

Effects of Resin Coatings and Thermocycling on the Surface and Mechanical Properties of a High-Viscosity Glass Ionomer Cement: An In Vitro Study

Tavan Al Zangana

University of Malaya

Noor Azlin Yahya

University of Malaya

Azwatee Abdul Aziz

azwatee@um.edu.my

University of Malaya

Research Article

Keywords: Glass ionomer cement, resin coating, thermocycling, surface roughness, colour difference, flexural strength

Posted Date: October 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11259117/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Background

High-viscosity glass ionomer cements (HVGICs) require surface protection during maturation; however, the durability of resin coatings under prolonged thermal ageing remains uncertain. This study evaluated the effects of two resin coatings and thermocycling on the surface and mechanical properties of EQUIA Forte® HT.

Methods

A total of 180 specimens (90 discs for surface roughness, colour difference, and microhardness; 90 bars for flexural strength) were prepared and allocated to nine experimental groups ($n = 10$ per group) based on coating condition (uncoated, EQUIA Forte Coat, or G-COAT PLUS) and thermocycling exposure (0, 5,000, or 10,000 cycles at 5°C/55°C). Surface roughness (R_a), colour difference (ΔE_{00}), microhardness, and three-point flexural strength were evaluated. Surface morphology was qualitatively assessed by scanning electron microscopy (SEM). Data were analysed using two-way ANOVA followed, where appropriate, by post-hoc or simple-effects comparisons ($\alpha = 0.05$).

Results

Significant coating $\times$ thermocycling interactions were observed for surface roughness, colour difference, and microhardness (all $p \leq 0.002$), whereas the interaction for flexural strength was not significant ($p = 0.118$). Surface roughness generally increased with thermocycling exposure, while greater cumulative thermocycling intervals were associated with greater between-group colour differences. Coated specimens showed lower surface roughness and between-group colour differences and higher flexural strength overall than uncoated specimens. Mean cumulative between-group colour difference (ΔE_{00} , 0–10,000 cycles) exceeded the acceptability threshold ($\Delta E_{00} = 1.8$) across all groups, although G-COAT PLUS remained below the acceptability threshold during the 5,000–10,000-cycle interval (mean $\Delta E_{00} = 1.47$). Measured surface microhardness in coated groups primarily reflected the outer resin layer. SEM showed greater surface deterioration in uncoated specimens, whereas coated specimens generally retained more uniform surfaces.

Conclusions

Resin coatings mitigated thermocycling-associated surface deterioration and between-group colour differences and were associated with higher flexural strength than the uncoated condition. However, their effects were property- and coating-dependent and did not completely prevent changes after prolonged thermal ageing.

Introduction

Glass ionomer cements (GICs) are widely used in restorative dentistry because of their ability to chemically adhere to tooth structure, release fluoride, and exhibit favourable biocompatibility [1, 2]. These materials are formed through an acid–base reaction between polyalkenoic acids and fluoroaluminosilicate glass particles, producing a restoration that closely resembles the thermal expansion characteristics of natural tooth tissues. Owing to these advantages, GICs have become established restorative materials for both conventional and minimally invasive treatment approaches.

Despite their clinical benefits, conventional GICs exhibit several limitations, including brittleness, moisture sensitivity during setting, and relatively low wear resistance [3]. To overcome these shortcomings, high-viscosity glass ionomer cements (HVGICs) have been developed through modifications in particle size distribution, powder-to-liquid ratio, and filler content, resulting in improved physical and mechanical properties [4]. Consequently, HVGICs have gained widespread acceptance for posterior restorations and extended clinical applications.

Water plays a critical role in the setting and maturation of GICs. It functions as a reaction medium during the acid–base process and subsequently becomes an integral component of the mature cement matrix. However, premature dehydration or excessive water uptake during maturation may adversely affect the development of mechanical properties and compromise long-term performance [5]. To minimise these effects, protective surface coatings are routinely applied immediately after placement. Conventional protective agents such as varnishes and petroleum jelly provide only temporary protection and may be rapidly lost under oral conditions. In contrast, light-cured resin coatings form a more durable surface barrier and are widely recommended for contemporary HVGIC systems [6].

Previous studies have demonstrated that resin coatings can improve the surface integrity, hardness, wear resistance, and strength of glass ionomer restorations [4, 7, 8]. These improvements have been attributed to formation of a protective resin layer that reduces moisture imbalance during maturation and seals superficial defects on the cement surface. Coated HVGICs have also been reported to exhibit lower surface roughness and improved resistance to degradation when exposed to acidic and aqueous environments [9, 10].

Thermocycling is a widely accepted laboratory method for simulating temperature fluctuations experienced in the oral environment and for evaluating the durability of restorative materials. Repeated thermal stress may induce dimensional changes, surface deterioration, microstructural defects, and reductions in mechanical performance [11, 12]. Although the effects of thermocycling on dental restorative materials have been extensively investigated, evidence regarding the long-term performance of resin-coated HVGIC systems remains limited.

Despite the documented short-term benefits of resin coatings, comparatively little is known about whether these protective effects persist during prolonged thermal ageing. Moreover, direct comparisons between commercially available resin coatings applied to the same contemporary glass hybrid material

remain limited. Because coating composition may influence resistance to moisture imbalance, thermal stress, and surface degradation, evaluating coating-dependent responses over increasing thermocycling exposure may provide clinically relevant information regarding the durability of these protective systems. EQUIA Forte® HT, a contemporary glass hybrid restorative material, provides an appropriate model for investigating coating performance under simulated thermal ageing conditions.

