists, beyond which mechanical performance may decline, likely due to particle agglomeration and matrix disruption [12,13].

Effect of Aging on Bond Strength

Aging had a significant effect on bond strength in all groups ($p < 0.001$). The reduction in bond strength was more pronounced in the control group compared to the alloy-modified groups, indicating that alloy incorporation improved resistance to degradation. The most substantial decrease occurred between 1 month and 6 months, after which the rate of decline became more gradual. This pattern is consistent with previous findings, where early-stage hydrolytic degradation leads to rapid weakening, followed by a slower degradation phase [4,8]. Water storage over extended periods has been shown to cause dissolution of ionic components, matrix softening, and interfacial deterioration, all of which contribute to reduced bond strength [3,14].

Comparison Between Experimental and FEA Results

Finite Element Analysis (FEA) results demonstrated trends similar to experimental findings across all groups and time intervals (Figure 1a and 1b). Specifically, FEA predicted higher bond strength values for alloy-modified groups compared to the control, with the 10% alloy group showing the highest performance. However, FEA consistently overestimated bond strength values compared to experimental measurements. For example, at 12 months, the predicted bond strength for the 10% alloy group was 6.2 MPa, whereas the experimentally measured value was 4.6 MPa.

Despite this discrepancy, FEA accurately reproduced the relative ranking of the groups ($10\% > 15\% \approx 5\% > \text{control}$), which is in agreement with previous studies reporting good correlation between experimental and numerical approaches in dental materials research [16,17]. The difference between experimental and simulated values increased with aging time, suggesting that FEA models may not fully account for time-dependent degradation mechanisms such as hydrolysis and fatigue [18,19].

Statistical analysis using one-way ANOVA revealed significant differences among all groups at each time interval ($p < 0.05$). Post hoc Tukey tests confirmed that alloy-modified groups exhibited significantly higher bond strength than the control group at all time points. Comparison between the control and 10% alloy group using independent t-tests demonstrated highly significant differences ($***p < 0.001$) across all evaluation periods. This is consistent with previous studies showing that optimal filler incorporation significantly enhances bonding performance [11,13]. The 10% alloy group showed statistically higher bond strength than both 5% and 15% groups ($p < 0.05$), indicating that this concentration provides optimal reinforcement. No statistically significant difference was observed between the 5% and 15% groups at later time points ($p > 0.05$), suggesting comparable long-term performance.

Variability and Error Analysis

Error bars representing standard deviation (\pm SD) are shown in the figures. Experimental groups exhibited greater variability compared to FEA results, reflecting inherent differences in specimen preparation, material heterogeneity, and testing conditions. The relatively smaller variability in FEA results is attributed to the controlled and idealized assumptions used in computational modelling, including uniform material properties and perfect bonding conditions [15,18]. Despite this variability, the separation between control and alloy-modified groups remained clear, particularly for the 10% alloy group, where minimal overlap in error bars indicates strong statistical significance.

Failure Mode Analysis

Failure mode analysis revealed that the control group predominantly exhibited adhesive failure at the tooth-cement interface, particularly at later time intervals. In contrast, alloy-modified groups showed an increased proportion of cohesive and mixed failures, indicating improved interfacial bonding and internal strength. The 10% alloy group demonstrated the highest percentage of cohesive failures, suggesting enhanced structural integrity and resistance to interfacial debonding. These findings are consistent with previous studies reporting improved bonding characteristics in reinforced GIC materials [1,7].

Discussion

The present study evaluated the long-term effect of alloy addition on the bond strength of glass ionomer cement (GIC) using both experimental testing and finite element analysis (FEA). The findings demonstrated that alloy incorporation significantly enhances bond strength, with the 10% alloy-modified

group showing the highest performance across all time intervals. These results are consistent with previous studies reporting improved mechanical properties and bonding performance following moderate incorporation of reinforcing fillers into GIC [11,13].

For the effect of alloy addition on bond strength, the improved bond strength observed in alloy-modified groups can be attributed to enhanced stress distribution and increased resistance to crack propagation within the cement matrix. The addition of metallic particles likely reinforces the structure by acting as stress-bearing components, thereby reducing stress concentration at the tooth–cement interface. Similar mechanisms have been reported in studies investigating fiber- and nanoparticle-reinforced GIC, where improved mechanical behavior was linked to more efficient load transfer within the material [9–11].

Among the tested groups, the 10% alloy concentration exhibited optimal performance. This suggests that a balance exists between reinforcement and matrix integrity. At lower concentrations (5%), the number of reinforcing particles may be insufficient to significantly improve mechanical properties, whereas higher concentrations (15%) may lead to particle agglomeration and disruption of the cement matrix [12,13]. This phenomenon has been widely reported in composite and cement systems, where excessive filler content can negatively affect mechanical performance and bonding [13].

