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Comparative Laboratory Performance of Glass Carbomer and Conventional Restorative Materials Across Interfacial and Surface Properties: An in Vitro Study

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Research Article

Keywords: glass carbomer, glass ionomer cement, shear bond strength, microleakage, microhardness, atomic force microscopy, surface roughness

Posted Date: November 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11349835/v1

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Additional Declarations: No competing interests reported.

Abstract

Objective

To compare glass carbomer with composite resin, compomer, bulk-fill composite, and conventional glass ionomer cement (GIC) in terms of shear bond strength, microleakage, surface microhardness, and surface roughness.

Materials and Methods

Five restorative materials were tested, with 20 specimens per material for each outcome. Shear bond strength was measured on sound human third-molar dentin using a universal testing machine, and failure modes were assessed stereomicroscopically. Microleakage was evaluated in standardized Class V restorations after 1,000 thermal cycles using 0.5% basic fuchsin and an ordinal 0–3 scoring system. Surface microhardness was measured with the Vickers method, and surface roughness was assessed by atomic force microscopy. The original continuous outcomes were analyzed with Kruskal–Wallis, Mann–Whitney U, and Wilcoxon tests as appropriate. Preserved microleakage-score and failure-mode frequency data were reanalyzed using Kruskal–Wallis/Dunn and Fisher–Freeman–Halton exact tests, respectively, with Holm adjustment for pairwise comparisons.

Results

Glass carbomer had a mean shear bond strength of 2.4 ± 1.3 MPa, compared with 0.5 ± 0.9 MPa for conventional GIC and 5.6–5.8 MPa for the resin-based materials; in the original unadjusted pairwise analysis, glass carbomer occupied an intermediate position. Adhesive failure was common in the glass carbomer (85%) and GIC (95%) groups, and their failure-mode distributions differed significantly from those of the resin-based materials after multiplicity adjustment. Microleakage was observed in 85% of glass-carbomer and 95% of GIC restorations versus 40–45% of resin-based restorations. Mean top-surface microhardness followed the descriptive order composite > compomer > bulk-fill composite > glass carbomer > GIC; pairwise significance was based on the archived unadjusted analysis. The archived analysis also showed higher surface roughness for compomer and conventional GIC, while glass carbomer had a comparatively low Ra value, close to those of composite and bulk-fill composite.

Conclusions

Glass carbomer showed a distinct laboratory performance profile. Under the tested protocols, its mean bond-strength value was higher than that of conventional GIC, whereas the numerical reduction in microleakage was not statistically significant after adjustment for multiple comparisons. Relative to the resin-based materials, glass carbomer showed lower bond-strength and top-surface microhardness

values and an intermediate microleakage pattern. Its polished surface roughness was comparatively low and similar in magnitude to composite and bulk-fill composite. Overall, the material's ion-releasing and mineralization-related potential should be considered separately from its mechanical and interfacial performance.

INTRODUCTION

Choosing a restorative material requires balancing adhesion to dental tissues, marginal sealing, mechanical durability, surface characteristics, handling, and biological considerations. This balance is especially important in pediatric dentistry, where limited cooperation and difficulties with moisture control can influence material choice. Conventional glass ionomer cements (GICs) remain useful because they interact chemically with dental hard tissues, release fluoride, and are relatively simple to place. Their lower mechanical strength, wear resistance, and long-term durability, however, can limit their use in stress-bearing areas [1]. Clinical performance also depends on the material selected, cavity configuration, operative technique, and operator-related factors [2].

Glass carbomer was developed as an apatite-containing, glass-ionomer-derived restorative material intended to improve the mineral-interaction potential and physical properties of conventional GICs. The material contains apatite-related components and relatively small glass particles, and its clinical protocol includes heat-assisted maturation and a surface coating. The rationale for adding apatite was supported by earlier work showing that hydroxyapatite or fluoroapatite nanobioceramics could improve the mechanical properties and dentin bond strength of conventional GICs [3]. Long-term changes at the GIC–tooth interface have also revealed calcium- and phosphorus-rich surface alterations consistent with progressive mineral interaction [4].

Subsequent laboratory findings on glass carbomer have been mixed. Cehreli et al. showed that surface protection had a marked effect on microleakage: uncoated specimens showed greater leakage and internal crack-like defects than coated specimens [5]. Olegario et al. later reported higher hardness and microshear bond strength for a high-viscosity GIC than for glass carbomer under their test conditions [6]. At the same time, other studies documented substantial fluoride uptake and release by glass carbomer [7], and more recent long-term microstructural work identified mineralized regions and hydroxyapatite-associated changes next to the material [8]. These findings suggest that its ion-releasing and mineralization-related behavior should be considered separately from its mechanical and interfacial performance.

Clinical evidence has similarly tempered early expectations for the material. In a three-year randomized trial in primary molars, glass-carbomer restorations had lower survival than high-viscosity GIC and compomer in both occlusal and occlusoproximal ART restorations [9]. Another randomized trial found poorer anatomical form and marginal adaptation for glass carbomer than for resin-modified GIC and composite resin in Class II primary-molar restorations [10]. A later systematic review reported marked heterogeneity across studies and annual failure rates of up to 46.2% for glass carbomer, while also

noting the limited quality of the available clinical evidence [11]. More recently, a 2026 systematic review and network meta-analysis of ion-releasing restorative materials in permanent teeth included glass carbomer in its eligibility framework but found too little connected comparative evidence to estimate its relative performance robustly [12].

No single laboratory property can fully describe restorative performance. Bond strength and microleakage capture different aspects of the tooth–restoration interface, whereas microhardness and roughness provide complementary information about surface and mechanical behavior that may affect durability and maintenance. Recent studies continue to show that glass-carbomer hardness, adhesion, and surface roughness vary considerably with the material and experimental protocol [13, 14, 15, 16].