Accordingly, this study investigated the influence of two resin coating systems on the surface and mechanical properties of EQUIA Forte® HT following thermocycling. Surface roughness, colour differences, microhardness, flexural strength, and surface morphology were evaluated after exposure to 0, 5,000, and 10,000 thermocycles. The null hypotheses were that (i) thermocycling would not affect the evaluated properties of EQUIA Forte® HT, (ii) resin coating would not influence these properties, and (iii) there would be no interaction between coating type and thermocycling condition.

Materials and Methods

This study evaluated EQUIA Forte® HT (GC Corporation, Tokyo, Japan), a glass hybrid restorative material supplied in encapsulated form (shade A2), together with two light-cured resin coating systems, namely EQUIA Forte Coat and G-COAT PLUS. All materials were obtained from the same distributor (GC Malaysia) and prepared from the same batch whenever possible to minimise variability. The materials used in this study are listed in Table 1.

Table 1 Material information		
Materials	Manufacturer	Components
EQUIA Forte® HT	GC Corporation, Tokyo, Japan	Powder: Fluoro-alumino-silicate glass, polyacrylic acid, pigment. Liquid: Water, polyacrylic acid, carboxylic acid.
EQUIA Forte® Coat		Multifunctional monomer, methacrylate, silicon dioxide, initiator, 10-Methacryloyloxydecyl dihydrogen phosphate, stabiliser.
G-COAT PLUS		Urethane methacrylate, methyl methacrylate, camphorquinone, silicon dioxide, phosphoric ester monomer.

Sample Size Calculation

The required sample size was calculated using G*Power version 3.1 (Heinrich Heine University, Düsseldorf, Germany) for an ANOVA (fixed effects, special, main effects and interactions). The sample size calculation assumed a large effect size ($f = 0.50$), with reference to effect magnitudes reported in previous studies evaluating surface roughness and colour stability [9], microhardness [13], and flexural strength [14]. Statistical power was set at 80% with a significance level of 0.05. A minimum of 10

specimens per cell was required. Accordingly, a total of 90 independent specimens per outcome geometry ($n = 10$ per cell across 9 separate experimental groups) was evaluated. A 3×3 factorial design was employed, comprising three coating conditions (uncoated, EQUIA Forte Coat, and G-COAT PLUS) and three independent thermocycling exposure levels (0, 5,000, and 10,000 cycles). Separate sets of specimens were prepared for each thermocycling interval to ensure independent observations across all experimental cells.

Specimen Preparation

A total of 180 specimens were prepared, comprising 90 disc-shaped specimens and 90 bar-shaped specimens. EQUIA Forte® HT capsules were mixed for 10 s using a triturator (Amelga MIX II, YDM Corporation, Tokyo, Japan) according to the manufacturer's instructions. For surface roughness, colour difference, and microhardness evaluations, disc-shaped specimens (8 mm diameter $\times$ 2 mm thickness) were fabricated using Teflon moulds. The material was covered with polyester strips and allowed to set for 5 min at 27°C. Specimens were finished using fine and superfine Sof-Lex™ discs (3M ESPE, St. Paul, MN, USA) under low-speed conditions. Dimensions were verified using a digital calliper (Mitutoyo, Kawasaki, Japan). For flexural strength testing, bar-shaped specimens (25 $\times$ 2 $\times$ 2 mm) were prepared using stainless-steel moulds and were similarly finished and dimensionally verified. Specimens were assigned identification numbers and randomly allocated using a computer-generated random sequence to the experimental groups shown in Table 2.

Resin coatings were applied according to the manufacturers' instructions using a microbrush and light-cured for 20 s with an LED curing unit (Demi Plus, KaVo Kerr, USA) operating at 1100 mW/cm². All specimens were stored at 37°C and 100% relative humidity for 24 h before thermocycling and testing. The overall experimental workflow is illustrated in Fig. 1.

Table 2
Experimental groups according to coating and thermocycling condition

Groups	Material	Coating	Thermocycling cycles
G1T0	EQUIA Forte® HT	Uncoated	0
G1T1			5,000
G1T2			10,000
G2T0		Coated (EQUIA Forte Coat)	0
G2T1			5,000
G2T2			10,000
G3T0		Coated (G-COAT PLUS)	0
G3T1			5,000
G3T2			10,000

Group 1 (G1): Uncoated; Group 2 (G2): EQUIA Forte Coat; Group 3 (G3): G-COAT PLUS; T0 = 0 cycles; T1 = 5,000 cycles; T2 = 10,000 cycles.

Thermocycling Procedure

Thermocycling was performed using a thermocycling machine (Zectron Sdn. Bhd., Kuala Lumpur, Malaysia) to simulate repeated thermal stresses encountered in the oral cavity. Specimens were subjected to 0, 5,000, or 10,000 cycles between 5°C and 55°C, with a dwell time of 15 s in each bath. The 5,000- and 10,000-cycle regimens were selected as commonly used laboratory protocols representing progressively greater thermal ageing exposure [15]. Direct equivalence between thermocycling cycles and duration of clinical service should, however, be interpreted cautiously. Following thermocycling, specimens were stored at 37°C for 24 h prior to testing.

Surface Roughness Evaluation

Surface roughness (Ra) was measured using a 3D optical surface texture analyser (Alicona InfiniteFocus Real3D, Raaba, Belgium) at 20× magnification. Five measurements were obtained from each specimen and averaged to provide the specimen-level Ra value. Results were expressed in micrometres (µm).

