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The ability of highly-filled flowable composites in preventing marginal gap in class V restorations: an optical coherence tomography study

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Abstract

Background Despite improvements in adhesive systems and restorative materials, interfacial gap opening and subsequent microleakage are major factors in the failure of resin-based composite (RBC) restorations. This study evaluated the marginal gap in class V restorations using two highly-filled flowable RBC with varying viscosities, both before and after aging process.

Methods Standardized class V cavities were created on the buccal side of intact single-root human upper premolars ($n = 48$). Specimens were randomly divided into three groups ($n = 16$) considering the selected restorative materials: a nanohybrid packable RBC serving as a control group (G1, Clearfil Majesty ES2, Kuraray Noritake) and two highly-filled RBCs with different viscosities (G2, Majesty ES Low Flow, Kuraray Noritake; G3, Majesty ES Super Low Flow, Kuraray Noritake). The initial marginal adaptation, both at the enamel and dentin substrate, was evaluated using optical coherence tomography (OCT). Specimens were then divided into two subgroups ($n = 8$) according to the aging process performed: thermocycling (TC) and thermomechanical cycling (TMC). After TC and TMC specimens were scanned again with OCT to evaluate margin degradation. Using a dedicated program, 2D cross-sectional images were obtained and the images were processed and quantitatively analyzed using Image J software. The interfacial gap between tooth and composite was linearly measured at baseline and after aging. A three-way analysis of variance (ANOVA) and a post-hoc Tuckey test were used to statistically analyze the data (Stata 17.0 software package).

Results ANOVA statistics regarding baseline and post aging results indicated that the employed material and the substrate were influent on interfacial gap ($p \leq 0.05$). The ANOVA test also showed that TMC induce significantly higher gap opening than the TC. G2 (Majesty ES Low Flow) performed significantly better than G1 (Clearfil Majesty ES2) and G3 (Majesty ES Super Low Flow) at baseline and then G1(Clearfil Majesty ES2) after the aging process in terms of interfacial adaptation. Dentin showed significantly lower adaptation at both the baseline and post aging process. Moreover, the thermomechanical cycling induced a significantly higher gap opening than the thermocycling alone.

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Conclusion Highly-filled flowable RBC showed promising results in terms of interfacial gap adaptation both at the baseline and after the aging process. The presence of a cervical substrate and the mechanical aging worsen the marginal adaptation.

Keywords Thermocycling, Class five, Marginal gap, Optical coherence tomography, Resin-based composite

Introduction

The durability of resin-based composite (RBC) restorations heavily depends on their capacity to form a dependable marginal seal, which is crucial for preventing microleakage at the junction between the material and the tooth [1, 2]. Despite advancements in both adhesive systems and restorative materials, the presence of interfacial gaps and the resulting microleakage remain significant contributors to the eventual failure of RBCs over time [3]. Research suggests that numerous factors can affect the formation of interfacial gaps, both initially and after the materials have undergone fatigue.

Gaps can arise due to shrinkage stress, which is linked to the material's composition, including filler particle size and shape aggregates, and resin loading. This also involves its physical properties like volumetric shrinkage and modulus of elasticity, the polymerization method used, c-factor, and how it is handled clinically [2, 4, 5]. When compared to other elements, polymerization tends to play a lesser role [6]. However, polymerization shrinkage has been extensively shown to lead to microleakage at adhesive interfaces because of the stress exerted on the cavity walls [7–9]. While the c-factor is significant, it cannot be controlled as it is dictated by the clinical circumstances. Additionally, material handling can impact outcomes, but analyzing this factor in controlled in-vitro studies is challenging due to potential human bias [10].

Flowable materials were created to make the placement process within the cavity easier, improve adaptation to internal surfaces, and enhance the interfacial seal [11]. In the initial compositions, in order to lower their viscosity, the filler loading was significantly reduced (37-53% volume) compared to the packable conventional materials (50-70% volume), while maintaining the same filler particle size as conventional hybrid RBCs [12]. As a result, these early flowable formulations demonstrated poor clinical performance with lower mechanical properties right from the start, exhibiting difficult manipulability and increased volumetric shrinkage during polymerization, and over time showed reduced resistance to mechanical and thermal stresses, which made them suitable only for low-stress internal areas [13–15].

