

Comparative in Vitro Analysis of Conventional Glass Ionomer Cements for Young Patients

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Abstract

Background: Dental caries remains the major oral health concern, affecting about 2.5 billion people with permanent teeth and more than 500 million children with caries in primary teeth worldwide. Dental restorative materials like GIC are essential for managing the tooth structure and function affected by caries, particularly in children where effective and durable restoration is essential. Therefore, improving their antibacterial, mechanical and remineralization properties is important for effective long-term restoration.

Objectives: To comparatively evaluate the mechanical properties, antimicrobial activity, and remineralization potential of commercially available conventional glass ionomer cements (GICs): GIC 1 (Crysta Cement; Type II restorative), GIC 2 (Lute; Type I luting), and GIC 3 (Prime; Type II restorative), with particular relevance to their potential use in pediatric restorative dentistry.

Materials and Methods: Standardized specimens (n = 5 per group) were prepared according to manufacturer's instructions and ISO specifications. Flexural strength was evaluated using a three-point bending test, while compressive strength was assessed using a universal testing machine. Surface microhardness was measured using a Vickers hardness tester at baseline, after demineralization, and after remineralization. Antimicrobial activity was determined by the agar well diffusion method against *Staphylococcus aureus*. Statistical analysis was performed using one-way ANOVA followed by Tukey's HSD post-hoc test with significance set at $p < 0.05$.

Results: GIC 2 demonstrated significantly higher flexural strength (40.87 ± 4.28 MPa) and compressive strength (52.36 ± 7.79 MPa) compared with the other tested materials ($p < 0.05$). It also exhibited the highest surface microhardness values at baseline, after demineralization, and after remineralization ($p < 0.001$). No statistically significant difference was observed in antimicrobial activity among the groups ($p = 0.676$), although all materials demonstrated inhibitory activity against *Staphylococcus aureus*.

Conclusion: Within the limitations of this in vitro study, formulation-specific differences significantly influenced the mechanical and remineralization properties of conventional glass ionomer cements. GIC 2 exhibited superior mechanical performance and microhardness recovery, while all tested materials demonstrated comparable antimicrobial activity. These findings may be useful while selection of conventional GICs for pediatric restorative applications, however clinical performance in pediatric patients cannot be established from the present in vitro study.

Keywords: Glass ionomer cement; pediatric dentistry; flexural strength; compressive strength; surface microhardness; remineralization; antimicrobial activity; dental materials.

Introduction

Dental caries remains a major oral health problem among children worldwide, with the World Health Organization (WHO) estimating a global prevalence of 43% for untreated caries of deciduous teeth among children aged 1–9 years, affecting approximately 514 million children globally.^[1] Dental caries, if untreated can lead to pain, infection, affect eating and sleeping, and other everyday activities; hence early prevention and appropriate management are important parts of pediatric dental care.^[2] Several factors may affect development of caries, including previous caries experience, salivary *Staphylococcus mutans* levels, oral hygiene, fluoride exposure, socioeconomic conditions, and family history of caries.^[3,4] Thus, prevention and early management have become important components of pediatric dental care. Treatment or management of dental caries in children includes preventive and non-operative approaches as well as restorative treatment when necessary.^[5] In situations where restoration is necessary, factors such as moisture control, patient cooperation, preservation of tooth structure, and the suitability of the material to perform in the oral environment become important considerations.^[5,6] Along with restoration durability, various factors like ease of handling, surface stability, fluoride release, remineralization potential and antibacterial properties may be particularly relevant when selecting restorative materials for pediatric applications.^[6,7]

Glass ionomer cement (GIC) is widely used in restorative dentistry including pediatric dentistry because of its chemical adhesion to tooth structure, fluoride-releasing ability, biocompatibility and relatively simple handling.^[6,7] The setting reaction of conventional GIC is based on an acid-base neutralization between fluoroaluminosilicate glass powder and aqueous polyacrylic acid. This reaction releases Ca^{2+} , Al^{3+} , and F^- ions, forming a polycarboxylate salt matrix that provides chemical adhesion to tooth structure while simultaneously liberating fluoride for sustained anticariogenic activity.^[8] The same ion-exchange mechanism enables direct bonding to enamel and dentin without separate etching or bonding agents, closely matches the coefficient of thermal expansion of dentin, and offers excellent biocompatibility, supports its use in clinical settings such as pediatric restorations, geriatric dentistry, atraumatic restorative treatment (ART), cervical and root caries, and situations with difficult moisture control.^[9–11] In addition to chemical adhesion and thermal compatibility, the continuous release and recharge of fluoride may contribute to two clinically important biological properties: antimicrobial activity against cariogenic bacteria and the ability to promote remineralization of demineralized tooth tissue.^[12,13] These attributes have positioned GICs as an effective restorative in caries prevention and minimally invasive dentistry. However, conventional GICs possess well-recognized mechanical limitations, including relatively low flexural and compressive strength, brittleness, and susceptibility to early moisture contamination or desiccation, which restrict their use in areas subjected to greater occlusal stress.^[14]