Colour Difference Evaluation

Colour measurements were performed using a spectrophotometer (CM-5, Konica Minolta, Tokyo, Japan) in the CIELAB (L*, a*, b*) colour space under standard illuminant D65, a 10° standard observer, and

Specular Component Excluded (SCE) mode with a 3 mm measurement aperture. The instrument was calibrated prior to each session using the manufacturer's standard black box and white calibration tile. Before evaluation, specimens were removed from storage, allowed to air dry at room temperature to remove excess surface moisture, and measured. Three readings were obtained from each specimen against a standard white background and averaged. Colour differences were calculated using the CIEDE2000 (ΔE_{00}) formula. For each coating condition, colour differences were calculated between independent thermocycling groups. ΔE_{00} (0–5,000) and ΔE_{00} (0–10,000) were calculated by comparing the L^* , a^* , and b^* values of specimens in the respective thermocycled groups with the mean L^* , a^* , and b^* values of the corresponding unaged (0-cycle) group. ΔE_{00} (5,000–10,000) was calculated by comparing the L^* , a^* , and b^* values of the 10,000-cycle specimens with the mean values of the corresponding 5,000-cycle group. Because separate specimens were used at each thermocycling level, these values represent between-group colour differences rather than longitudinal within-specimen changes [16].

Microhardness Evaluation

Microhardness was determined using a Vickers microhardness tester (HMV-2, Shimadzu, Kyoto, Japan) equipped with a standard pyramidal diamond indenter. Following thermocycling, specimens allocated for microhardness testing were stored dry at 37°C for 24 h before measurement. Five indentations were made on each specimen using a 50 g load applied for 15 s. Indentations were spaced 300 μm apart and positioned near the specimen centre to eliminate edge effects and stress-field interactions. The Vickers Hardness Number (VHN) was calculated using the formula:

$$\text{VHN} = (1.854 \times F) / d^2$$

where F is the applied load in kilograms-force (kgf) and d is the average diagonal length of the indentation in millimeters. Indentation depth (h) was estimated using the geometric relationship $h \approx d/7$, yielding an approximate depth of 7.26 μm . The reported coating thickness of EQUIA Forte Coat and G-COAT PLUS was 30–50 μm , according to the manufacturers' specifications. As the estimated indentation depth was smaller than the reported coating thickness, microhardness measurements in coated specimens were interpreted primarily as reflecting the surface resin layer rather than the underlying HVGIC.

Flexural Strength Evaluation

Flexural strength was determined using a three-point bending test performed on a universal testing machine (AGS-X, Shimadzu, Kyoto, Japan) at a crosshead speed of 1 mm/min. Specimens were placed on two parallel supports set at a fixed support span (L) of 20 mm. Flexural strength values were calculated using the following formula:

$$FS = 3FL/2bd^2$$

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

Scanning Electron Microscopy

A total of 12 specimens were randomly selected across the nine experimental groups for qualitative SEM evaluation, with at least one specimen examined from each group. Specimens were examined without conductive sputter-coating, as preliminary evaluation demonstrated adequate surface charge dissipation under the low-vacuum operating conditions of the microscope (Phenom Pro XL, Thermo Fisher Scientific, Netherlands). Top-down surface morphology and coating–substrate interfaces (cross-sectional views, where visible) were examined across 3–5 random fields per specimen at magnifications ranging from 200×–1000× and accelerating voltages between 5 and 10 kV. Images were qualitatively evaluated for surface irregularities, microcracks, delamination, interfacial separation, and coating deterioration. SEM findings were interpreted qualitatively and were not subjected to statistical analysis.

Statistical Analysis

Data were analysed using SPSS version 28 (IBM Corp., Armonk, NY, USA). Normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test before analysis. Surface roughness, microhardness, and flexural strength were analysed using two-way ANOVA to determine the effects of coating type and thermocycling condition. Colour difference (ΔE_{00}) was analysed according to coating type and thermocycling interval. When significant main effects or interactions were identified, post hoc or simple-effects comparisons were performed using the Least Significant Difference (LSD) procedure. Statistical significance was established at $p < 0.05$. For flexural strength, exploratory within-coating comparisons across thermocycling conditions were additionally performed despite the absence of a statistically significant coating $\times$ thermocycling interaction; these comparisons were interpreted as secondary analyses.

Results

The results of the two-way ANOVA and subsequent post hoc or simple-effect analyses for all evaluated properties are summarised in Table 3.

Table 3

Two-way ANOVA and significant post hoc/simple-effect comparisons for the evaluated properties