Nevertheless, studies indicate that flowable RBCs can potentially lower shrinkage stress at the bonded interface and form a stress-absorbing layer due to their elastic modulus's stress-relieving effect [16].

In recent times, highly-filled flowable resin-based composites (HFRBCs) have been developed to combine the optimal characteristics of both flowable and standard resin-based composites. The advancement in resin filler technology permits higher filler content by reducing the filler size to the nanometer scale, thereby achieving a uniform shape and enhanced distribution within the monomer [17]. This novel resin filler composition enables the filler particles to be positioned very closely, which minimizes the spacing between particles and ensures a consistent dispersion within the resin matrix, thereby boosting reinforcement and safeguarding the matrix [18]. Furthermore, the chemical treatment applied to the filler particles ensures that the monomer can effectively wet the filler surface, resulting in improved dispersion and a stable, stronger bond between the filler and the matrix [18]. As stated by manufacturers, HFRBCs are claimed to provide mechanical, physical, and aesthetic attributes that are comparable to or exceed those of many traditional hybrid composites [19]. Clinically, this material offers advantages such as easier placement and handling, better adaptation to internal cavity walls, enhanced wear resistance, increased elasticity, color stability, superior polishability, retention of polish, and radiopacity akin to enamel [14]. Due to these advantageous properties, HFRBCs are already being successfully employed as liners in deep margin relocation [20]. Given their increased filler content, HFRBCs are likely to experience less volumetric shrinkage during polymerization, potentially reducing the formation of interfacial gaps at enamel and dentin restorations and enhancing bond strength [21]. Ferracane et al. confirmed a positive linear relationship between filler content and polymerization stress [22]. Moreover, a high filler volume percentage typically enhances the mechanical and physical properties of composites [23].

The newly introduced HFRBCs have mechanical characteristics comparable to traditional composites, with the added advantage of being easier to apply within the cavity [19]. This attribute makes HFRBCs essential for the long-term success of class V cavities, as the materials are exposed to mechanical or erosive stress. Additionally, the degradation of the material over time due to its function must be considered. It is well-known that cyclic loads and thermal stress negatively impact all adhesive interfaces [24].

Despite the promising performance of HFRBCs, to the best of the authors' knowledge, no studies have explored their performance in high C-factor cavities or their ability to create a sufficient and stable marginal seal. Therefore, the purpose of this in vitro study was to assess the interfacial sealing capabilities of two different HFRBCs in class V restorations. The null hypotheses tested were that the marginal gap in class V restorations is not affected [1] by the different RBCs tested, [2] the substrate (enamel or dentin), [3] or the different fatigue tests.

Materials and methods

Study design

This study was designed in three study groups ($n = 16$ each), where the specimens were randomly allocated considering the following:

a. "Restorative Material". Class V cavities were restored with 3 different resin-based materials: a packable nanohybrid RBC, used as control group and 2 HFRBCs with different viscosities. Materials employed in the present study are detailed in Table 1.
b. "Aging treatment". Specimens were subjected to 2 different aging protocols: thermocycling and thermomechanical cycling.

Specimen preparation

A power analysis was carried out with a software program (G*Power v3.0.10), which revealed that at least 8 specimens were required for the highest power level (power = 80, $\alpha = 0.05$) ($N = 48$, n per group = 16).

Intact single-root human upper premolars ($n = 48$) with similar diameter, extracted for periodontal or orthodontic reasons within four months with mature apices, were selected and stored in 0.5% chloramine solution at 4° in a temperature humidity-controlled incubator [27, 28]. The following inclusion criteria were applied: absence of carious lesions, demineralization, abrasions, or cracks under 10x optical magnification and transillumination, and intact CEJ (cementoenamel junction). Ultrasonic scaling and polishing were used for root and coronal surface debridement. Specimens were then stored in distilled water at room temperature for at least 72 h after cleaning procedures. The study was granted ethics approval by the local ethics committee of the Dental School, University of XXXXX (DS_2021_011).