Considerable inter-product variability exists among commercially available conventional GICs due to differences in glass composition including strontium substitution, particle size distribution, powder-to-liquid ratio, and proprietary additives. Such formulation differences directly influence mechanical performance, fluoride-release kinetics, surface hardness, antibacterial behaviour and remineralization potential.^[15] Although numerous studies have examined individual GIC products or modifications such as resin-modified, nano-filled, or bioactive GICs, comparative evidence regarding commercially available conventional GICs remain limited, particularly under identical laboratory conditions with respect to the combined assessment of antimicrobial activity, mechanical properties (flexural strength, compressive strength, and surface microhardness), and remineralization capacity.^[16–18]

This comparative evaluation is relevant to pediatric restorative dentistry, where the selection of a restorative material depends on both its mechanical strength and biological properties. However, since the present study was conducted in vitro, the findings cannot be considered direct evidence of clinical performance or superiority in pediatric patients. Instead, they provide comparative information on the material properties that may be useful when considering their potential pediatric applications.^[6]

The present in vitro study was therefore designed to comparatively evaluate the antimicrobial activity, mechanical properties, and remineralization potential of three commercially available conventional (non-resin-modified) glass ionomer cements: GIC 1 (Crysta Cement; Type II restorative), GIC 2 (Lute; Type I luting), and GIC 3 (Prime; Type II restorative).^[19–21] The null hypothesis tested was that no statistically significant differences would exist among the materials in flexural strength, compressive strength, surface microhardness at baseline, after demineralization, and after remineralization, antimicrobial efficacy, or remineralization potential.^[22,23]

Materials and methods

Materials

Commercially available conventional (non-resin-modified) hand-mixed GICs were selected for evaluation: GIC 1 (Crysta Cement; Type II restorative), GIC 2 (Lute; Type I luting), and GIC 3 (Prime; Type II restorative).^[24,25] All materials were used strictly according to their respective manufacturer's instructions and within validated expiry dates. Detailed information on glass composition, fluoroaluminosilicate formulation, powder-to-liquid ratios, and clinical indications was obtained from the original product literature provided by each manufacturer.^[26] Materials were stored at ambient temperature (10–24 °C) in sealed, unopened packaging until use, and handling was performed under standardized laboratory conditions (temperature 23 ± 1 °C, relative humidity $50 \pm 5\%$).^[27–29] As this was an in vitro material-based study not involving human or animal subjects, ethical approval was not required.

Setting time determination

The setting time of the commercially available conventional glass ionomer cements was determined in accordance with ISO 9917-1:2025 specifications for water-based cements using a Vicat needle apparatus.^[30] Three groups of materials (GIC 1, GIC 2, and GIC 3) were evaluated, with five samples prepared for each group ($n = 5$). Freshly mixed GIC, prepared at the manufacturer-specified powder-to-liquid ratio, was packed into a standardized cylindrical mold

(internal diameter 10 mm, height 5 mm). The mold was immediately transferred to an incubator maintained at $37 \pm 1^\circ\text{C}$ and $>90\%$ relative humidity to simulate intraoral conditions.^[31] A standard Vicat needle (1.0 mm diameter, 400 g load) was applied perpendicular to the surface at 30-second intervals.