Analysis level	Factor / Comparison	Statistic / Comparison	p-value
Surface roughness (Ra)			
Two-way ANOVA	Coating type	$F(2,81) = 239.28$	< 0.001
	Thermocycling condition	$F(2,81) = 355.16$	< 0.001
	Coating $\times$ Thermocycling condition	$F(4,81) = 27.26$	< 0.001
Post hoc (LSD)	Uncoated	0 cycles $<$ 5,000 cycles $<$ 10,000 cycles	< 0.001
	EQUIA Forte Coat	10,000 cycles $>$ 0 cycles; 10,000 cycles $>$ 5,000 cycles	< 0.001
	G-COAT PLUS	0 cycles $<$ 5,000 cycles $<$ 10,000 cycles	< 0.001
Colour difference (ΔE_{00})			
Two-way ANOVA	Coating type	$F(2,81) = 29.79$	< 0.001
	Thermocycling interval	$F(2,81) = 55.42$	< 0.001
	Coating $\times$ Thermocycling interval	$F(4,81) = 4.83$	0.002
Post hoc (LSD)	Uncoated	0–10,000 cycles $>$ 0–5,000 cycles	< 0.001
	EQUIA Forte Coat	0–10,000 cycles $>$ 0–5,000 cycles; 0–10,000 cycles $>$ 5,000–10,000 cycles	≤ 0.008
	G-COAT PLUS	0–10,000 cycles $>$ 0–5,000 cycles; 0–10,000 cycles $>$ 5,000–10,000 cycles	< 0.001
Microhardness (HV)			
Two-way ANOVA	Coating type	$F(2,81) = 3351.64$	< 0.001
	Thermocycling condition	$F(2,81) = 21.29$	< 0.001
	Coating $\times$ Thermocycling condition	$F(4,81) = 46.46$	< 0.001

Analysis level	Factor / Comparison	Statistic / Comparison	p-value
Surface roughness (Ra)			
Post hoc (LSD)	Uncoated	0 cycles > 5,000 cycles; 0 cycles > 10,000 cycles	< 0.001
	EQUIA Forte Coat	10,000 cycles > 0 cycles	0.010
	G-COAT PLUS	10,000 cycles > 0 cycles; 10,000 cycles > 5,000 cycles	< 0.001
Flexural strength (MPa)			
Two-way ANOVA	Coating type	F(2,81) = 201.34	< 0.001
	Thermocycling condition	F(2,81) = 24.06	< 0.001
	Coating × Thermocycling condition	F(4,81) = 1.90	0.118
Secondary within-coating comparisons	Uncoated	0 cycles vs 5,000 cycles	0.005
	EQUIA Forte Coat	0 cycles vs 5,000 cycles; 0 cycles vs 10,000 cycles	< 0.001
	G-COAT PLUS	0 cycles vs 10,000 cycles	0.001

Only statistically significant post hoc/simple-effect or secondary within-coating comparisons are reported ($p < 0.05$).

Surface Roughness

Mean surface roughness (Ra) values for all groups are presented in Table 4. Two-way ANOVA revealed significant effects of coating type, thermocycling condition, and their interaction on surface roughness (all $p < 0.001$; Table 3).

Surface roughness generally increased with increasing thermocycling exposure. The magnitude of change differed between coating systems, consistent with the significant coating × thermocycling interaction. Both resin-coated groups showed numerically lower mean surface roughness than the uncoated group at each thermocycling condition. Post hoc analysis showed significant increases in Ra with increasing thermocycling in the uncoated and G-COAT PLUS groups (0 cycles < 5,000 cycles < 10,000 cycles; $p < 0.001$). In the EQUIA Forte Coat group, no significant difference was observed between 0 and 5,000 cycles, whereas Ra at 10,000 cycles was significantly higher than at both 0 and 5,000 cycles ($p < 0.001$).

Table 4
Mean (SD) values for the evaluated outcomes

Outcome	Group	Mean (SD)		
		0 cycles	5,000 cycles	10,000 cycles
Surface roughness (Ra, μm)	Uncoated (G1)	0.176 (0.009)	0.244 (0.042)	0.441 (0.019)
	EQUIA Forte Coat (G2)	0.107 (0.02)	0.118 (0.025)	0.223 (0.035)
	G-COAT PLUS (G3)	0.116 (0.021)	0.159 (0.024)	0.248 (0.023)
Microhardness (HV)	Uncoated (G1)	140.10 (8.27)	116.48 (3.18)	119.18 (3.73)
	EQUIA Forte Coat (G2)	34.37 (0.99)	35.74 (5.26)	40.11 (7.15)
	G-COAT PLUS (G3)	28.02 (3.51)	30.51 (3.61)	46.15 (4.15)
Flexural strength (MPa)	Uncoated (G1)	9.40 (2.47)	4.99 (2.86)	6.60 (2.88)
	EQUIA Forte Coat (G2)	16.64 (5.32)	8.69 (3.08)	9.25 (3.62)
	G-COAT PLUS (G3)	33.97 (7.25)	26.43 (3.96)	24.05 (4.96)
Colour difference (ΔE_{00})	Group	0–5,000 cycles	0–10,000 cycles	5,000–10,000 cycles
	Uncoated (G1)	5.52 (1.02)	5.96 (1.15)	2.08 (1.38)
	EQUIA Forte Coat (G2)	3.28 (0.97)	3.86 (0.64)	2.08 (0.96)
	G-COAT PLUS (G3)	3.04 (0.75)	3.37 (1.15)	1.47 (0.61)

Colour Difference

Colour difference (ΔE_{00}) values are presented in Table 4. Two-way ANOVA showed significant effects of coating type ($p < 0.001$), thermocycling interval ($p < 0.001$), and their interaction ($p = 0.002$; Table 3). Colour difference differed according to thermocycling interval within the coating conditions, although not all pairwise interval comparisons were statistically significant. Uncoated specimens exhibited higher mean ΔE_{00} values than coated specimens for the cumulative 0–5,000 and 0–10,000-cycle comparisons. For the cumulative 0–10,000-cycle comparison, mean ΔE_{00} exceeded the acceptability threshold of 1.8 [16] in all three coating conditions. For the 5,000–10,000-cycle interval, the mean ΔE_{00} for G-COAT PLUS (1.47) remained below the acceptability threshold but exceeded the perceptibility threshold of 0.8 [16].