The preparation of Class V cavities was performed on the buccal side of each specimen, using a cylindrical diamond bur (model 835KR; Komet) mounted on a high-speed handpiece under abundant water as coolant. A single expert operator (NS) was responsible for all the preparations, to avoid bias related to the different experiences of different operators. The bur was replaced after every sixth cavity. The class V cavity was standardized according to the following design (Fig. 1): 5 mm apical-coronal extension, 3 mm mesial-distal extension, and 2 mm depth. The cervical margin was 90° and the coronal margin was 45° bevel (1.5 mm length). The occlusal cavity margin was located in enamel and the radicular cavity margin was located in dentin. The two margins were clearly visible so that the marginal gap could be easily analyzed at both the dentin and enamel levels. A periodontal probe was used to check cavity sizes.

A standardized adhesive protocol was performed on all specimens as follows: selective enamel etching for 30 s with 35% phosphoric acid (K-Etchant, Kuraray Noritake, Japan), 30 s of rinsing, 30 s of air drying and application of a two-step self-etch adhesive system (Clearfil Se Bond 2, Kuraray Noritake, Japan) following the manufacturer's instructions. After mild air drying, the adhesive was light cured for 40 s at 1400 mW/cm2 with LED lamp (Cefalux 2, VOCO, Germany).

After that, specimens were randomly divided into three groups ($n = 16$ each) according to the materials selected for the restoration: a nanohybrid packable RBC serving as control (Clearfil Es2, Kuraray Noritake, Japan; G1); a medium-viscosity flowable HFRBC (Majesty Es Low Flow, Kuraray Noritake, Japan; G2); a low-viscosity flowable HFRBC (Majesty Es Super Low Flow, Kuraray Noritake, Japan; G3).

Since cavity design was purposely superficial (2 mm depth), all tested materials were applied with a single 2 mm thick layer, avoiding biases related to layering

Table 1 Employed materials and their manufacturing compositions

Material	Classification	Main Components
Clearfil Se Bond 2 (Kuraray Noritake)	Etch & Dry two-steps adhesive	Primer: 10-Methacryloyloxydecyl dihydrogen phosphate (MDP), 2-ydroxyethyl methacrylate (HEMA), Hydrophilic aliphatic dimetacrylate, dl-Camphoroquinone, water Bond: 10-Methacryloyloxydecyl dihydrogen phosphate (MDP), 2-ydroxyethyl methacrylate (HEMA), Bisphenol A diglycidylmethacrylate (Bis-GMA), Hydrophilic aliphatic dimetacrylate, dl-Camphoroquinone, initiators, accelerators, silanated colloidal silica
Clearfil Majesty Es2 (Kuraray Noritake)	Nanohybrid composite	Matrix: Bis-GMA, hydrophobic aromatic DMA and hydrophobic aliphatic, dl-camphorquinone Filler: silanated barium glass (particle size 0.37–1.5 µm) and prepolymerized organic filler. 78 wt%, 40 vol%
Majesty Es Super Low Flow (Kuraray Noritake)	Highly filled flowable resin composite– low viscosity	Matrix: TEGDMA, hydrophobic aromatic DMA, dl-camphorquinone, PI Filler: barium glass filler, silica filler 78 wt%, 64 vol% [25]
Majesty Es Low Flow (Kuraray Noritake)	Highly filled flowable resin composite– medium viscosity	Matrix: TEGDMA, hydrophobic aromatic DMA, dl-camphorquinone, PI Filler: barium glass filler, silica filler 81 wt%, 62 vol% [26]

