ORIGINAL ARTICLE

Differences in the mechanical performance of type II glass ionomer cement modified with hydroxyapatite in terms of diametral tensile strength and compressive strength: an experimental study

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ABSTRACT

Introduction: Glass ionomer cement (GIC) is widely used because of its chemical adhesion to tooth structure, fluoride release, and biocompatibility. However, its low tensile strength and brittleness limit its application in stress-bearing restorations. Hydroxyapatite (HA) has been investigated as a bioactive filler to improve the mechanical properties of GIC. This study aimed to analyze the differences in the mechanical performance (diametral tensile strength and compressive strength) of Type II GIC modified with hydroxyapatite. **Methods:** The materials used in this research were Type II GIC (Fuji IX) and pure hydroxyapatite (Sigma Aldrich's). Twenty-eight specimens were allocated into four groups for the diametral tensile strength (DTS) test, and another twenty-eight specimens for the compressive strength (CS) test (n= 7 per group): a control group (K, conventional GIC without modification) and three treatment groups modified with 1% (P1), 3% (P2), and 5% (P3) of hydroxyapatite powder. Mechanical evaluation was performed using a Universal Testing Machine (UTM) at a crosshead speed of 0.5 mm/min. Statistical analysis comprised tests of data normality and variance homogeneity, followed by one-way analysis of variance (ANOVA) and the Least Significant Difference (LSD) post hoc test (p=0.05). **Results:** The addition of HA altered mechanical performance in a highly concentration-dependent and stress-specific manner. The highest DTS was observed in Group P1, with a value of 9.5300 ± 4.0896 MPa, which was significantly higher than those of the control and all other groups ($p<0.05$). Conversely, CS was highest in Group P2 (66.7114 ± 11.8779 MPa), which was significantly higher than that of the control group (43.3614 ± 10.6778 MPa, p=0.002). Higher mass loading in Group P3 resulted in a pronounced decline in both tensile and compressive performance. **Conclusion**: There are differences in the mechanical performance (diametral tensile strength and compressive strength) of Type II glass ionomer cement (GIC) modified with hydroxyapatite. Hydroxyapatite integration enhances the mechanical properties of Type II GIC, with 1% HA improving DTS and 3% HA producing the highest CS.

KEYWORDS

Glass ionomer cement, diametral tensile strength, compressive strength, hydroxyapatite

INTRODUCTION

Dental and oral health are inseparable components of overall well-being. Among the conditions affecting the oral cavity, dental caries remains one of the most prevalent, characterized by the progressive deterioration of enamel, dentin, and cementum driven by the metabolic activity of bacterial plaque. Epidemiological data consistently show that a large proportion of the population

experiences untreated carious lesions, which, if left unmanaged, may progress to pain, infection, and tooth loss.[1] The Basic Health Research of the Indonesian Ministry of Health in 2018 reported that 45.3% of the Indonesian population exhibited dental caries. These findings show that dental caries remains a major public health concern in Indonesia.[2] Consequently, Epidemiological assessments consistently document that a substantial global subpopulation suffers from untreated carious lesions, which frequently progress to localized infection and eventual tooth loss if left unmanaged. Restorative dental materials play a vital role in clinical management by replacing excavated pathological tissue, restoring anatomical form, and establishing an effective seal against reinfection.[3]

Glass ionomer cement (GIC) has maintained a significant role in restorative dentistry since their material due to its several advantageous properties.[4] These include its ability to chemically bond to tooth structure, a coefficient of thermal expansion to that of tooth structure, and sustained fluoride release, which contributes to remineralization and the inhibition of secondary caries.[3] In addition, GIC is relatively easy to manipulate and does not require complex bonding protocols, making it particularly useful in pediatric dentistry and community-based treatments. Despite these advantages, conventional GIC presents notable mechanical limitations. Its relatively low tensile strength and brittleness make it more susceptible to fracture under functional loading, especially in stress-bearing areas.[5] Compared to resin-based composites, GIC demonstrates inferior resistance to tensile and flexural stresses, which restricts its application in posterior restorations subjected to high occlusal forces. To overcome these limitations without compromising its bioactivity, incorporating advanced nanocomposites has gained substantial traction.[6]