Microhardness

Microhardness values are presented in Table 4. Two-way ANOVA demonstrated significant effects of coating type, thermocycling condition, and their interaction on measured microhardness (all $p < 0.001$; Table 3).

The uncoated group showed lower microhardness following thermocycling, whereas measured surface hardness was higher at 10,000 cycles in both coated groups. Because the estimated indentation depth (7.26 μm) was substantially smaller than the reported coating thickness (30–50 μm), microhardness values in coated specimens primarily reflected the surface properties of the resin coating layer rather than the underlying HVGIC substrate. In contrast, values for the uncoated group reflected the intrinsic hardness of the GIC material. Direct numerical comparisons between coated and uncoated groups should therefore be interpreted in light of this distinct measurement layer, rather than as a direct intrinsic hardening of the cement itself.

Flexural Strength

Flexural strength values for all groups are shown in Table 4. Significant main effects of coating type and thermocycling condition were observed (both $p < 0.001$), whereas the coating $\times$ thermocycling interaction was not significant ($p = 0.118$; Table 3).

Flexural strength decreased following thermocycling in all groups. In the uncoated group, a significant reduction was observed between 0 and 5,000 cycles ($p = 0.005$). In the EQUIA Forte Coat group, values at both 5,000 and 10,000 cycles were significantly lower than at 0 cycles ($p < 0.001$). In the G-COAT PLUS group, flexural strength at 10,000 cycles was significantly lower than at 0 cycles ($p = 0.001$).

Scanning Electron Microscopy

Representative SEM micrographs are shown in Fig. 2. Uncoated specimens exhibited progressive surface deterioration with increasing thermocycling, characterised by surface roughening, pitting and microcrack formation (Fig. 2a–c).

Specimens coated with EQUIA Forte Coat maintained relatively smooth surface morphology; however, localised separation at the coating-cement interface was observed following thermocycling and became more apparent after 10,000 cycles (Fig. 2d–f). In contrast, G-COAT PLUS specimens generally maintained a smooth and homogeneous appearance throughout the experimental period, with no conspicuous microcracks or interfacial discontinuities in the representative fields examined (Fig. 2g–i).

Overall, SEM observations demonstrated greater surface deterioration in uncoated specimens, whereas coated specimens maintained more uniform surface characteristics following thermocycling.

Discussion

The present study evaluated the influence of resin coatings on the response of EQUIA Forte HT, a glass hybrid restorative material, to thermocycling. Thermocycling significantly affected all evaluated properties, including surface roughness, colour difference, measured microhardness, and flexural

strength. Significant coating × thermocycling interactions were observed for surface roughness, colour difference, and microhardness, indicating that the response to thermal ageing depended on the coating condition. In contrast, the interaction for flexural strength was not significant, indicating insufficient evidence that the pattern of strength change differed among coating conditions, despite overall differences associated with coating and thermocycling.

Surface roughness is an important determinant of restoration performance because increased roughness may promote plaque accumulation, staining, and surface deterioration. In the present study, surface roughness generally increased with increasing thermocycling exposure, although the pattern differed according to coating type. Repeated expansion and contraction during thermocycling may induce interfacial stresses, filler debonding, and microcrack formation, thereby accelerating surface degradation. The coated groups exhibited lower roughness values than the uncoated specimens throughout the ageing period, suggesting reduced surface deterioration in the presence of a resin coating. These findings are consistent with previous studies reporting that resin coatings improve surface integrity and reduce roughness in glass ionomer restorations following simulated oral challenges [9, 17]. Although differences were observed between coating systems, the overall pattern suggests that the degree of surface protection may diminish with increasing thermal ageing. Similar observations have been reported in clinical evaluations of glass hybrid restorations in which coating wear and surface deterioration became evident over time [18, 19].

Between-group colour differences were also influenced by thermocycling exposure. Greater cumulative thermocycling exposure was generally associated with larger between-group colour differences, and the magnitude of discolouration was influenced by both coating type and thermocycling interval. Coated specimens exhibited lower mean ΔE_{00} values than uncoated specimens for the main cumulative comparisons, suggesting that surface protection may reduce susceptibility to colour alteration. Increased water sorption and surface degradation may alter light scattering and contribute to greater colour differences. Mean ΔE_{00} values exceeded the perceptibility threshold in all coating conditions, while the colour difference between the 0- and 10,000-cycle groups exceeded the acceptability threshold in all groups. Thus, the coatings reduced, but did not prevent, thermocycling-associated between-group colour differences. Previous investigations have likewise reported improved colour stability following application of protective resin coatings to restorative materials [17].

Microhardness was significantly influenced by coating condition and thermocycling. In the uncoated group, hardness decreased after thermal ageing, consistent with Bardakci et al. (2026) [20], who reported that thermocycling altered the microhardness of contemporary glass ionomer-based restorative materials. In the coated groups, measured hardness increased after thermocycling; however, these findings should be interpreted cautiously because the estimated indentation depth was smaller than the reported coating thickness. Consequently, measurements from coated specimens predominantly reflected the resin coating layer rather than the underlying cement. The observed changes therefore provide information on the behaviour of the coating surface during ageing rather than direct evidence of changes in intrinsic HVGIC hardness. Similar masking effects of protective coatings on hardness

measurements have been reported previously [21, 22]. The lower measured hardness values in coated specimens compared with uncoated specimens are consistent with differences in surface mechanical characteristics between the resin coating and the glass ionomer substrate. However, the clinical implications of this difference require further investigation.