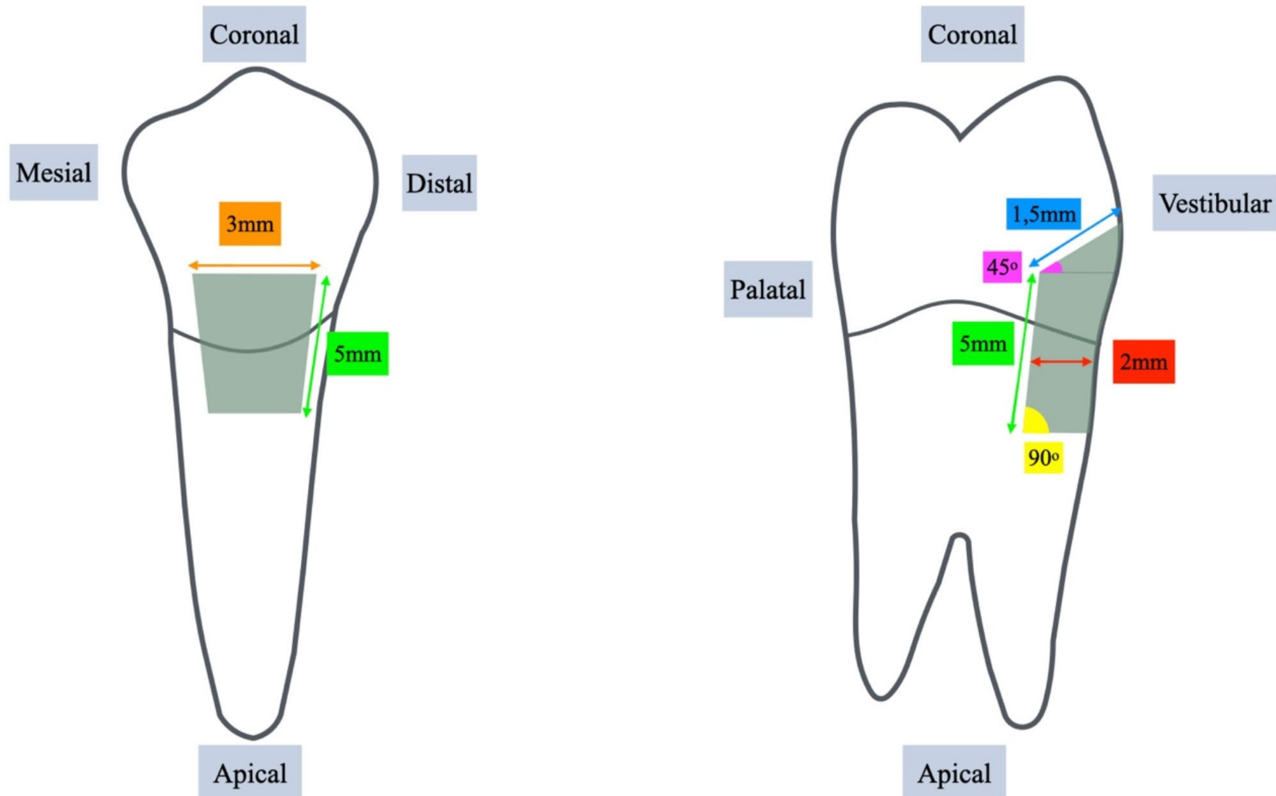

Fig. 1 Graphical representation of the class V cavity design

techniques and material thickness. The layer was light cured for 20 s at 1400 mW/cm2 with the same LED lamp (Cefalux 2, VOCO, Germany), then a final 20 s light curing was performed under air-barrier transparent gel [29]. Specimens were then polished using fine and extra fine diamond burs (max 10 use), rubber tips (Twist DIA, Kuraray Noritake, Japan) and a nylon brush and then stored in water at 37 °C. All specimens were restored by a single operator (BP).