Against this background, the present in vitro study compared the shear bond strength, microleakage, surface microhardness, and surface roughness of a glass carbomer restorative system with those of composite resin, compomer, bulk-fill composite, and conventional GIC under standardized laboratory conditions. The null hypothesis was that the tested materials would not differ significantly in the evaluated interfacial and surface properties.

MATERIALS AND METHODS

Study Design and Ethical Approval

This in vitro laboratory study compared five restorative materials with respect to shear bond strength, microleakage, surface microhardness, and surface roughness. The study was approved by the Erciyes University Clinical Research Ethics Committee (approval no. 2015/549; December 18, 2015). All experimental procedures involving human biological samples were performed in strict accordance with relevant guidelines and regulations, including the ethical principles outlined in the Declaration of Helsinki. Extracted human third molars were obtained following routine clinical indications. In accordance with institutional guidelines and national regulations for the use of anonymized waste biological tissues, specific informed consent from individual patients was waived by the Erciyes University Clinical Research Ethics Committee. The original study protocol reported a power analysis establishing 20 specimens per material group for each outcome; the archived documentation does not specify the input assumptions used for that calculation.

The restorative materials evaluated were a nanohybrid composite resin (Filtek Z550; 3M ESPE, Germany), a compomer (F2000; 3M ESPE, Germany), a bulk-fill composite (Filtek Bulk Fill; 3M ESPE, Germany), a conventional glass ionomer cement (Ketac Molar; 3M ESPE, Germany), and a glass carbomer restorative material (GCP Glass Fill; Glass Carbomer Products, Leiden, the Netherlands). GCP Gloss was used as the surface coating for the glass carbomer group according to the manufacturer's instructions.

Table 1
Restorative materials used in the study.

Material	Manufacturer	Composition documented in original thesis
Filtek Z550 nanohybrid composite resin	3M ESPE, Germany	81.8 wt% filler; 20-nm silica and 0.1–10 μm zirconia particles; Bis-GMA, UDMA, Bis-EMA, PEGDMA, TEGDMA
F2000 compomer	3M ESPE, Germany	Fluoroaluminosilicate glass; colloidal silica; CDMA; GDMA
Filtek Bulk Fill composite	3M ESPE, Germany	76 wt% filler; 20-nm silica and 4-11-nm zirconia particles; AUDMA, UDMA, 1,12-dodecane-DMA
Ketac Molar conventional GIC	3M ESPE, Germany	Glass powder; polyacrylic acid
GCP Glass Fill glass carbomer	GCP, the Netherlands	> 90% fluoroaluminosilicate glass; <6% apatite; <4% polyacid; GCP Gloss: modified polysiloxane

Compositions are reproduced from the archived thesis documentation.

Tooth Selection and Storage

Extracted, caries-free human third molars obtained following extraction for clinical indications, including lack of space or impaction, were used for the bond-strength and microleakage experiments. Teeth with caries or existing restorations were excluded. After removal of residual soft and hard tissues, the teeth were stored in 10% formalin for 1 week and subsequently maintained in distilled water at 37°C until use; the storage water was replaced weekly. According to the archived study documentation, all teeth were used within 6 months of extraction.

A total of 200 teeth were used, comprising 100 specimens for the shear bond-strength experiment and 100 specimens for the microleakage experiment, with 20 teeth allocated to each material group for each test.

Shear Bond-Strength Test

For the shear bond-strength test, the roots were embedded in autopolymerizing acrylic resin up to the cementoenamel junction. The occlusal enamel and a superficial layer of dentin were removed under water cooling to obtain a flat dentin surface parallel to the cementoenamel junction. The exposed dentin surfaces were standardized using 600-grit silicon carbide abrasive paper for 10 s, rinsed with distilled water, and air-dried. The 100 specimens were randomly allocated to the five restorative-material groups.

For the composite, compomer, and bulk-fill composite groups, a self-etch adhesive (Easy Bond Self-Etch Adhesive; 3M ESPE, Seefeld, Germany) was applied to the prepared dentin surface with a microbrush for 10 s, gently air-thinned, and light-cured for 10 s using an LED curing unit (Planmeca Lumion; Planmeca,

Helsinki, Finland). The archived thesis records that the curing-light irradiance used for the resin-based procedures was standardized at 400 mW/cm² and that A2-shade resin materials were used to reduce variation related to shade-dependent light transmission. Cylindrical plastic molds measuring 3 mm in diameter and 3 mm in height were positioned on the dentin surfaces. Composite resin and compomer were placed incrementally in two layers, whereas the bulk-fill composite was inserted as a single increment. Each resin-based material was light-cured for 40 s.

For the conventional GIC group, the material was prepared at a 1:1 powder-to-liquid ratio and placed within the same cylindrical molds. No dentin conditioner was applied before placement of the conventional GIC. For the glass carbomer group, the capsule was mixed for 15 s according to the manufacturer's instructions and applied using the corresponding applicator. A high-power LED curing unit (VALO; Ultradent Products Inc., South Jordan, UT, USA) was applied to the material surface for 90 s to provide the heat required during the initial setting process. The plastic molds were removed after 30 min.

Following preparation, specimens were stored in distilled water at room temperature for 24 h. No thermocycling was performed before the shear bond-strength test. Shear bond strength was measured using a universal testing machine (AGS-1000kg/W; Shimadzu Corp., Tokyo, Japan) at a crosshead speed of 1 mm/min. A knife-edge steel loading device was positioned parallel to the dentin-restorative material interface, and load was applied until failure. The maximum load at failure was recorded in newtons and divided by the bonded surface area to obtain shear bond strength in megapascals (MPa).