Tooth restoration is the standard treatment when dental caries has damaged the tooth structure. In recent years, there has been growing interest in enhancing the performance of dental restorative materials, particularly through the incorporation of bioactive components.[5] The rationale behind this strategy is to enhance the material's structural integrity by modifying its microstructure, improving load distribution, and reducing crack propagation. Various types of fillers have been explored, including metallic particles, fibers, and bioactive ceramics. Among these, hydroxyapatite (HA) has gained particular attention due to its close resemblance to the mineral component of natural teeth. Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) is a calcium phosphate ceramic that constitutes the primary inorganic phase of enamel and dentin.[6]

The baseline chemical structure of GIC involves an acid-base reaction that yields high biocompatibility but suffers from low tensile strength.[7] Hydroxyapatite (HA), which incorporates approximately 4% to 6% carbonate substitutions depending on its anatomical site, is the major inorganic constituent of hard tissues, comprising roughly 70% of bone and 96% of dental enamel. Structurally, the HA crystallographic unit cell exhibits a hexagonal symmetry and forms a three-dimensional unit-cell geometry, characterized by lattice parameters of a = b = 0.944nm and c = 0.688nm. This spatial configuration is stabilized by a distinct atomic distribution, wherein calcium, phosphate, and hydroxyl ions are strategically oriented across parallel basal planes and vertical axes, establishing an interconnected crystalline framework shared with adjacent unit cells.[8]

Its excellent biocompatibility, bioactivity, and osteoconductive properties make HA commonly used in biomedical and dental applications. When incorporated into restorative materials, HA has the potential to improve mechanical properties while also promoting biological interactions at the tooth–material interface. This dual function makes HA an attractive candidate for modifying GIC.[9] One promising approach is the incorporation of hydroxyapatite (HA), a mineral that closely resembles the natural composition of teeth and

bone. By adding HA, particularly in nano- or microparticle form, to Type II GIC, researchers aim to improve properties such as compressive strength, flexural strength, hardness, and bonding ability. These modifications may make GICs more suitable for demanding dental applications while maintaining their biocompatibility and fluoride-releasing capabilities.[10]

While previous scoping studies have confirmed that hydroxyapatite improves the bioactivity of dental restorative materials[11], a critical gap remains regarding how incremental mass fractions simultaneously dictate diametral tensile and compressive properties under identical experimental constraints, as structural enhancements noted in tensile vectors do not uniformly translate to uniaxial compression resistance.[12] Some studies have shown that HA incorporation leads to significant improvements in compressive strength, whereas others report limited or even negative effects at higher concentrations.[13]

Glass ionomer cement (GIC) is prepared by mixing a specific glass powder with an acid liquid that hardens into a solid structure through an acid–base reaction.[12] What makes GIC attractive in clinical practice is its ability to bond well to tooth structure without requiring an adhesive, and it also releases fluoride over time, which helps prevent secondary caries. On top of that, it does not undergo polymerization shrinkage, which reduces the risk of marginal gaps. GIC materials are categorized into Type I (luting), Type II.1 (esthetic restorative), Type II.2 (reinforced restorative), and Type III (base, lining, and fissure sealant), with particle diameters ranging from 4–50 μm depending on functional indications.[13]

These discrepancies are often attributed to differences in HA concentration, particle size, distribution within the matrix, and its combination with the acid–base setting reaction of GIC.[14] The mechanical behavior of modified Type II glass ionomer cements are heavily influenced by filler geometry, composition, and concentration-dependent effects. Phyto-mediated nanocomposites offer versatile approaches to augmenting restorative systems, balancing cross-linking with underlying physical stability.[9] At low concentrations, HA particles may be well dispersed within the matrix, contributing to improved stress distribution and reduced defect formation. In contrast, excessive filler loading may lead to particle agglomeration, creating internal voids and weak interfaces that compromise mechanical integrity. Therefore, identifying the optimal concentration of HA is essential to achieving improved performance without introducing new structural weaknesses.[15]

Previous investigations have reported an increased compressive performance of GIC following the incorporation of nano-sized HA at concentrations of 1%, 3%, 5%, and 7%.1[4,15] Although numerous studies have reported that nano-hydroxyapatite (nano-HA) enhances the mechanical properties of glass ionomer cement (GIC), most have focused on individual mechanical parameters or overall reinforcement effects. Consequently, it remains unclear whether the optimal nano-HA concentration is consistent across different loading conditions.

The novelty of the present study lies in the systematic evaluation of the concentration-dependent mechanical behavior of Type II GIC modified with nano-HA by simultaneously assessing diametral tensile strength and compressive strength under identical experimental conditions. This approach enables the identification of loading-mode-specific optimal concentrations, providing a more comprehensive understanding of the reinforcing effects of nano-HA and practical guidance for optimizing Type II GIC formulations according to specific mechanical requirements. Therefore, this study aimed to analyze the differences in the mechanical performance (diametral tensile strength and compressive strength) of Type II glass ionomer cement (GIC) modified with hydroxyapatite.