Optical coherence tomography (OCT) analysis

Similar to the work of Sampaio et al. [30], after 24 h of storage, the initial marginal adaptation of each specimen was evaluated using OCT (Vivo Sight OCT scanner Tel200, Michelson Diagnostics, United Kingdom). The LSM03 OCT Scan Lens from Thorlabs Inc is an optical lens with a wavelength Range of 1315 ± 65 nm, a magnification of 5X, and a back focal length of 36 mm. To allow visualization of the composite-tooth interface, specimens were positioned with the buccal surface, including the class V restoration, facing upward. A silicone specimen holder was fabricated for each tooth to individually fix it to the OCT worktable and allow comparable assessment of each tooth before and after aging treatments. The scanning beam was oriented perpendicularly (0°) to the restoration surface, with the tooth positioned horizontally. Cross-sectional 2D images of 1600 × 519 pixels were obtained using the SR Scan program (Thorlabs Inc). These images were obtained every 250 μm by scanning the class V restorations in the mesiodistal direction [5].

The change in the signal intensity at the interface of resin and enamel or dentin, which appeared as bright areas, indicated a marginal gap (Figs. 2 and 3). When light traverses the interface through two different media, it undergoes refraction as well as partial reflection. The reflection of a fraction of the light at an interface between two media with different refractive indices depends on the angle of incidence and the refractive index contrast. The refractive index of air, which in the present study was assumed to correspond to the gap is $n = 1.0$, whereas those of both teeth and resin composites are in the range of $n = 1.4–1.6$ [31].

Specimen aging treatment

Specimens were then divided into two subgroups ($n = 8$ each) according to the aging process performed: thermocycling (TC) for 10.000 cycles and thermomechanical cycling (TMC) for 500.000 cycles in a chewing simulator with simultaneous TC.

Concerning TC, similarly to Lucena-Martín et al. [32], specimens were immersed in alternate water baths at