Flexural strength decreased following thermocycling, confirming the adverse influence of thermal ageing on the mechanical performance of the tested HVGIC system. Coated specimens exhibited higher flexural strength overall than uncoated specimens; however, the absence of a significant coating × thermocycling interaction indicates that there was insufficient evidence that the pattern of strength reduction differed among coating conditions. The higher strength observed in coated groups may be related to sealing of surface defects that could otherwise act as crack-initiation sites, together with reduced moisture-related deterioration during maturation. These findings are consistent with Zambon et al. (2026) [23], who reported improved mechanical properties following surface treatment or coating of EQUIA Forte® HT. Similar findings have been reported for resin-coated glass ionomer systems, in which protective coatings were associated with improved flexural performance and fracture resistance [8, 14].

The qualitative SEM observations were generally consistent with the quantitative surface findings. Uncoated specimens exhibited greater surface irregularities, including roughening and microcrack formation, whereas coated specimens maintained relatively smoother surface characteristics following thermocycling. Localised interfacial separation was observed in some EQUIA Forte Coat specimens after ageing, while G-COAT PLUS specimens generally exhibited fewer conspicuous surface defects within the representative fields examined. Because SEM evaluation was qualitative and limited to representative specimens, these observations should not be interpreted as definitive evidence of coating degradation mechanisms. These findings suggest that resin coatings can provide surface protection to HVGICs during thermocycling, although the persistence and clinical significance of this protection require further investigation.

Several limitations should be considered when interpreting the present findings. Only one HVGIC system was evaluated, and thermocycling served as the sole laboratory ageing method. Clinically relevant challenges, such as mechanical wear, abrasion, pH fluctuations, staining exposure, and biofilm activity, were not investigated. Additionally, because the estimated indentation depth was smaller than the reported coating thickness, microhardness measurements in coated specimens primarily reflected the surface resin layer rather than intrinsic cement hardening. SEM evaluations were also qualitative and limited to representative fields. Furthermore, colour differences were derived from comparisons between independent specimen groups rather than repeated measurements of the same specimens and therefore should not be interpreted as longitudinal within-specimen colour difference. Consequently, direct extrapolation of these *in vitro* findings to clinical performance should be undertaken with caution.

Despite these limitations, the findings suggest that resin coatings may mitigate selected thermocycling-associated changes in EQUIA Forte® HT, with coated specimens exhibiting more favourable surface characteristics and higher flexural strength than uncoated specimens. From a clinical perspective, these

findings are consistent with the rationale for using protective resin coatings during material maturation. However, as the protective effects were property- and coating-dependent, further studies incorporating combined thermal, mechanical, chemical, and biological ageing challenges, together with long-term clinical studies, are required to clarify the intraoral durability and clinical relevance of these protective systems.

Conclusions

Within the limitations of this *in vitro* study, thermocycling significantly influenced the surface and mechanical properties of EQUIA Forte® HT. Both resin coatings reduced thermocycling-associated increases in surface roughness and between-group colour differences and were associated with higher flexural strength than the uncoated condition. However, these effects were property- and coating-dependent, and neither coating completely prevented changes associated with thermal ageing. Microhardness measurements in coated specimens primarily reflected the resin coating layer rather than the underlying HVGIC and should therefore be interpreted separately. As laboratory thermocycling does not reproduce the complex mechanical, chemical, and biological challenges of the oral environment, further studies incorporating combined ageing protocols and long-term clinical evaluation are required to determine the durability and clinical relevance of these protective systems.

Abbreviations

Abbreviation

Full Term

ANOVA

Analysis of Variance

CIELAB

Commission Internationale de l'Éclairage L*, a*, b* colour space

GIC

Glass Ionomer Cement

HVGIC

High-Viscosity Glass Ionomer Cement

LED

Light-Emitting Diode

LSD

Least Significant Difference

SCE

Specular Component Excluded

SD

Standard Deviation

SEM

Scanning Electron Microscopy

VHN
Vickers Hardness Number

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Funding

The authors received no specific funding for this work.

Author Contribution

T.A.Z. contributed to the investigation, specimen preparation, data collection, data analysis, and preparation of the initial manuscript draft. N.A.Y. contributed to the study methodology, supervision, interpretation of the data, and critical revision of the manuscript. A.A.A. contributed to the conceptualization and design of the study, methodology, supervision, interpretation of the data, and critical revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

Acknowledgement

The authors would like to thank the Biomaterials Research Laboratory (BRL), Faculty of Dentistry, Universiti Malaya, for providing the facilities and technical support required to carry out this study. We are also grateful to the laboratory staff for their assistance with testing procedures.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