The initial setting time was recorded as the elapsed time from the start of mixing until the needle failed to penetrate the specimen by more than 1 mm.^[32] The final setting time was recorded as the time when the needle produced no perceptible indentation on the surface. One-way analysis of variance (ANOVA) was used to compare the mean setting time among groups, followed by Tukey's post hoc test for pairwise comparisons. A p-value of less than 0.05 was considered statistically significant.^[33]

Specimen preparation

Fabrication was performed on a total of 45 specimens ($n = 15$ per material) which were equally divided into test groups (mechanical) ($n = 5$ per test per material). GIC was freshly mixed at the powder-to-liquid ratio specified by the manufacturer and incrementally pressed in specially-dimensioned Teflon (polytetrafluoroethylene) or stainless-steel split molds.^[34] The molds were then covered with Mylar polyester strip and a glass slab to provide a smooth and flat surface with uniform thickness and a standard compressive load was used to the mold during the initial setting period. The specimens were allowed to set at $37 \pm 1^\circ\text{C}$, as recommended by the manufacturer, and were then kept at the same temperature for maturation.^[35]

GIC specimen dimensions and preparation of specimens used in Fig. 1. consisted of: (i) disc-shaped GIC surface microhardness specimens (10 mm diameter $\times$ 2 mm thickness); (ii) rectangular bar-shaped GIC flexural strength specimens (25 mm $\times$ 2 mm length and width respectively); and (iii) cylindrical GIC compressive strength specimens (6 mm diameter $\times$ 3 mm height).^[36] After demoulding, a visual and tactile examination under magnification was done in each specimen, those containing visible voids, surface cracks, or dimensional inaccuracies greater than 0.1 mm was discarded and replaced.^[37] To isolate all accepted specimens, 24 hours of storage in distilled water at $37 \pm 1^\circ\text{C}$ was done before mechanical testing was conducted to mimic early intraoral hydration. To evaluate antimicrobials, freshly mixed GIC was placed in 6 mm diameter wells prepared in agar plates previously inoculated ($n = 3$ plate/material, 5 wells/plate) immediately upon mixing.^[38]

Mechanical testing

Flexural strength

Flexural strength was determined using a three-point bending configuration on a computerized universal testing machine (UNITEST-10, ACME Engineers, India; load cell accuracy $\pm 1\%$).^[39] Rectangular bar specimens were positioned on two supporting rollers separated by a span length (L) of 20 mm and loaded at a crosshead speed of 1 mm/min until fracture.^[40] Flexural strength (σ , MPa) was calculated as:

$$\sigma = 3FL / (2bd^2)$$

where F is the maximum load at fracture (N), L is the support span (mm), b is the specimen width (mm), and d is the specimen thickness (mm).

Compressive strength

Compressive strength was measured on cylindrical specimens using the same universal testing machine at a crosshead speed of 1 mm/min. Specimens were loaded axially along their long axis until failure. Compressive strength (σ , MPa) was calculated as:

$$\sigma = F / (\pi r^2)$$

where F is the maximum load at failure (N) and r is the specimen radius (mm).^[41]

Surface microhardness and remineralization assessment

Surface microhardness was measured using a calibrated Vickers hardness tester at sequential time points: (i) baseline after 24 h storage in distilled water at 37°C ; (ii) post-demineralization after immersion in a standardized acidic demineralization solution (0.05 M acetic acid, pH 4.5, 37°C) for a defined period; and (iii) post-remineralization after subsequent immersion in a simulated remineralization solution (containing Ca^{2+} , PO_4^{3-} , and F^- ions at physiologically relevant concentrations, pH 7.0, 37°C) for a defined period.^[42] The Surface microhardness was evaluated using a calibrated Vickers microhardness tester under a load of 100 g with a dwell time of 15 seconds. Three indentations were made on each specimen at different locations, and the mean Vickers Hardness Number (VHN) was calculated.^[43] Indentations were made per specimen, and mean values were calculated. The

microhardness recovery ratio (post-remineralization VHN / baseline VHN × 100%) was used as an index of remineralization potential.^[44]

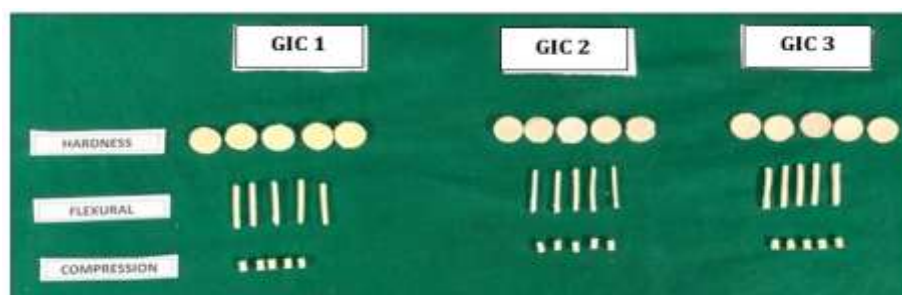
Antimicrobial activity

Antimicrobial activity was assessed by the agar well diffusion method using Mueller-Hinton agar plates inoculated with a standardized suspension (0.5 McFarland standard) of *Staphylococcus aureus*.^[45,46] Wells of 6 mm diameter were bored aseptically using a sterile corn borer, and freshly mixed GIC was immediately deposited into each well to the agar surface level.^[14] Plates were incubated at 37 °C for 24 hours under aerobic conditions.^[47] Fig. 3. Shows Zones of inhibition-(ZOI) (diameter, mm) surrounding each well were measured with a calibrated digital caliper by an examiner blinded to material identity.^[14,48]