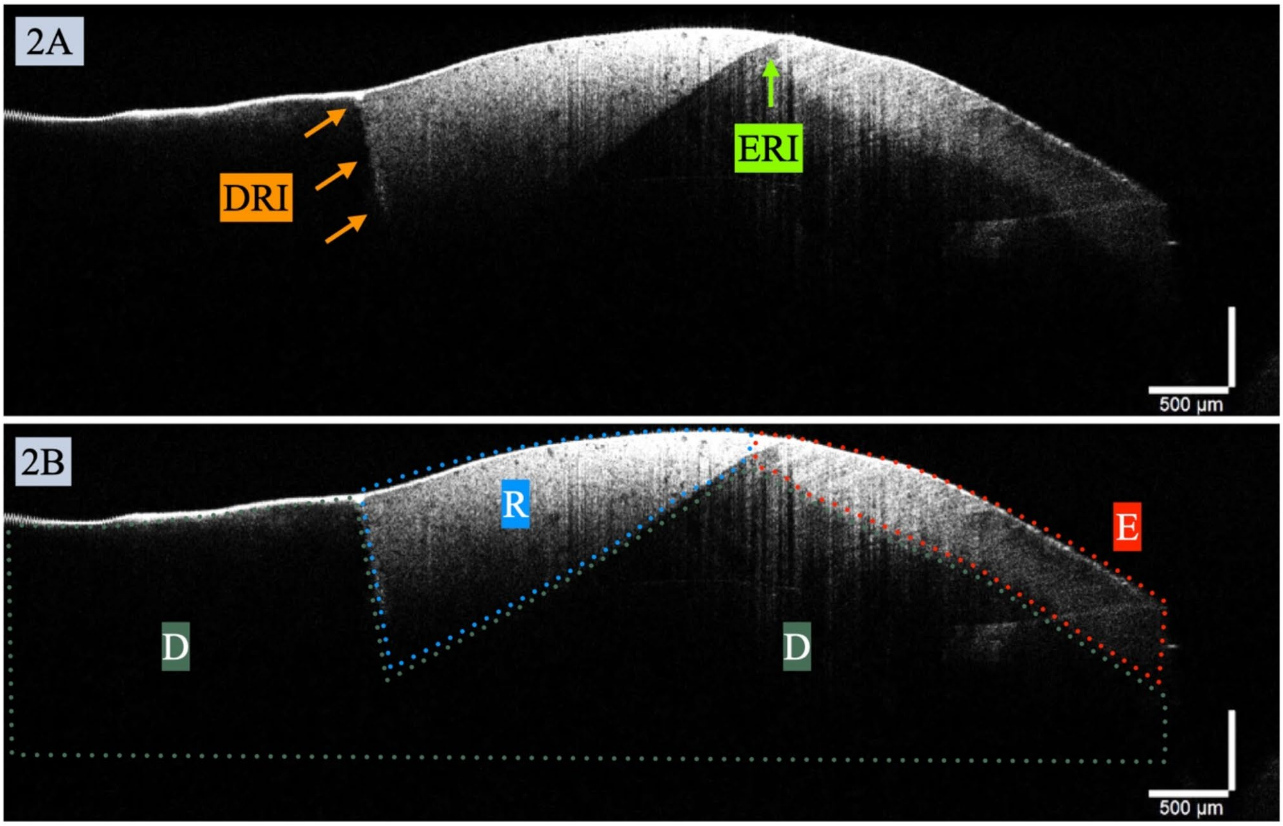

Fig. 2 Random specimen from G2 (Majesty ES Super Low Flow) in which there is no visible gap. The same image has been reported twice. Figure **2A** shows dentin-resin interface (DRI) and enamel-resin interface (ERI) where no gap is visible (continuous line with no white areas). Figure **2B** is a schematic representation of the sample to improve understanding D: dentin; R: resin, E: enamel

5 °C and 55 °C in distilled water, with dwell and transfer times of 120 s and 2 s, respectively (SD Mechatronik).

Regarding TMC, a 50 N force was applied on the occlusal surface of the specimens using 6 mm diameter steatite balls (CS-4.4 chewing simulator, SD Mechatronik, Germany). The following settings were applied: vertical stroke 1 mm, stroke down 1 mm, horizontal stroke 2 mm, speed 90,0 mm/s. Like those in the TC group, specimen chambers were alternately filled with distilled water, varying from 5 °C to 55 °C with a dwell time for each cycle of 120 Sect. [33].

After the aging test, specimens were rinsed for 1 min under running tap water and completely air-dried, before being subjected to a second OCT scan with the same baseline protocol to ensure consistency between data.

Marginal gap analysis

Ten cross-sectional images were processed and quantitatively analyzed for each sample using Image J software (ImageJ 1.45, NIH, Bethesda, Maryland, MD, USA). The interfacial gap was linearly measured by a single expert operator along the dentin-composite interface and enamel-composite interface and converted into microns. For each specimen, the procedure is repeated before and after aging aligning samples through a custom-made silicone guide. Than the difference measured in µm of the interfacial gaps was calculated [7].

After aging process, two samples were also analyzed using SEM (Fig. 3). Specimens from each group were randomly chosen and cleansed in an ultrasonic bath containing alcohol (TUC-150, Telsonic AG, Switzerland) for three minutes before being left to air dry. Impressions were then obtained using Polyvinylsiloxane (Flexitime Light Flow, Heraeus Kulzer, Germany) and poured with a type of epoxy resin (EpoFix, Struers, Denmark) to create a duplicate. These duplicates were then placed on aluminum stubs and sputter-coated (100 s, 50 mA) with gold and palladium using a sputter-coating device (Balzers SCD 050). The replications were subsequently assessed under a scanning electron microscope (Emission Scanning Electron Microscopy, Zeiss Supra 40 Field, Germany). Images at multiple magnification levels (66×; 500×; 1500×) were taken using the following settings: WD = 27 mm, aperture size = 30.00 µm, EHT = 15 kV, signal A = In Lens, stage at T = 0°. The images were taken centered in the interfacial area, with progressively higher magnification, to visualize both the tooth and the restorative material, as shown in Fig. 4. Qualitative analysis of