Failure-Mode Analysis

Following shear bond-strength testing, fractured surfaces were examined under a stereomicroscope (Olympus SZ-CTV; Olympus, Tokyo, Japan) at ×40 magnification. Failure modes were classified as adhesive when failure occurred at the dentin-restorative material interface, cohesive when fracture occurred within dentin, and mixed when both adhesive and cohesive failure patterns were present.

Microleakage Evaluation

For the microleakage experiment, 100 additional caries-free third molars were used. Root apices were sealed with composite resin, and standardized Class V cavities measuring 3 mm mesiodistally, 2 mm occlusogingivally, and 2 mm in depth were prepared on the buccal surfaces under water cooling. The teeth were randomly allocated to the same five material groups (n = 20 per group). Because the cavity depth did not exceed 2 mm, all restorative materials were inserted using a bulk-placement approach for the microleakage experiment. The corresponding adhesive procedures were applied where required. In the glass carbomer group, GCP Gloss (Glass Carbomer Products, Leiden, the Netherlands) was applied over the completed restoration in accordance with the manufacturer's instructions.

After finishing and polishing, all tooth surfaces were coated with two layers of nail varnish, leaving a 0.5-mm-wide uncoated area around the restoration margins. The specimens were stored in distilled water at 37°C for 24 h and then subjected to 1,000 thermal cycles between 5°C and 55°C, with a dwell time of 15 s in each bath.

Following thermocycling, the specimens were immersed in 0.5% basic fuchsin solution for 24 h, rinsed under running water for 5 min, and sectioned longitudinally in the buccolingual direction through the restorations using a low-speed diamond disk. Dye penetration was evaluated under a stereomicroscope at ×20 magnification using the following ordinal scoring system: 0, no dye penetration; 1, penetration extending up to one-third of the cavity; 2, penetration extending between one-third and two-thirds of the cavity; and 3, penetration reaching the pulpal wall.

Preparation of Specimens for Surface Analyses

Disk-shaped specimens were prepared using custom metal molds containing circular wells 10 mm in diameter. Specimen thickness was 2 mm for composite resin, compomer, conventional GIC, and glass carbomer and 4 mm for the bulk-fill composite. Materials were manipulated according to the manufacturers' instructions. A transparent strip and a 1-mm-thick glass plate were placed over the upper surface of each specimen, and the curing-light tip was positioned in direct contact with the glass plate to standardize the irradiation distance.

Forty disk specimens were prepared for each material, yielding 200 specimens in total. Specimens were stored in distilled water at 37°C for 1 week to allow completion of the setting reaction and were subsequently divided into two groups of 20 specimens for microhardness and surface-roughness testing.

Both surfaces of each disk specimen were sequentially polished using medium-, fine-, and superfine-grit polishing disks. Each polishing disk was applied for 30 s using a low-speed handpiece. Between successive polishing steps, specimens were rinsed under running water for 10 s and air-dried for 5 s.

Surface Microhardness

Twenty specimens from each material group were allocated to surface-microhardness testing. Vickers microhardness was measured by making three indentations on each evaluated surface under a 300-g load, with the indentations positioned approximately 1 mm apart. The mean of the three measurements was recorded as the Vickers hardness value for that surface. For photoactivated and heat-assisted materials, both upper and lower surfaces were evaluated. Conventional GIC was evaluated on one surface only because the original experimental protocol did not distinguish irradiated and non-irradiated surfaces for this chemically setting material.

Surface Roughness

Twenty disk specimens from each restorative material were evaluated for surface roughness using atomic force microscopy (AFM). Three different areas of each specimen surface were scanned, and the mean arithmetic surface roughness (Ra) was calculated from the three measurements for each specimen. Representative two- and three-dimensional surface topography images were also recorded. The archived AFM images document a scan size of 20 × 20 μm, a scan rate of approximately 1.001 Hz, and 256 samples per scan. Surface topography was recorded at the nanometer scale.

Statistical Analysis

Descriptive statistics included mean, standard deviation, median, minimum, maximum, frequency, and percentage, as appropriate. Distributional characteristics of quantitative variables were assessed using the Kolmogorov–Smirnov test. Quantitative outcomes were analyzed using the Kruskal–Wallis test, followed by Mann–Whitney U tests for pairwise comparisons where applicable. Paired upper- and lower-surface measurements were compared using the Wilcoxon signed-rank test. Categorical data in the original study were analyzed using the chi-square test or Fisher's exact test when chi-square assumptions were not satisfied. Statistical analyses were originally performed using SPSS version 22.0, with statistical significance set at $p < 0.05$. Because the complete frequency distribution of the ordinal microleakage scores was preserved in the archived thesis, these data were reanalyzed for the present manuscript using the Kruskal–Wallis test followed by Dunn's pairwise comparisons with Holm adjustment for multiple testing. Complete failure-mode frequencies were also preserved for all specimens. Failure-mode distributions were reanalyzed using the Fisher–Freeman–Halton exact test. Pairwise 2 × 3 exact comparisons were subsequently performed with Holm adjustment for multiple testing. The archived statistical documentation does not indicate that a multiplicity adjustment was applied to the original pairwise analyses of the continuous outcomes; therefore, these results are reported as originally analyzed and interpreted cautiously.

Because individual-level data for shear bond strength, microhardness, and surface roughness were no longer available, the original rank-based pairwise analyses for these continuous outcomes could not be retrospectively reanalyzed with multiplicity adjustment. Accordingly, these pairwise findings are reported as results of the archived original analysis and are interpreted cautiously. The reanalyses of the preserved microleakage and failure-mode data were performed in Python 3.13.5 using SciPy 1.17.0 and statsmodels 0.14.6 for statistical computations and multiplicity adjustment.