Statistical analysis

All data were entered and analysed using IBM SPSS Statistics Version 26.0 (IBM Corp., Armonk, NY, USA). Normality of distribution was verified using the Shapiro-Wilk test. All variables were tested within each experimental group. For each outcome variable, one-way analysis of variance (ANOVA) was performed to detect overall differences among the groups.^[49] Where a statistically significant ANOVA result was obtained, Tukey's Honest Significant Difference (HSD) post-hoc test was applied for pairwise comparisons.^[50] Effect sizes were calculated using eta-squared (η^2). Statistical significance was set at $p < 0.05$ for all tests.

Fig. 1. Specimens Preparations of GIC



Representative mechanical specimens from each group (hardness discs, flexural bars, and compression cylinders) arranged according to the tests shown in fig. 1.

After initial setting the specimens were gently removed from the moulds. Any flash or excess material was carefully trimmed with a sharp scalpel blade. All specimens were inspected visually under magnification for surface defects, voids or irregularities; defective specimens were discarded and replaced.

Results

Hypothesis testing

Hypothesis testing indicating statistically significant differences among the materials as shown in table 1. The null hypothesis was accepted for zone of inhibition ($p = 0.676$), showing comparable antibacterial activity in. Detailed ANOVA results, effect sizes (η^2).

Normality assessment using the Shapiro–Wilk test indicated that all study variables followed a normal distribution across GIC 1, GIC 2 and GIC 3 groups ($p > 0.05$ for all comparisons). Hence, parametric statistical tests were employed for further analysis.

Table 1. Statistics Comparison of GIC Groups Based on Mechanical Strength, Microhardness, and Antimicrobial Activity

Variable	p-value from ANOVA	Decision on H_0	Which groups differ (Tukey)
ZOI	0.676	Fail to reject H_0	No differences
CS	0.009	Reject H_0	GIC 2 > GIC 3

FS	<0.001	Reject H ₀	GIC 2> GIC 1 & GIC 2> GIC 3
MICRO_BASE	<0.001	Reject H ₀	GIC 2> GIC 3 > GIC 1
MICRO_DEMIN	<0.001	Reject H ₀	GIC 2≈ GIC 3 > GIC 1
MICRO_REMIN	<0.001	Reject H ₀	GIC 2> GIC 3 > GIC 1

Setting time

The mean setting time for GIC 1, GIC 2, and GIC 3 was 9.48 ± 0.06 min, 3.73 ± 0.27 min, and 13.31 ± 0.07 min respectively as mentioned in table 2. GIC 2 demonstrated the shortest setting time, whereas GIC 3 exhibited the longest setting time.

Levene's test indicated that the assumption of homogeneity of variance was violated ($p < 0.05$). However, one-way ANOVA revealed a highly statistically significant difference among the groups ($p < 0.001$).

Post hoc Tukey analysis showed statistically significant differences between all pairwise group comparisons ($p < 0.05$), indicating that each material differed significantly in its setting behavior.

The effect size ($\eta^2 = 0.999$) indicated a very strong influence of material type on setting time.

Table 2. Comparison of setting time among different glass ionomer cements

Material	N	Mean	Std. Deviation
GIC 1	5	9.4820	.06058
GIC 2	5	3.7260	.27772
GIC 3	5	13.3080	.07463
Total	15	8.8387	4.07945

Flexural strength results

Fig. 2. Flexural Strength using UTM



The mean flexural strength (FS) values for the -glass ionomer restorative materials are presented in Table 3 and flexural strength testing shown in Fig. 2. One-way ANOVA revealed a statistically significant difference among the groups ($F(2,12) = 27.621$, $p < 0.001$, $\eta^2 = 0.822$). Tukey post-hoc test showed that GIC 2 had significantly higher flexural strength than GIC 1 ($p < 0.001$) and GIC 3 ($p < 0.001$). No significant difference was observed between GIC 1 and GIC 3 ($p = 0.744$).