References

1. Tezel H, Mulabdic M, Akin D, Barhan FS, Atalayin Ozkaya C, Kose T, et al. The effect of different glass ionomer cements and surface coating applications on fluoride release and microhardness values. *BMC Oral Health*. 2025;25(1):1730. 10.1186/s12903-025-07099-4.
2. Zhang Y, Fu Y, Li KC, Ekambaram M, Dai R, Cooper PR, Li QL, Mei ML. A scoping review of hydroxyapatite-modified glass ionomer cements used for restorative dentistry. *J Dent*. 2025;163:106149. 10.1016/j.jdent.2025.106149.
3. Abed FM, Kotha SB, AlShukairi H, Almotawah FN, Alabdulaly RA, Mallineni SK. Effect of Different Concentrations of Silver Nanoparticles on the Quality of the Chemical Bond of Glass Ionomer Cement Dentine in Primary Teeth. *Front Bioeng Biotechnol*. 2022;10:816652. 10.3389/fbioe.2022.816652.
4. Alqasabi SY, Sulimany AM, Almohareb T, Alayad AS, Bawazir OA. The Effect of Different Coating Agents on the Microhardness, Water Sorption, and Solubility of EQUIA Forte® HT. *Coatings*. 2024;14:751. 10.3390/coatings14060751.
5. Schwendicke F, Kniess J, Paris S, Blunck U. Margin Integrity and Secondary Caries of Lined or Non-lined Composite and Glass Hybrid Restorations After Selective Excavation In Vitro. *Oper Dent*. 2017;42:155–64. 10.2341/16-095-L.
6. Akgül S, Hazar A, Yıkılğan İ, Özcan S, Üçtaşlı MB, Bala O. Effect of Thermocycling On Mechanical and Surface Properties of Three Posterior Restorative Materials. *Selcuk Dent J*. 2021;8:352–8. 10.15311/selcukdentj.646987.
7. Al Zangana T, Tuygunov N, Yahya NA, Abdul Aziz A. The impact of resin coatings on the properties and performance of glass ionomer cements: A systematic review. *J Mech Behav Biomed Mater*. 2025;169:107044. 10.1016/j.jmbbm.2025.107044.
8. Alebady MH, Hamama HH, Mahmoud SH. Effect of various surface coating methods on surface roughness, micromorphological analysis and fluoride release from contemporary glass ionomer restorations. *BMC Oral Health*. 2024;24:504. 10.1186/s12903-024-04234-5.
9. Habib SI, Yassen AA, Bayoumi RE. Influence of Nanocoats on the Physicomechanical Properties and Microleakage of Bulk-fill and Resin-modified Glass Ionomer Cements: An In Vitro Study. *J Contemp Dent Pract*. 2021;22:62–8.
10. Xin JOE, U-Jin AY, Yahya NA. Can resin coatings improve the flexural properties of highly viscous glass ionomer cements? *Sains Malaysiana*. 2022;51(6):1875–83. 10.17576/jsm-2022-5106-22.
11. Bousses Y, Brulat-Bouchard N, Bouchard PO, Tillier Y. A numerical, theoretical and experimental study of the effect of thermocycling on the matrix-filler interface of dental restorative materials. *Dent Mater*. 2021;37:772–82. 10.1016/j.dental.2021.01.010.
12. Ghavami-Lahiji M, Firouzmanesh M, Bagheri H, Jafarzadeh Kashi TS, Razazpour F, Behroozibakhsh M. The effect of thermocycling on the degree of conversion and mechanical properties of a microhybrid dental resin composite. *Restor Dent Endod*. 2018;43:e26. 10.5395/rde.2018.43.e26.

13. Mishra N, Agarwal M, Singh M, Khullar A, Magwa K, Thakur SS. Comparative Evaluation of effect of resin protective coatings on the surface hardness and shear punch strength of different GICs-An InVitro Study. *Endodontia Today*. 2021;19:160–5.
14. Thongbai-On N, Banomyong D. Flexural strengths and porosities of coated or uncoated, high powder-liquid and resin-modified glass ionomer cements. *J Dent Sci*. 2020;15:433–6. 10.1016/j.jds.2020.02.004.
15. Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. *J Dent*. 1999;27:89–99. 10.1016/s0300-5712(98)00037-2.
16. Paravina RD, Ghinea R, Herrera LJ, Bona AD, Igiel C, Linninger M, et al. Color difference thresholds in dentistry. *J Esthet Restor Dent*. 2015;27(Suppl 1):S1–9. 10.1111/jerd.12149.
17. Bagis B, Tuzuner T, Turgut S, Korkmaz FM, Baygin O, Bagis YH. Effects of protective resin coating on the surface roughness and color stability of resin-based restorative materials. *ScientificWorldJournal*. 2014;2014:832947. 10.1155/2014/832947.
18. Balkaya H, Arslan SA, Two-year. Clinical Comparison of Three Different Restorative Materials in Class II Cavities. *Oper Dent*. 2020;45:E32–42. 10.2341/19-078-C.
19. Hesse D, Bonifacio CC, Kleverlaan CJ, Raggio DP. Clinical wear of approximal glass ionomer restorations protected with a nanofilled self-adhesive light-cured protective coating. *J Appl Oral Sci*. 2018;26:e20180094. 10.1590/1678-7757-2018-0094.
20. Bardakci E, Ozdemir Ozenen D, Yavuz I. The Effect of Thermocycling on the Microhardness of Contemporary Glass Ionomer-Based Restorative Materials: An In Vitro Study. *Bioeng (Basel)*. 2026;13:161. 10.3390/bioengineering13020161.
21. Faraji F, Heshmat H, Banava S. Effect of protective coating on microhardness of a new glass ionomer cement: Nanofilled coating versus unfilled resin. *J Conserv Dent*. 2017;20:260–3. 10.4103/JCD.JCD_83_16.
22. Lee JS, Chan WN, Yahya NA, Omar RA. Effect of Resin Coating on Surface Roughness and Microhardness of High Viscous Glass Ionomer Cements. *Arch Orofac Sci*. 2021;16:209–21. 10.21315/aos2021.16.2.11.
23. Zambon G, Cagetti MG, Cirio S, De Bortoli G, Allam A, Ionescu AC. Surface treatments and coatings of hybrid glass ionomer cement to improve mechanical and physical properties. *Sci Rep*. 2026;16:571. 10.1038/s41598-025-30202-2.