RESULTS

Shear Bond Strength

The original Kruskal–Wallis analysis indicated an overall difference in shear bond strength among the restorative material groups ($p < 0.05$). Mean shear bond strength was 5.6 ± 2.0 MPa for composite resin, 5.7 ± 1.3 MPa for compomer, 5.8 ± 2.4 MPa for bulk-fill composite, 0.5 ± 0.9 MPa for conventional GIC, and 2.4 ± 1.3 MPa for glass carbomer. In the archived pairwise analysis, the three resin-based materials

were reported as comparable, conventional GIC as having the lowest bond strength, and glass carbomer as showing an intermediate value. Because multiplicity adjustment could not be retrospectively applied to these pairwise comparisons, the pairwise inferential findings should be interpreted cautiously.

Table 2
Shear bond-strength values of the restorative materials (n = 20 per group).

Material	Minimum-maximum (MPa)	Median (MPa)	Mean ± SD (MPa)
Composite resin	2.9–11.1	5.4	5.6 ± 2.0
Compomer	3.0-7.7	5.8	5.7 ± 1.3
Bulk-fill composite	0.1–11.3	5.7	5.8 ± 2.4
Conventional GIC	0.0-3.5	0.1	0.5 ± 0.9
Glass carbomer	0.7–4.8	1.8	2.4 ± 1.3

The original Kruskal–Wallis analysis indicated an overall group difference ($p < 0.05$). Archived pairwise Mann–Whitney U comparisons were not adjusted for multiplicity and are therefore not displayed as statistical groupings.

Failure-Mode Analysis

Failure-mode distributions differed significantly among the five restorative materials (Fisher–Freeman–Halton exact test, $p < 0.001$). Adhesive failure predominated in the conventional GIC and glass carbomer groups, occurring in 95% and 85% of specimens, respectively, whereas the resin-based materials showed more balanced distributions of adhesive, cohesive, and mixed failures. After Holm adjustment for multiple pairwise comparisons, both conventional GIC and glass carbomer differed significantly from each of the three resin-based materials. No significant difference was observed between conventional GIC and glass carbomer or among the three resin-based groups.

Table 3
Failure-mode distribution following shear bond-strength testing (n = 20 per group).

Material	Adhesive, n (%)	Cohesive, n (%)	Mixed, n (%)	Grouping
Composite resin	8 (40%)	6 (30%)	6 (30%)	A
Compomer	7 (35%)	7 (35%)	6 (30%)	A
Bulk-fill composite	6 (30%)	7 (35%)	7 (35%)	A
Conventional GIC	19 (95%)	1 (5%)	0	B
Glass carbomer	17 (85%)	3 (15%)	0	B
Total	57	24	19	

Overall comparison: Fisher–Freeman–Halton exact test, p < 0.001. Pairwise 2 × 3 exact comparisons were adjusted using the Holm method. Groups sharing the same letter did not differ significantly in Holm-adjusted pairwise exact comparisons (p > 0.05).

Microleakage

Microleakage score distributions differed significantly among the five restorative materials (Kruskal–Wallis H(4) = 22.619, p < 0.001; ε²=0.196). Conventional GIC demonstrated the highest frequency of leakage, with dye penetration observed in 19 of 20 specimens (95%), followed by glass carbomer in 17 of 20 specimens (85%). After Holm adjustment for multiple pairwise comparisons, conventional GIC showed significantly greater microleakage than composite resin (adjusted p = 0.009), compomer (adjusted p = 0.003), and bulk-fill composite (adjusted p = 0.006). Glass carbomer showed significantly greater microleakage than compomer (adjusted p = 0.036), whereas its differences from composite resin (adjusted p = 0.071), bulk-fill composite (adjusted p = 0.054), and conventional GIC (adjusted p = 1.000) were not statistically significant.

Table 4
Distribution of microleakage scores among the restorative materials (n = 20 per group).

Material	Score 0	Score 1	Score 2	Score 3	Any leakage
Composite resin	11 (55%)	4 (20%)	5 (25%)	0 (0%)	9 (45%)
Compomer	12 (60%)	4 (20%)	4 (20%)	0 (0%)	8 (40%)
Bulk-fill composite	11 (55%)	5 (25%)	4 (20%)	0 (0%)	9 (45%)
Conventional GIC	1 (5%)	8 (40%)	7 (35%)	4 (20%)	19 (95%)
Glass carbomer	3 (15%)	8 (40%)	6 (30%)	3 (15%)	17 (85%)

Overall comparison: Kruskal–Wallis H(4) = 22.619, p < 0.001, ε²=0.196. Pairwise comparisons were performed using Dunn's test with Holm adjustment; adjusted p values are reported in the text.

Surface Microhardness

Bottom-Surface Microhardness

The original analysis indicated an overall difference in bottom-surface microhardness among the four evaluated materials (p < 0.05). Composite resin showed the highest mean bottom-surface hardness (82.3 ± 12.7), whereas compomer, bulk-fill composite, and glass carbomer showed mean values of 61.6 ± 14.3, 69.7 ± 4.6, and 69.0 ± 3.2, respectively. In the archived pairwise analysis, composite resin was reported to differ from the other three materials, whereas no pairwise differences were reported among compomer, bulk-fill composite, and glass carbomer. These pairwise findings derive from the original unadjusted analysis and should be interpreted cautiously. Conventional GIC was not included in the

bottom-surface comparison because only one surface was measured for this chemically setting material in the original protocol.

Table 5
Bottom-surface Vickers microhardness values (n = 20 per group).

Material	Minimum-maximum	Mean ± SD
Composite resin	60.3-103.8	82.3 ± 12.7
Compomer	37.6–82.7	61.6 ± 14.3
Bulk-fill composite	59.5–78.3	69.7 ± 4.6
Glass carbomer	61.8–75.1	69.0 ± 3.2

The original analysis indicated an overall group difference ($p < 0.05$). Pairwise statistical groupings are not displayed because the archived Mann–Whitney U comparisons were not adjusted for multiple testing.