Table 3. Mean $\pm$ standard deviation (SD) flexural strength (MPa) of the glass ionomer cements and corresponding ANOVA statistics (n = 5 per group). Superscript letters denote homogeneous subsets by Tukey's HSD (groups sharing a letter do not differ significantly at $p < 0.05$).

Material	Mean $\pm$ SD (MPa)	F- value	p-value	η^2
GIC 1	32.25 ± 8.11	7.198	0.009	0.545

GIC 2	40.87 ± 4.28	7.198	0.009	0.545
GIC 3	25.87 ± 5.84	7.198	0.009	0.545

Fig. 3. Compression strength testing using UTM



Compressive strength results

Statistically significant differences in compressive strength were observed among the materials ($F=7.198$, $p=0.009$, $\eta^2=0.545$). GIC 2 demonstrated the highest mean compressive strength (40.87 ± 4.28 MPa), which was significantly greater than that of GIC 3 (25.87 ± 5.84 MPa; $p = 0.009$). Pairwise comparisons between GIC 2 and GIC 1 (32.25 ± 8.11 MPa; $p=0.009$) and between GIC 1 and GIC 3 ($p=0.009$) did not reach statistical significance (Table 4). Compression strength testing using Universal testing machine was shown in fig. 3.

Table 4: Mean ± SD compressive strength (MPa) of the glass ionomer cements and corresponding ANOVA statistics (n=5 per group). Superscript letters denote homogeneous subsets by Tukey's HSD.

Material	Mean ± SD (MPa)	F- value	p-value	η^2
GIC 1	24.99 ± 6.57	27.621	<0.001	0.822
GIC 2	52.36 ± 7.79	27.621	<0.001	0.822
GIC 3	21.62 ± 7.10	27.621	<0.001	0.822

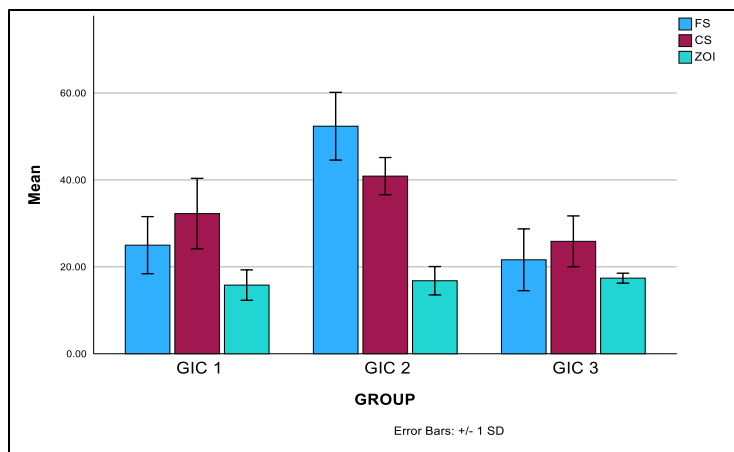
Antimicrobial Results

One-way ANOVA revealed no statistically significant difference in zones of inhibition among the GICs ($F=0.405$, $p=0.676$, $\eta^2=0.063$). Mean zones of inhibition ranged from 15.80 ± 3.49 mm GIC 1 to 17.40 ± 1.14 mm GIC 3, with GIC 2 yielding an intermediate value (16.60 ± 2.07 mm) as shown in table 5 and Figure 4. All materials demonstrated substantial inhibitory activity against *Staphylococcus aureus*, consistent with their shared fluoride-release mechanism. The ZOI of the GIC was shown in figure 5.

Table 5: Mean ± SD zone of inhibition (MPa) of the glass ionomer cements and corresponding ANOVA statistics (n = 5 per group).

Material	Mean ± SD (MPa)	F- value	p-value	η^2
GIC 1	15.80 ± 3.49	0.405	0.676	0.063
GIC 2	16.80 ± 3.27	0.405	0.676	0.063
GIC 3	17.40 ± 1.14	0.405	0.676	0.063

Fig. 4. Bar charts showing mean (± SD) flexural strength, compressive strength, and zone of inhibition of the - glass ionomer restorative materials. Error bars represent standard deviation. (A) Flexural strength (FS in MPa) groups on X-axis, FS (MPa) on Y-axis (B) Compressive strength (C) Zone of inhibition



Microhardness Results

Significant inter-material differences in Vickers microhardness were observed at all evaluation stages (Table 6). At baseline, GIC 2 recorded the highest microhardness (78.82 ± 5.23 VHN; $F(2,12) = 23.118$, $p < 0.001$, $\eta^2 = 0.794$), followed by GIC 3 (71.21 ± 2.20 VHN) and GIC 1 (61.74 ± 3.92 VHN).