METHODS

This research was a true experimental laboratory study with a post-test-only control group design.[16,17] The sample size was determined based on the results of a preliminary diametral tensile strength (DTS) study and data obtained from a previouspilot study. Initially, the pooled standard deviation was calculated using the standard deviations and sample sizes of the two comparison groups. Subsequently, the minimum sample size per group was estimated using a formula that incorporated the pooled standard deviation, the significance level ($Z\alpha = 1.64$), the study power ($Z\beta = 1.28$), and the minimum expected difference between the group means considered clinically significant.

Based on this calculation, the minimum sample size required was seven specimens per group. The specimens used for the DTS investigation were prepared using a cylindrical acrylic mold with a diameter of 6mm and a height of 4mm (Figure 1.a), whereas the specimens used for the CS test were prepared using cylindrical acrylic mold with a diameter of 4mm and a height of 6mm (Figure 1.b).

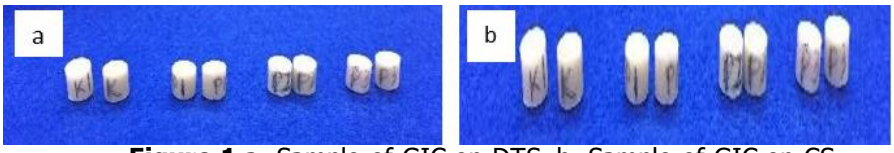

Figure 1.a. Sample of GIC on DTS, b. Sample of GIC on CS

The materials used were Type II glass ionomer cement (GIC), GC Fuji IX GP (GC Corporation, Tokyo, Japan; Batch No. 220315A), and hydroxyapatite (Sigma Aldrich) product No. 677418-5G (St. Louis, MO, USA). A total of 56 cylindrical specimens were prepared, consisting of 28 specimens for diametral tensile strength (DTS) evaluation and 28 specimens for compressive strength (CS) testing. The specimens were equally distributed across four experimental groups (n = 7 per group): an unmodified control group (Group K) and three groups in which GIC was modified with hydroxyapatite (HA) at concentrations of 1% (P1), 3% (P2), and 5% (P3).

To ensure uniform filler dispersion, the designated mass of HA powder was incorporated into the GIC powder using an analytical microbalance and homogenized by mechanical vortex mixing for 5 minutes before the liquid was introduced. The manufacturer-recommended powder-to-liquid ratio was carefully maintained across all groups to prevent confounding variations in the liquid content. The powder and liquid were stirred on a paper pad using a plastic spatula until a homogeneous mixture was obtained. The mold was placed on a glass slab, after which the mixture was placed into the mold, which had been coated with petroleum jelly, using a plastic filling instrument within a working time of 1 minute and 52 seconds. The top of the mold was then covered with a celluloid strip and subjected to a load of 1 kg until initial setting was achieved at approximately 3 minutes and 18 seconds.

Following 24 hours of storage in an incubator at 37°C, mechanical testing was performed using a Universal Testing Machine (UTM Shimadzu AGS-X, Kyoto, Japan) operated with Trapezium X software at a uniform crosshead displacement speed of 0.5 mm/min. For DTS testing, the specimens were positioned horizontally, subjected to a compressive load along their diametral plane until failure occurred. The maximum load at fracture was recorded and converted to tensile strength using the following standard mathematical equation: $DTS = 2P/(\pi DT)$. The variables are defined as follows: DTS represents the diametral tensile strength (MPa); P is the maximum compressive force recorded at fracture (N); D is the measured diameter of the specimen (mm); and T is the total thickness of the specimen (mm).

For CS testing, specimens were oriented vertically on the testing platform and subjected to uniaxial compression along their longitudinal axis. The compressive strength was calculated using the following formula: $CS = P/(\pi r^2)$ The variables are defined as follows: CS represents the compressive strength (MPa); P is the maximum force recorded at fracture (N); and r is the radius of the circular cross-section of the specimen (mm).

The gathered numerical datasets were compiled and processed using descriptive and inferential statistics. Data normality was verified via the Shapiro-Wilk test, and homogeneity of variance across groups was confirmed using Levene's test. Statistical significance among the groups was evaluated using One-way Analysis of Variance (ANOVA). Upon establishing a significant omnibus effect, multiple pairwise comparisons were conducted using the Least Significant Difference (LSD) post hoc test. All statistical procedures were conducted at a pre-specified significance level of $\alpha = 0.05$.