Top-Surface Microhardness

The original analysis indicated an overall difference in top-surface microhardness among the five restorative materials ($p < 0.05$). Descriptively, mean top-surface hardness followed the order composite resin (111.5 ± 4.5) > compomer (95.6 ± 21.5) > bulk-fill composite (81.1 ± 3.3) > glass carbomer (71.4 ± 1.8) > conventional GIC (62.8 ± 5.2). The archived pairwise analysis reported differences among all groups; however, because those comparisons were not documented as having undergone multiplicity adjustment, the pairwise inferential findings should be interpreted cautiously.

Table 6
Top-surface Vickers microhardness values (n = 20 per group).

Material	Minimum-maximum	Mean ± SD
Composite resin	105.6-121.6	111.5 ± 4.5
Compomer	61.3-121.6	95.6 ± 21.5
Bulk-fill composite	74.9–86.8	81.1 ± 3.3
Conventional GIC	54.5–69.6	62.8 ± 5.2
Glass carbomer	68.1–75.4	71.4 ± 1.8

The original Kruskal–Wallis analysis indicated an overall group difference ($p < 0.05$). Pairwise statistical groupings from the archived analysis are not shown because multiplicity adjustment could not be verified.

Comparison of Top and Bottom Surfaces

In the original paired analyses, bottom-surface microhardness values were reported as lower than the corresponding top-surface values for all four materials in which both surfaces were evaluated (Wilcoxon signed-rank test, $p < 0.05$ for each material); multiplicity adjustment for these four within-material comparisons could not be verified from the archived statistical documentation.

Table 7
Comparison of top- and bottom-surface Vickers microhardness.

Material	Bottom surface, mean ± SD	Top surface, mean ± SD
Composite resin	82.3 ± 12.7	111.5 ± 4.5
Compomer	61.6 ± 14.3	95.6 ± 21.5
Bulk-fill composite	69.7 ± 4.6	81.1 ± 3.3
Glass carbomer	69.0 ± 3.2	71.4 ± 1.8

In the archived paired analyses, top- and bottom-surface measurements differed at $p < 0.05$ for each material (Wilcoxon signed-rank test); adjustment for multiple within-material comparisons could not be verified.

Surface Roughness

The original analysis indicated an overall difference in AFM surface roughness among the restorative materials ($p < 0.05$). Mean Ra values were 46.6 ± 18.5 for composite resin, 68.0 ± 17.0 for compomer, 48.1 ± 15.4 for bulk-fill composite, 64.0 ± 12.7 for conventional GIC, and 43.8 ± 9.1 for glass carbomer. In the archived pairwise analysis, compomer and conventional GIC were reported to have greater roughness than composite resin, bulk-fill composite, and glass carbomer, whereas no differences were reported within those two clusters. Because the original pairwise comparisons were not documented as multiplicity-adjusted, these inferential findings should be interpreted cautiously.

Table 8
AFM surface-roughness values (Ra, nm; n = 20 per group).

Material	Minimum-maximum	Mean ± SD
Composite resin	26.5–87.2	46.6 ± 18.5
Compomer	41.1–93.1	68.0 ± 17.0
Bulk-fill composite	30.2–80.1	48.1 ± 15.4
Conventional GIC	40.1–97.2	64.0 ± 12.7
Glass carbomer	28.0-64.2	43.8 ± 9.1

The original Kruskal–Wallis analysis indicated an overall group difference ($p < 0.05$). Pairwise statistical groupings from the archived analysis are not displayed because multiplicity adjustment could not be verified.

Representative three-dimensional AFM surface topography images of all five restorative materials are shown in Fig. 1.

Overall, the materials showed different patterns of performance across interfacial behavior, microleakage, hardness, and surface roughness.

DISCUSSION

When the four outcomes are considered together, glass carbomer did not perform consistently better or worse than the comparison materials. In the archived continuous-outcome analyses, its shear bond strength fell between conventional GIC and the resin-based materials, while its top-surface microhardness was lower than the resin-based materials but higher than conventional GIC. Reanalysis of the preserved ordinal microleakage data, with adjustment for multiple comparisons, also placed glass carbomer in an intermediate position and showed no significant difference from conventional GIC. Its surface roughness was comparatively low after the polishing protocol used in this study. Because the original pairwise analyses for shear bond strength, microhardness, and roughness could not be retrospectively adjusted for multiple testing, those comparisons are interpreted with caution.

Shear Bond Strength and Failure Behavior

Glass carbomer had a mean shear bond strength of 2.4 ± 1.3 MPa, compared with 0.5 ± 0.9 MPa for conventional GIC and approximately 5.6–5.8 MPa for composite, compomer, and bulk-fill composite. The failure patterns provided additional information about the interface. Adhesive failure predominated in glass carbomer (85%) and conventional GIC (95%), whereas the resin-based groups showed a more even distribution of adhesive, cohesive, and mixed failures. After adjustment for multiple comparisons, the failure-mode distributions of glass carbomer and conventional GIC differed from each of the three resin-based groups but not from one another. The higher bond-strength values of the resin-based materials are consistent with their use with a self-etch adhesive, which provides micromechanical interaction with dentin, whereas glass carbomer and conventional GIC rely mainly on their inherent interaction with dental tissues.

These bond-strength values should not be compared directly with those from studies using different test designs. Olegario et al., for example, reported higher microshear bond strength for high-viscosity GIC than for glass carbomer in both sound and caries-affected dentin [6], but their study used bovine dentin and a microshear configuration. Test design, bonded surface area, substrate, specimen geometry, and loading configuration can all influence bond-strength measurements; values obtained with different laboratory protocols therefore should not be treated as interchangeable material constants [17].