Figures

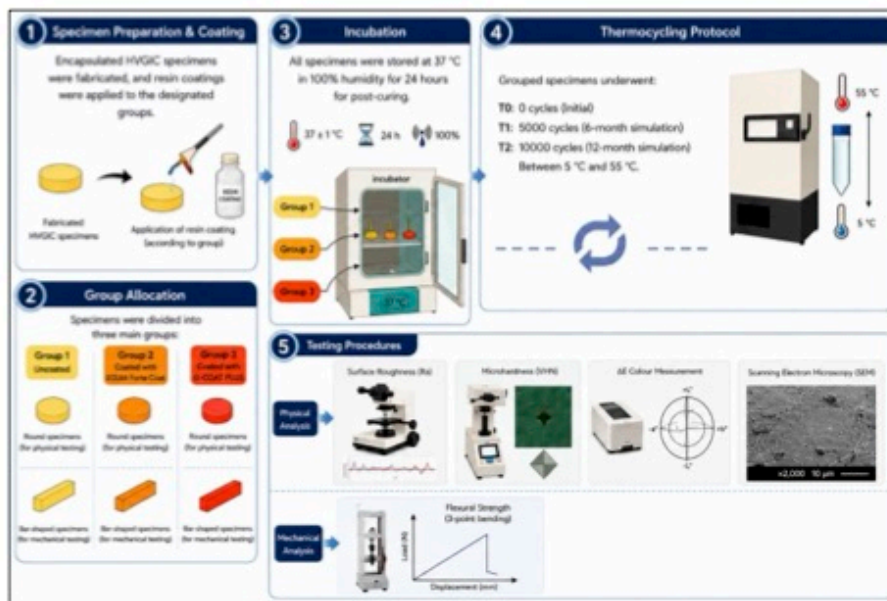


Figure 1

Overall experimental workflow. Encapsulated HVGIC specimens were prepared and assigned according to coating condition. After incubation, specimens underwent thermocycling (0, 5,000, or 10,000 cycles between 5 °C and 55 °C) to provide progressively greater thermal ageing exposure. Physical and mechanical properties were then evaluated.

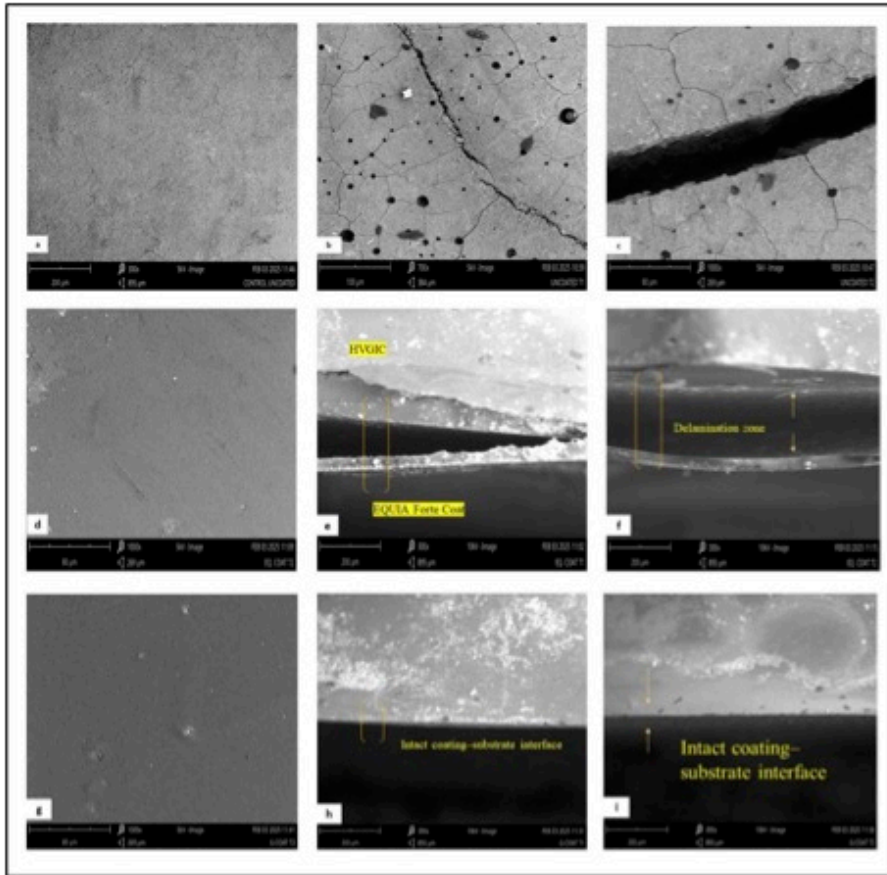


Figure 2

Representative scanning electron microscopy (SEM) images of EQUIA Forte[®] HT specimens. Representative scanning electron microscopy (SEM) images, according to surface coating and thermocycling condition: (a - c) uncoated specimens at 0, 5,000, and 10,000 cycles, respectively; (d-f) EQUIA Forte Coat specimens at 0, 5,000, and 10,000 cycles, respectively; and (g-i) G-COAT PLUS

specimens at 0, 5,000, and 10,000 cycles, respectively. Images are representative and were interpreted qualitatively.