Following demineralization, all materials exhibited a significant reduction in microhardness shown in figure 6; however, GIC 2 retained the highest absolute value (52.78 ± 2.88 VHN; $F(2,12) = 114.518$, $p < 0.001$, $\eta^2 = 0.950$). After the subsequent remineralization cycle, microhardness partially recovered in all groups, with GIC 2 again demonstrating the highest post-remineralization value (61.76 ± 1.90 VHN; $F(2,12) = 128.726$, $p < 0.001$, $\eta^2 = 0.955$). All pairwise between-group differences at each stage were statistically significant (Tukey's HSD, $p < 0.05$). The microhardness was evaluated using the Vickers microhardness testing method, as illustrated in Figure 7.

Table 6: Mean $\pm$ standard deviation of microhardness (VHN) of the -glass ionomer restorative materials at baseline, after demineralization, and after remineralization (n = 5 per group).

Time Point	GIC 1	GIC 2	GIC 3	F-value	p-value	η^2
Micro Base	61.74 ± 3.92^c	78.82 ± 5.23^a	71.21 ± 2.20	23.118	<0.001	0.794
Micro Demin	35.22 ± 0.94^c	52.78 ± 2.88^a	51.92 ± 1.91	114.518	<0.001	0.950
Micro Remin	42.88 ± 0.69^c	61.76 ± 1.90^a	56.42 ± 2.64	128.726	<0.001	0.955

Fig. 5. Zone of Inhibition (ZOI) demonstrating the antimicrobial activity of GIC 1, GIC 2, and GIC 3 against the test microorganism.

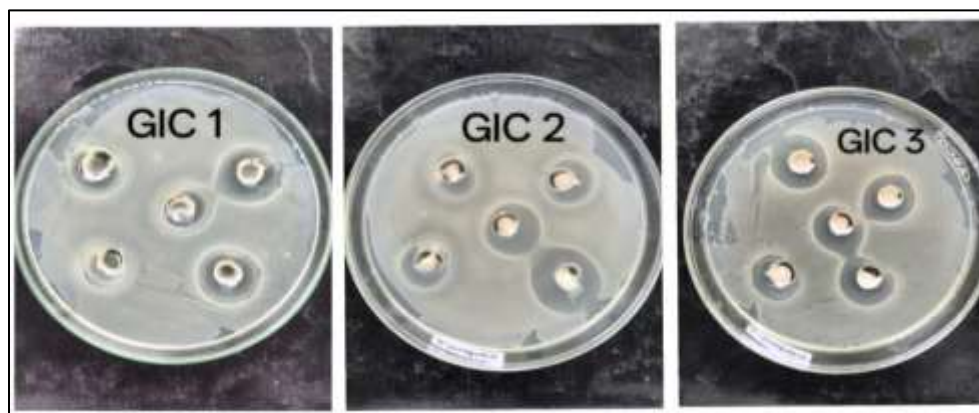


Fig. 6. Bar chart showing mean microhardness ($\pm$ SD) at baseline, after demineralization, and after remineralization for the -glass ionomer restorative materials. Error bars represent standard deviation.