RESULTS

The research data were examined using descriptive statistical parameters to provide an overview of the data distribution and summarize the findings, including the computed means and standard deviations (±SD) of DTS and CS expressed in megapascals (MPa).

The data in Table 1 show the mean and standard deviation of the DTS values in each group, with the highest value observed in group P1 and the lowest observed in group P2.

Table 1. Mechanical performance values of diametral tensile strength (DTS) and compressive strength (CS) in each experimental group (Mpa)

Group	DTS Mean ± SD (MPa)	CS Mean ± SD (MPa)
Control (K)	5.4486 ± 1.57091	43.3614 ± 10.67775
1% HA (P1)	9.5300 ± 4.08960	51.7571 ± 12.45646
3% HA (P2)	5.2743 ± 1.60961	66.7114 ± 11.87786
5% HA (P3)	5.3943 ± 2.40836	62.5914 ± 14.21784

The LSD post hoc test results indicated significant differences in diametral tensile strength between the control (K) and P1, as well as between P1 and P2 and between P1 and P3. However, no significant differences were observed in diametral tensile strength between the control and P2 groups, the control and P3 groups, or between P2 and P3, as presented in Table 2.

As shown in Table 2, the Post Hoc LSD test of mechanical performance results demonstrated statistically significant differences ($p < 0.05$) between the K, P1, and P3, between P1, P2, and P3, as well as between P2 and P3. A significance level of $p < 0.05$ was observed in the comparison between the control (K) and P2, suggesting no significant difference between them.

The inferential One-way ANOVA revealed a statistically significant difference in DTS across the tested groups ($p<0.05$). Pairwise evaluations using the LSD post hoc test (Table 2) indicated that the incorporation of 1wt% HA (P1) yielded a distinct mechanical advantage, generating the highest mean DTS value of 9.5300 ± 4.0896 MPa. This value was significantly higher than that of the control Group K (5.4486 ±1.5709 MPa, $p=0.008$). However, this improvement was not observed at higher concentrations, as the DTS values of Group P2 (3% HA) and Group P3 (5% HA) were not significantly different from those of control group ($p=0.902$ and $p= 0.969$, respectively).

Table 2. Least significant differences (LSD) post hoc matrix for diametral tensile strength

Kel	K	P1	P2	P3
K		0.008*	0.902	0.969
P1			0.006*	0.007*
P2				0.933
P3				

* p < 0.05 (there is a significant difference)

The one-way ANOVA revealed a statistically significant difference in comprehensive strength among the experimental groups ($p<0.05$). The LSD multiple comparison test (Table 3) confirmed that compressive strength was highest at a moderate HA concentration of 3% (Group P2), with a mean CS of 66.7114 ± 11.8779 MPa.

This value was significantly higher than those of both the control Group K (43.3614 ± 10.6778 MPa, $p = 0.002$) and the 1% HA formulation (Group P1; 51.7571 ± 12.4565 MPa, $p = 0.033$). Although Group P3 (5% HA) also exhibited significantly higher CS than the control (62.5914 ± 14.2178 MPa, $p=0.008$), it exhibited a visible lower mean CS than Group P2, demonstrating that increasing the HA concentration from 3% to 5% did not result in a statistically significant further improvement in compressive strength.

On the other hand, some groups showed no statistically significant difference in compressive strength. The control group performed similarly to the 1% hydroxyapatite group, with no significant difference between. them Similarly, the 3% and 5% hydroxyapatite groups also showed no significant difference.

Table 3. Least significant differences (LSD) post hoc matrix for compressive strength

Group	K	P1	P2	P3
K		0.216	0.002*	0.008*
P1			0.033*	0.114
P2				0.539
P3				

As presented in Table 3, significant differences in compressive strength were found between several groups. The control group (GIC without hydroxyapatite) was significantly different from both the 3% and 5% hydroxyapatite groups. Similarly, the 1% hydroxyapatite group showed a significant difference from the 3% hydroxyapatite group.

However, not all groups differed significantly from one another. The control group and the 1% hydroxyapatite group showed no significant difference. The same was true for the 1% and 5% hydroxyapatite groups, as well as the 3% and 5% hydroxyapatite groups, which also showed no statistically significant difference between them.