The failure pattern also points to a relatively vulnerable glass-carbomer–dentin interface under the conditions tested here. Glass carbomer showed a failure-mode distribution that differed significantly from all three resin-based groups and was dominated by adhesive failures. Later studies have also reported weak adhesive behavior for glass carbomer, although the interfaces tested were not always the

same. Isik and Cilingir, for instance, found low shear-bond values for glass carbomer when evaluating adhesion between restorative materials and resin composite [15]. Because the bonding configuration was different, direct numerical comparison is not appropriate, but the finding reinforces the need to interpret bond strength in the context of the specific interface and protocol used.

The use of permanent third-molar dentin is also important when considering pediatric applications. Primary and permanent dentin differ in ways that can affect adhesion; Burrow et al. reported higher overall bond strengths to permanent dentin, although the primary–permanent difference was not significant for every material tested [18]. A later meta-analysis likewise highlighted the limited evidence available for bonding newer glass-ionomer formulations to primary teeth [19]. The bond-strength values reported here therefore should not be extrapolated directly to primary dentin.

Microleakage

The microleakage results showed a similarly mixed pattern. Leakage was found in 95% of conventional GIC restorations and 85% of glass-carbomer restorations, compared with 40–45% of the resin-based groups. After correction for multiple pairwise comparisons, conventional GIC showed significantly greater microleakage than all three resin-based materials. Glass carbomer differed significantly from compomer, but not from composite resin, bulk-fill composite, or conventional GIC. Score-3 dye penetration reaching the pulpal wall occurred only in the conventional GIC and glass-carbomer groups. Taken together, these findings point to substantial marginal leakage in both acid-base-setting systems under the present conditions and do not support interpreting the numerical difference between glass carbomer and conventional GIC as a statistically confirmed advantage.

Surface protection is an important part of interpreting these findings. In primary teeth, Cehreli et al. found the greatest leakage with uncoated glass carbomer, followed by uncoated conventional GIC, while coated glass carbomer did not differ significantly from coated GIC or compomer [5]. They also reported severe internal crack-like defects in uncoated glass-carbomer specimens.

That observation is particularly relevant here because GCP Gloss was applied to glass carbomer according to the manufacturer’s protocol, whereas conventional GIC did not receive a comparable protective coating. Although glass carbomer showed less microleakage numerically, the difference from conventional GIC was not statistically significant after multiplicity adjustment. The result should therefore be viewed as a comparison of complete restorative systems used according to their respective protocols, rather than evidence that the glass-carbomer formulation itself provides a better seal. This distinction matters because early moisture protection can influence maturation and marginal behavior in acid-base-setting materials.

Before dye penetration testing, the specimens underwent 1,000 thermal cycles between 5°C and 55°C, introducing repeated temperature-related stresses at the interface. Even so, dye penetration remains a laboratory surrogate. It does not reproduce the combined effects of occlusal loading, saliva, pH changes, bacterial challenge, wear, and long-term degradation. The leakage scores are therefore useful for

comparing marginal behavior under controlled conditions, but they should not be interpreted as direct measures of secondary-caries risk or clinical survival.

Surface Microhardness

The original analysis showed an overall difference in top-surface microhardness among the five materials ($p < 0.05$). Mean values followed the descriptive order composite resin > compomer > bulk-fill composite > glass carbomer > conventional GIC. In the archived unadjusted pairwise analysis, glass carbomer fell below the resin-based materials and above conventional GIC; because multiplicity adjustment could not be verified, those pairwise comparisons are interpreted cautiously.

Earlier studies have not consistently favored glass carbomer over other GIC formulations. Olegario et al. reported significantly higher Knoop hardness for high-viscosity GIC than for glass carbomer [6]. Other work has shown that glass-carbomer hardness is sensitive to specimen thickness, maturation conditions, thermo-light exposure, and aging. Buldur and Karaarslan found higher upper-surface than bottom-surface hardness, lower bottom-surface hardness with increasing thickness, and effects of both thermo-light treatment and thermal aging on microhardness and surface integrity [13].

In the archived paired analyses, bottom-surface hardness was lower than top-surface hardness for all four materials in which both surfaces were measured; however, multiplicity adjustment across these within-material comparisons could not be verified. For the resin-based materials, reduced curing energy with increasing depth is a plausible explanation. Glass carbomer requires a different interpretation because the high-intensity light was used primarily to generate heat and accelerate maturation rather than to initiate resin photopolymerization. The top-to-bottom difference for glass carbomer was numerically smaller than for the resin-based materials, but the experiment was not designed to investigate setting chemistry, so mechanistic conclusions would be speculative.

Specimen thickness also differed by material: bulk-fill specimens were 4 mm thick, whereas the other surface-analysis specimens were 2 mm thick in keeping with their respective application protocols. For that reason, top-to-bottom comparisons are most meaningful within each material rather than as a direct between-material measure of depth of cure.

Aging may further change these surface properties. Birant and Gumustas evaluated several bioactive restorative materials, including Glass Fill glass carbomer, before and after thermal aging and found material-dependent changes in Vickers microhardness and surface characteristics [16]. The short-term hardness values reported here should therefore be viewed as measurements at a particular stage of material maturation, not as fixed properties.

Surface Roughness

AFM provided a quantitative view of surface roughness. The original analysis showed an overall difference in Ra among the materials ($p < 0.05$), with higher mean values for compomer and conventional GIC than for composite resin, bulk-fill composite, and glass carbomer. The archived pairwise analysis

reported differences between these two clusters, although those comparisons must be interpreted cautiously because multiplicity adjustment could not be verified. Representative three-dimensional AFM images are shown in Fig. 1.

Later studies have not always reproduced the relatively low roughness observed for glass carbomer here. Using AFM, Kelten et al. reported material-dependent roughness differences involving glass carbomer and found no significant correlation between roughness and Streptococcus mutans biofilm formation in their experimental system [14]. Isik and Cilingir later reported the highest surface roughness for glass carbomer among the four ion-releasing materials they tested [15].