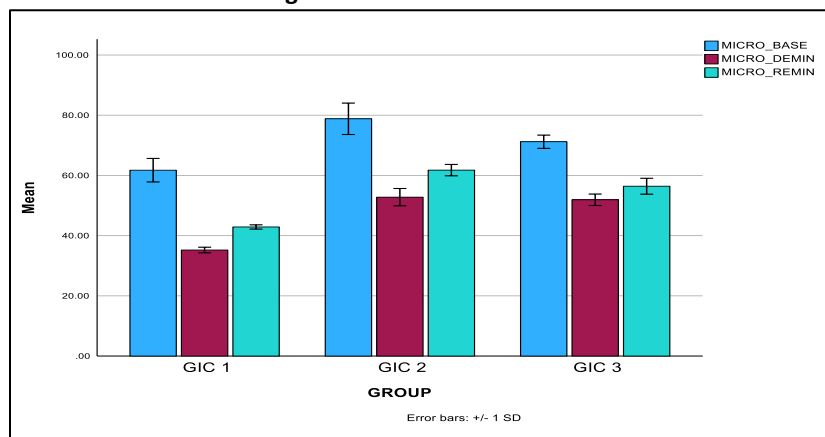


Fig. 7. Micro Vickers hardness



Discussion

This research demonstrated apparent formulation-specific variations in the performance of commercially available conventional glass ionomer cements (GICs). More importantly, GIC 2 cement was found to perform better than the two dedicated restorative-type cements (GIC 1 and GIC 3) on all the mechanical and surface-property results. It recorded the highest flexural strength (40.87 ± 4.28 MPa), compressive strength (52.36 ± 7.79 MPa), and Vickers microhardness at baseline (78.82 ± 5.23 VHN), after demineralization (52.78 ± 2.88 VHN), and after remineralization (61.76 ± 1.90 VHN). These were statistically significant ($p < 0.001$ flexural strength, compressive strength and all stages of microhardness; $p = 0.009$ compressive strength) with large effect sizes (η^2 between 0.545 and 0.955), meaning that formulation was the main factor influencing the material's performance rather than intended clinical application. These findings may be relevant to pediatric restorative dentistry, where the selection of a restorative material often requires consideration of both mechanical performance and biological properties. The high mechanical integrity of GIC 2 is especially interesting and, initially, counter-intuitive. Traditionally, luting cements are developed with a reduced powder/liquid ratio and smaller particle size to provide high flowability and thin-film thickness in the crown/bridge cementation.

In comparison, restorative-type GICs are designed to be loaded with a greater amount of filler to resist occlusal forces. The current results indicate that GIC 2 maximized strontium-based fluoroaluminosilicate glass content, particle-size distribution refinement, and polyacid-glass cross-linking yield a denser matrix that has less internal porosity and better stress distribution. These microstructural benefits are directly related to increased bending and compressive failure resistance, and better surface hardness retention. The high η^2 values also support that these formulation differences account 54-96 percent of the observed variance and this is a significant impact of proprietary glass chemistry on clinical longevity. The findings of remineralization are equally important. GIC 2 demonstrated the greatest recovery in microhardness after remineralization with values being significantly greater than restorative cements ($p < 0.05$) after a standardized demineralization challenge. The enhanced surface recovery can be due to the

prolonged release of Ca^{2+} , Sr^{2+} , and F^{-} ions, which promote ion exchange and mineral deposition on the surface matrix. From a pediatric perspective, this property may be of interest because maintaining surface integrity and supporting mineral recovery are relevant when restorative materials are used in a caries-prone oral environment. Calcium has been replaced by strontium ions, specifically, which have proven to be more effective in substituting calcium in hydroxyapatite to produce a more acid-resistant fluorapatite-like phase.

The microhardness measurements thus give indirect yet strong evidence of increased bioactivity in GIC 2, that is not normally anticipated of a luting material. Conversely, there were no statistically significant differences in antimicrobial activity in terms of zone of inhibition against *Staphylococcus aureus* among the materials (15.8017.40 mm, $p=0.676$, 0.063). This correspondence is exactly the same as the common fluoride-release mechanism of all traditional GICs and supports the idea that anticariogenic potential is not much dependent on the mechanical-property differences that are evident. The similarity of antimicrobial effectiveness of the products is a clinically encouraging observation, because it suggests that all cements can play an equal role in caries prevention at secondary level irrespective of their mechanical positioning. These laboratory findings are in line with previous comparative research studies that have reported significant inter-product variability in GIC performance due to variations in glass composition, particle size, powder/liquid ratio, and additive packages.

The current study builds on those observations by directly attributing the excellent mechanical and remineralization profile of a luting-type cement to its strontium-based formulation, a finding that questions the conventional dichotomy between GICs as either luting or restorative. The findings may have implications for evidence-based material selection. Despite its classification as a luting cement, GIC 2 demonstrated better mechanical performance and surface-property retention than the other tested materials under the conditions of this study. These findings may be of interest in pediatric restorative dentistry, where both mechanical performance and biological properties are important considerations during material selection. However, the present *in vitro* results alone cannot establish the suitability of GIC 2 for clinical use beyond its intended indication or demonstrate improved restoration longevity or reduced secondary caries. On the other hand, GIC 1 and GIC 3 are still suitable options when handling properties (e.g. increased viscosity due to bulk fill) or aesthetic considerations are of a higher priority. Such data thus enable clinicians to go beyond what the manufacturers label them and choose GICs based on the performance profile actually measured by each clinical scenario. A number of restrictions should be admitted. The group sizes ($n=5$) were not very large, but the large effect sizes and low p -values suggest that the observed differences had sufficient statistical power.