DISCUSSION

The present study demonstrated that the incorporation of hydroxyapatite (HA) significantly influenced the mechanical performance of Type II glass ionomer cement (GIC) in a concentration-dependent manner. As shown in Table 1, the highest diametral tensile strength (DTS) was obtained with the addition of 1 wt% HA, whereas the highest compressive strength (CS) was achieved with 3 wt% HA, indicating that the optimal HA concentration differs depending on the type of mechanical loading.

These findings are consistent with previous studies reporting that HA reinforcement improves the mechanical behavior of conventional GIC by enhancing stress transfer within the cement matrix.[7] Moshaverinia et al. reported that the incorporation of hydroxyapatite nanoparticles improved the

mechanical properties of conventional GIC through enhanced interaction between apatite particles and the polyacrylate matrix.[7]

Likewise, Murugan et al. demonstrated that nano-hydroxyapatite incorporation positively affected the mechanical performance of GIC, particularly at low-to-moderate concentrations, while Zhang et al., in a recent scoping review, concluded that excessive HA loading may reduce reinforcement due to particle agglomeration and disruption of matrix continuity.[8,10] Similar findings were also reported by Bilić-Prcić et al., who observed that marine-derived hydroxyapatite significantly improved the mechanical performance of GIC when incorporated at appropriate concentrations.[11]

Furthermore, Mederos et al. demonstrated that the reinforcing effect of hydroxyapatite on diametral tensile strength depends strongly on filler concentration and particle distribution within the cement matrix.[12] Therefore, the present findings are consistent with previous reports while extending current knowledge by demonstrating that the concentration associated with the greatest mechanical performance may differ depending on the type of mechanical loading. Under identical experimental conditions, 1 wt% HA produced the greatest improvement in diametral tensile strength, whereas 3 wt% HA yielded the highest compressive strength.

These results suggest that different reinforcement mechanisms govern tensile and compressive behavior in HA-modified Type II GIC and emphasize the importance of optimizing HA concentration according to the intended mechanical function of the restorative material.[7-8,11-12] The differential response observed between DTS and CS suggest that the concentration associated with optimal mechanical performance may depend on the type of mechanical loading.

The LSD post hoc analysis (Table 2) revealed that only the 1% HA group showed a significant improvement in DTS compared with the control group, while increasing the HA concentration to 3% and 5% did not produce additional benefits. This result suggests that a low concentration of HA improves tensile resistance by promoting better particle dispersion and reducing crack propagation. However, excessive HA loading may lead to particle agglomeration, increased porosity, and disruption of the GIC matrix, thereby reducing tensile strength. These findings are consistent with previous studies reporting that low concentrations of hydroxyapatite improve the mechanical properties of GIC by enhancing matrix reinforcement and bonding. Conversely, higher HA concentrations have been reported to reduce mechanical performance because particle aggregation creates structural defects that act as stress concentration sites.

For compressive strength, the LSD analysis (Table 3) showed significant differences between the control group and the 3% and 5% HA groups, whereas no significant differences were found between the 3% and 5% HA groups. This indicates that incorporating 3% HA was associated with a significant improvement compressive strength compared with the control group, but increasing the concentration to 5% did not result in a statistically significant difference compared with 3% HA. The improvement in compressive strength may be attributed to the ability of HA particles to fill microscopic voids within the GIC matrix, resulting in better stress distribution during compressive loading.

Similar findings have been reported in previous studies, which demonstrated that moderate HA concentrations enhance compressive strength, whereas excessive filler content may reduce the reinforcing effect due to particle agglomeration. Overall, the results indicate that hydroxyapatite can improve the mechanical performance of conventional GIC in a concentration-dependent manner. Based on the present study, 1% HA was associated with the highest diametral tensile strength, whereas 3% HA provided the greatest improvement in compressive strength.

The superior tensile performance observed on the 1% HA group may be attributed to the relatively uniform dispersion of the HA particles within the GIC matrix. Hydroxyapatite incorporation has been reported to modify the structure of conventional glass ionomer frameworks, resulting in structural adaptations that may influence its material performance.[10] Marine-derived hydroxyapatite configurations demonstrate unique geometric packing structures that enhance internal stress transfer properties.[11]

Setting characterization using oscillating rheometry has indicated that phosphate-based components can influence the setting and maturation behavior of restorative materials.[18] Biocompatibility studied have also reported that combining advanced multi-component nanocomposites can preserve cell viability and support structural integration.[19] Furthermore, hybrid reinforcement frameworks containing zinc oxide and hydroxyapatite nanoparticles have been reported to modify localized matrix packing densities.[20]