These differences across studies are not necessarily inconsistent. Surface roughness depends on specimen preparation, finishing and polishing, surface coatings, storage and aging, and the measurement technique itself. In this study, all specimens underwent the same sequential polishing procedure before AFM analysis. The relatively low Ra value for glass carbomer therefore describes the surface produced by this specific polishing protocol rather than an inherent roughness characteristic of the material in all settings.

Interpretation in the Context of Subsequent Clinical Evidence

Later clinical evidence provides useful context for these laboratory findings. In a three-year randomized trial of ART restorations in primary molars, glass carbomer survival was 62% for occlusal and 36% for occlusoproximal restorations, compared with 83% and 56% for high-viscosity GIC and 78% and 56% for compomer, respectively [9].

El-Housseiny et al. similarly reported 12-month success rates for anatomical form and marginal adaptation of 67% and 54% with glass carbomer, compared with 98% and 93% for resin-modified GIC and 98% and 98% for composite resin [10]. A subsequent systematic review of 29 randomized clinical trials reported annual failure rates of up to 46.2% for glass carbomer, while also noting substantial clinical and methodological heterogeneity and an overall high risk of bias in the primary-tooth literature [11].

The lower bond-strength and hardness values, together with the numerically greater leakage seen with glass carbomer than with the resin-based groups, are broadly consistent with later reports of less favorable clinical performance. That comparison should not be pushed too far: after multiplicity adjustment, the microleakage difference was significant only versus compomer, and laboratory findings cannot establish a causal link with clinical outcomes. Glass carbomer also showed greater bond strength and numerically less microleakage than conventional GIC in this laboratory model, yet the microleakage difference was not significant after adjustment and high-viscosity GIC performed better clinically in the three-year ART trial [9]. This contrast is a useful reminder that laboratory ranking is not the same as clinical ranking. Bond-strength tests themselves are highly protocol dependent and show only limited relationships with clinical outcomes [17].

More recent reviews support the same cautious interpretation. A 2024 umbrella review concluded that GIC longevity is influenced by formulation, cavity type, operative technique, and operator experience, and that evidence for medium- and long-term superiority remains inconsistent [2]. In 2026, Chaple Gil et al. assessed ion-releasing restorative materials in permanent teeth using network meta-analysis; glass carbomer met the review criteria, but the comparative evidence was too sparse and disconnected to support robust network estimates of its relative performance [12]. Thus, even after a decade of additional research, direct comparative clinical evidence for glass carbomer remains limited.

Bioactivity and Mechanical Performance Should Not Be Conflated

Mechanical limitations do not rule out potentially useful biological or mineral-interaction effects. Hasan et al. demonstrated fluoride uptake and release by glass carbomer and reported greater fluoride release than from the conventional and resin-modified GICs included in their experiment [7].

Turjanski et al. more recently followed glass carbomer and conventional GICs for 12 months using field-emission scanning electron microscopy and energy-dispersive X-ray spectroscopy. They observed hydroxyapatite-associated mineralized regions, greater fluoride uptake into dentin, and a distinct pattern of mineral interaction with glass carbomer compared with the conventional GICs tested [8]. The authors also emphasized that these findings require in vivo confirmation.

Taken together, the available evidence argues for separating bioactivity from mechanical and clinical performance. A material can release ions, take up minerals, or show apatite-associated changes without necessarily providing stronger bonding, better marginal integrity, greater hardness, or longer restoration survival. The present study adds to this distinction by describing several interfacial, mechanical, and surface properties within the same experimental framework.

Strengths and Limitations

A key strength of this study is that four complementary properties were assessed within the same experimental framework rather than examining glass carbomer through a single outcome. Shear bond strength and failure mode were evaluated alongside thermocycled microleakage, Vickers microhardness, and AFM-based surface characterization, with 20 specimens per material for each outcome.

The study also has several limitations. Permanent third molars were used instead of primary teeth, so the interfacial findings should not be extrapolated directly to primary dentin [18, 19]. As an in vitro study, the experiment could not reproduce the combined effects of fatigue, oral biofilm, saliva, pH variation, dietary exposure, and long-term degradation. The restorative systems also followed different manufacturer-specific protocols: the resin-based materials were used with a self-etch adhesive, glass carbomer underwent heat-assisted maturation and received a surface coating in the microleakage experiment, and conventional GIC was not coated. The results therefore compare complete restorative systems under the tested protocols rather than isolated intrinsic material properties. Conventional GIC was measured on only one surface in the microhardness experiment because the original protocol

assumed that a chemically setting material would not show a light-dependent top-to-bottom difference, preventing a paired comparison with the other materials. Long-term mechanical aging was not performed for the shear-bond or surface-analysis specimens. Some technical details were also not preserved in the archived documentation, including the AFM instrument model, operating mode and probe specifications, the microhardness tester model and indentation dwell time, the exact relationship of the Class V cavity margins to enamel and dentin, and whether the ordinal microleakage score represented the maximum dye penetration across the sectioned restoration margins. The method used to generate the random allocation sequence was not recorded, and blinding and examiner-reliability procedures for the ordinal microleakage and failure-mode assessments could not be verified retrospectively. The extracted teeth had also been stored in 10% formalin for 1 week before transfer to distilled water, which may have influenced absolute bond-strength values. Finally, because this is an archival dataset, the original individual-level data are no longer available. The original continuous-outcome analyses therefore cannot be independently reconstructed or supplemented with contemporary effect-size estimates from the raw observations.

Even with these limitations, the study offers a broad laboratory view of glass carbomer and places its early experimental performance in the context of the much larger evidence base that has since developed.