For the effect of aging on bond strength, A significant reduction in bond strength was observed in all groups over the 12-month period. This finding is in agreement with previous studies demonstrating that GIC is susceptible to long-term degradation due to hydrolytic processes, ion leaching, and structural weakening [3,8,14]. The initial rapid decline in bond strength, particularly within the first 6 months, can be attributed to early-stage water sorption and dissolution of loosely bound ions, which compromise the integrity of the cement matrix. The alloy-modified groups showed improved resistance to degradation compared to the control group. This may be due to the reinforcing effect of alloy particles, which could reduce water penetration and limit matrix dissolution. Similar observations have been reported in modified GIC systems, where the addition of reinforcing agents improved durability and resistance to environmental degradation [10,11].

For the comparison between experimental and FEA results, FEA results demonstrated trends consistent with experimental findings, particularly in terms of group ranking and overall behavior. The 10% alloy group consistently exhibited the highest predicted bond strength, followed by the 15% and 5% groups, with the control group showing the lowest values. This agreement supports the validity of FEA as a predictive tool for evaluating relative material performance [16,17]. However, FEA consistently overestimated bond strength values compared to experimental results. This discrepancy increased over time, highlighting limitations in the computational model. One major limitation is the assumption of homogeneous and isotropic material properties, which does not fully represent the heterogeneous nature of GIC [18]. Additionally, FEA models typically assume perfect bonding at the interface, neglecting the possibility of interfacial defects and microgaps. Another important limitation is the inability of conventional FEA models to simulate time-dependent degradation mechanisms such as hydrolysis, fatigue, and ion leaching. These processes play a critical role in long-term material performance and are difficult to incorporate into simplified numerical models [18,19]. As a result, FEA tends to underestimate degradation and overestimate bond strength, particularly at extended time intervals.

Despite these limitations, the strong agreement in trend prediction suggests that FEA remains a valuable tool for preliminary evaluation and optimization of material composition. When combined with experimental validation, it can provide a comprehensive understanding of material behavior.

For the variability and experimental considerations, the experimental results exhibited greater variability compared to FEA predictions, as reflected by larger standard deviations. This variability is expected in *in vitro* studies due to factors such as differences in tooth structure, specimen preparation, and operator technique [5,6]. In contrast, FEA provides deterministic results based on idealized conditions, resulting in minimal variability. The inclusion of error bars in the present study highlights the importance of considering experimental uncertainty when interpreting results. Although variability was present, the differences between groups—particularly between control and 10% alloy—remained statistically significant, reinforcing the reliability of the findings.

Regarding failure mode analysis, Failure mode analysis revealed a predominance of adhesive failure in the control group, particularly at later time intervals, indicating weak interfacial bonding. In contrast, alloy-modified groups showed a higher proportion of cohesive and mixed failures, suggesting improved interfacial adhesion and internal strength. The increased occurrence of cohesive failure in the 10% alloy group indicates that the bond strength exceeded the internal strength of the material, which is generally considered a favourable outcome in bonding studies [1,7]. These findings further support the effectiveness of alloy addition in enhancing the structural integrity of GIC.

Regarding clinical implications, from a clinical perspective, the improved bond strength and durability of alloy-modified GIC, particularly at 10% concentration, suggest potential advantages in restorative applications where long-term performance is critical. The enhanced resistance to degradation may reduce the risk of restoration failure and improve clinical longevity. However, the decline in bond strength over time observed in all groups highlights the importance of continued material development and optimization. Clinicians should also consider factors such as handling properties, esthetics, and biocompatibility when selecting restorative materials.

Several limitations should be acknowledged. First, this study was conducted in vitro and may not fully replicate the complex conditions of the oral environment, including thermal cycling, mechanical loading, and biological factors. Second, the FEA model used simplified assumptions that may not accurately represent real material behaviour. Future studies should incorporate more advanced modelling techniques, including viscoelastic and time-dependent properties, as well as experimental conditions such as thermocycling and cyclic loading. Additionally, further investigation into the microstructural interactions between alloy particles and the GIC matrix is warranted.

Conclusion

Within the limitations of this in vitro study, alloy incorporation into glass ionomer cement (GIC) enhanced bond strength and durability compared to the control. The 10% alloy concentration provided the most favourable balance, yielding consistently higher values and superior long-term stability. Although all groups showed gradual degradation over time, alloy addition reduced the rate of decline. Finite Element Analysis (FEA) reproduced overall trends but overestimated strength and underestimated degradation, underscoring the need for experimental validation. Overall, 10% alloy-modified GIC demonstrates promising potential for improved clinical performance and restoration longevity.

Conflict of interest. Nil

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