Studies evaluating setting time and microleakage have reported that modifications with bioceramic materials can influence sealing behavior and the physical properties of restorative materials. Green synthesis protocols may improve particle distribution and reduce defect formation, potentially contributing to enhanced mechanical properties.[21] Microhardness assessments across different commercial formulations confirm that micro-hydroxyapatite incorporation increases surface hardness.[22] Physical characterization studies have also indicated that the incorporation of silver-phosphate elements with hydroxyapatite may lead to more stabilized structural network frameworks.[23] In addition, natural bioceramics derived from sources such as Nile tilapia scales have been investigated as sustainable filler materials that can enhance surface hardness.[24]

Novel additives have been reported to consistently modify both the physical properties and biological characteristics of conventional water-based dental materials.[25] Combining multi-functional elements such as silver, hydroxyapatite, and silica, in hybrid systems may provide simultaneous mechanical reinforcement and controlled ion release.[26] Surface roughness assessment have shown differences between micro-hydroxyapatite-containing materials and alternative biopolymers-based materials, such as chitosan.[27] Previous mechanical analysis highlights that incorporating micro-hydroxyapatite structures can alter flexural properties and influence crack propagation.[28] Similarly magnesium-doped hydroxyapatite properties while maintaining the fundamental chemical characteristics of the materials..[29]

Thermocycling studies have demonstrated that dynamic thermal aging can influence the long-term mechanical stability of restorative materials.[26] Calcium-releasing particles integrated into restorative cements can directly modify the mineral content and mechanical properties of adjacent dentin.[30] Advanced nanofiber structures may improve fracture resistance, by enhancing cross-linking within the polysalt matrix. Wear resistance evaluation using chewing simulators have also confirmed that green-synthesized nanocomposites may reduce long-term microstructural deterioration.[31]

Systematic reviews of remineralization have reported that the release of calcium and phosphate ion contribute to mineral recovery. Comparative flexural strength studies have further demonstrated that appropriate combinations of secondary fillers including titanium dioxide, can avoid the mechanical properties of restorative materials[32]

Ultimately, the distinct concentration-response patterns observed for diametral tensile strength and compressive profiles in this study highlight the complex mechanical behavior of particle-reinforced matrices and support previous findings that the reinforcing effect of HA may vary according to the type of mechanical loading rather than increase uniformly with filler concentration.[29] This behavior may be related to the interaction between HA particles and the polycarboxylate matrix, which can maintain high chemical

stability under lower filling thresholds but may experience physical disruption as matrix spatial network continuity is blocked by excess particulates.[33] When reaching critical mass-loading boundaries such as 5 wt%, the structural performance decline can be attributed directly to the localized agglomeration thresholds inherent to micro-particulate bioceramics, creating unwetted internal defects that act as structural flaw sites.[34] These structural changes compromise localized fracture toughness and introduce severe internal stress-concentration points under heavy mechanical displacement.[35]

Consequently, these findings support the importance of identifying a suitable HA concentration that provides mechanical reinforcement without compromising the structural integrity of the GIC matrix. The concentration associated with the highest DTS (1% HA) differed from that associated with the highest CS (3% HA), suggesting that reinforcement mechanisms depend on the loading mode. A limitation of this study is that scanning electron microscopy (SEM) and elemental mapping analyses were not performed. Consequently, interpretations regarding particle dispersion and agglomeration are based on plausible mechanisms reported in previous literature rather than direct experimental evidence from the present study, and should therefore be interpreted with caution.

CONCLUSION

The present study demonstrated differences in the mechanical performance of Type II glass ionomer cement (GIC) modified with hydroxyapatite as reflected in diametral tensile strength (DTS) and compressive strength (CS). The addition of 1% HA significantly improved DTS, compared with the unmodified GIC, whereas 3% HA produced the highest CS. However, the CS at 3% HA was not significantly different from that at 5% HA. These findings indicate that the mechanical response of Type II GIC to HA incorporation varies according to the concentration and type of mechanical loading.

The implication of these findings is that HA concentration in GIC formulations should be tailored according to the specific mechanical demands of clinical applications. Lower HA concentrations may be more suitable for improving tensile resistance, whereas moderate concentrations may provide greater compressive reinforcement. Further study incorporating microstructural and elemental analyses are needed to clarify the mechanism underlying these concentration-dependent effects.

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