CONCLUSIONS

Within the limitations of this in vitro study, glass carbomer showed a distinct, property-dependent performance profile. In the archived analysis, its mean shear bond strength was higher than that of conventional GIC, while the numerical reduction in microleakage was not statistically significant after adjustment for multiple comparisons. Compared with the resin-based materials, glass carbomer showed lower bond-strength and top-surface microhardness values, whereas its polished surface roughness was comparatively low and similar in magnitude to composite resin and bulk-fill composite. Considered together with later laboratory and clinical evidence, these findings suggest that glass carbomer's ion-releasing and mineralization-related potential should be judged separately from its mechanical, interfacial, and clinical performance.

Declarations

Ethics Approval and Consent to Participate: The study was approved by the Erciyes University Clinical Research Ethics Committee (approval no. 2015/549; December 18, 2015). All experimental procedures involving human teeth were performed in strict accordance with relevant guidelines and regulations, including the ethical principles outlined in the Declaration of Helsinki. Extracted human third molars were obtained following routine clinical indications. In accordance with institutional guidelines and national regulations for the use of anonymized waste biological tissues, specific informed consent from individual patients was waived by the Erciyes University Clinical Research Ethics Committee.

Consent for Publication: Not applicable.

Data Availability Statement: The original individual-level dataset is no longer available because of the archival age of the study. All available aggregate data supporting the reported findings are presented in the manuscript and preserved in the associated dental specialty thesis.

Funding: This study was supported by the Erciyes University Scientific Research Projects Unit under project number TDH-2016-6441.

Conflicts of Interest: The authors declare no conflicts of interest.

Funding:

This study was supported by the Erciyes University Scientific Research Projects Unit under project number TDH-2016-6441.

The study was approved by the Erciyes University Clinical Research Ethics Committee (approval no. 2015/549; December 18, 2015). Extracted human teeth were used in this in vitro investigation.

Not applicable. The study was conducted using extracted human teeth and received institutional ethical approval.

The original individual-level dataset is no longer available because of the archival age of the study. All available aggregate data supporting the reported findings are presented in the manuscript and preserved in the associated dental specialty thesis.

The authors declare no conflicts of interest.

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Figures

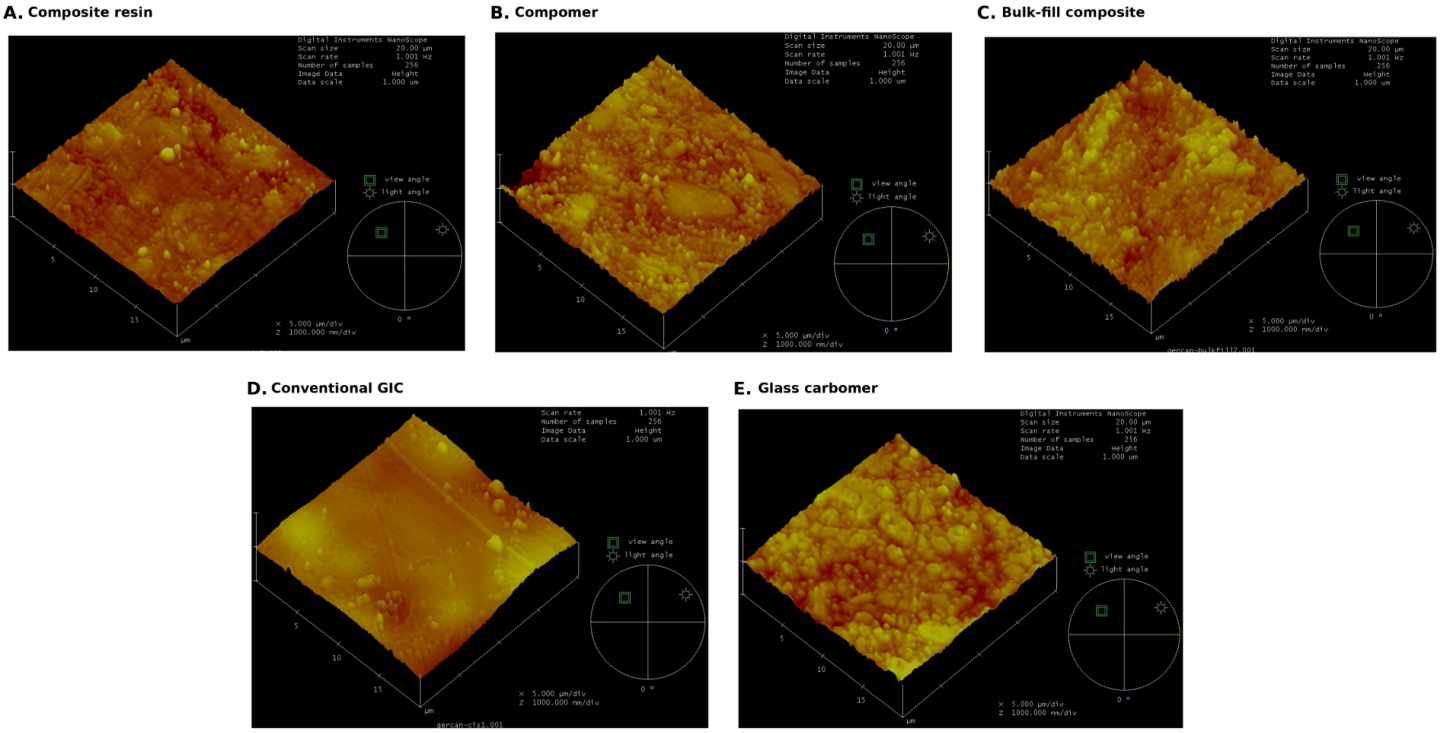

Figure 1

Representative three-dimensional atomic force microscopy (AFM) surface topography images of the polished restorative materials: (A) composite resin, (B) compomer, (C) bulk-fill composite, (D) conventional glass ionomer cement, and (E) glass carbomer. Images were obtained from 20 × 20 μm scan areas at approximately 1.001 Hz with 256 samples per scan.