All experiments were short-term *in vitro* (24 h storage and then immediate mechanical testing), which is not a reflection of the complex intraoral conditions of thermocycling, cyclic occlusal loading, salivary pellicle formation, or long-term degradation. There were no quantitative ion-release kinetics or microstructural analyses (e.g., scanning electron microscopy of fracture surfaces or energy-dispersive X-ray spectroscopy); the microhardness recovery data only give indirect evidence of remineralization. Lastly, the demineralization/remineralization protocol, though standardized and reproducible, was not fully described in the current report, which restricts a direct comparison with other published protocols. These gaps need to be filled by future studies on long-term clinical trials to confirm the *in vitro* superiority of strontium-containing preparations in actual oral conditions. Other parameters like the profiles of ion-release of fluoride and strontium ions over prolonged durations, shear bond strength to dentin and enamel, wear strength, marginal adaptation during thermocycling, and fatigue behaviour are to be considered.

The newer bioactive, nano-filled, or resin-modified GIC variants would be further clarified by comparative studies, which would help in designing the next generation materials that would be able to combine the biological benefits of the traditional GICs with even high mechanical reliability. To summarize, the current paper has shown that formulation-specific differences may dominate the conventional material classification, and GIC 2 is the best in mechanical integrity and remineralization potential, and still has the same antimicrobial activity. These important results demonstrate the need to conduct independent, head-to-head comparisons of commercial dental materials and give actionable evidence to inform optimized clinical decisions and future material development.

Conclusion

Within the limitations of this *in vitro* study, significant differences were observed among the tested commercially available conventional glass ionomer cements with respect to their mechanical properties, surface microhardness, and remineralization potential. Among the evaluated materials, GIC 2 demonstrated superior performance in terms of flexural strength, compressive strength, and Vickers microhardness at baseline, after demineralization, and after

remineralization, indicating enhanced mechanical integrity and surface property retention. These properties may be important when selecting restorative materials for pediatric applications, where adequate mechanical strength and stable surface properties can contribute to restoration durability. These findings suggest that formulation-specific variations, including differences in glass composition and material characteristics, may substantially influence the overall performance of conventional glass ionomer cements.

Although all tested materials exhibited inhibitory effects against *Staphylococcus aureus*, no statistically significant differences were observed in antimicrobial activity among the groups, suggesting a comparable fluoride-mediated antibacterial effect. The findings of the present study highlight the importance of evidence-based material selection rather than relying solely on manufacturer classification or intended clinical indication.

However, the results should be interpreted cautiously due to the *in vitro* design, limited sample size, and absence of long-term aging procedures such as thermocycling and cyclic loading. Therefore, these findings should not be interpreted as direct evidence of clinical superiority in pediatric patients. Further studies involving long-term clinical evaluation, fluoride release assessment, and advanced microstructural characterization are recommended to validate these findings and better understand the clinical applicability of the tested materials particularly in primary teeth and pediatric clinical settings.

Abbreviations:

Abbreviation	Full Form
GIC	Glass Ionomer Cement
ART	Atraumatic Restorative Treatment
ANOVA	Analysis of Variance
HSD	Honest Significant Difference
η^2	Eta-squared (Effect Size)
MPa	Megapascal
VHN	Vickers Hardness Number
ZOI	Zone of Inhibition
FS	Flexural Strength
CS	Compressive Strength
ISO	International Organization for Standardization
SPSS	Statistical Package for the Social Sciences
UTM	Universal Testing Machine

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Authors' contribution:

SAH: Conceptualized and designed the study, performed specimen preparation, experimental procedures, and data collection, drafted the original manuscript and contributed to critical revision of the manuscript.

RMS: Performed specimen preparation, experimental procedures and data collection; conducted the statistical analysis and interpretation of data and contributed to critical revision of the manuscript.

SPS: Assisted in data interpretation, manuscript review, and critical intellectual input.

SSW: Contributed to literature review, visualization, manuscript editing and writing of the manuscript.

MJU: Contributed to supervision of the study, interpretation of results, and critical revision of the manuscript.

VVK: Contributed to methodology standardization, validation of findings, validation of results, and critical revision of the manuscript.

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