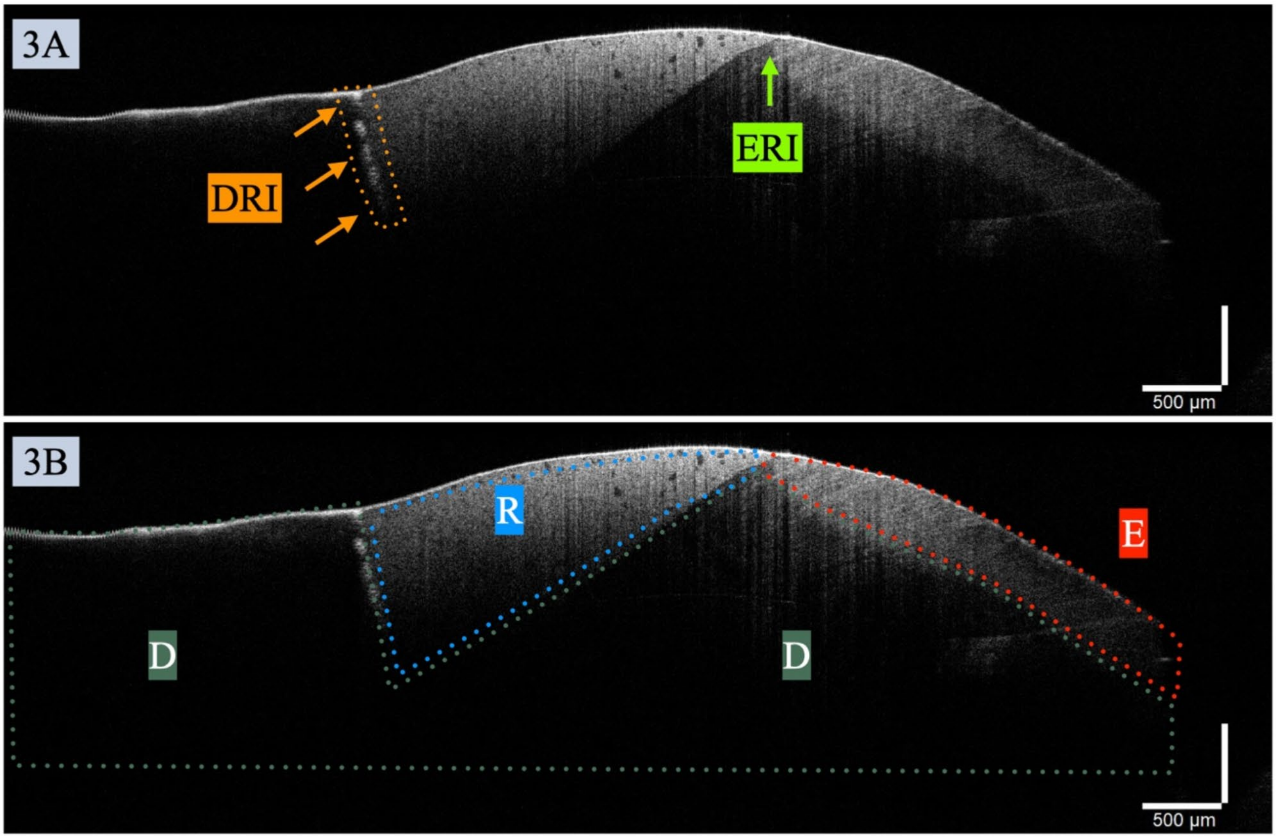

Fig. 3 Random specimen from G2 (Majesty ES Super Low Flow) in which there is visible gap. The same image has been reported twice. Figure **3A** shows dentin-resin interface (DRI) and enamel-resin interface (ERI) where gap is visible appearing like a white area highlighted by orange narrows. Figure **3B** is a schematic representation of the sample to improve understanding D: dentin; R: resin, E: enamel

the marginal continuity was then performed by an expert operator at 1500x magnification. Through the SEM software (Phenom ProSuite, 2.9.0.0, Netherlands), auto focus and contrast were applied in order to improve image quality as much as possible.

Statistical analysis

After testing the normality (Shapiro-Wilk test) and homoscedastic (modified Levene's test) assumptions of data sets, to evaluate the effects of tested materials, substrate and aging test on interfacial gap, a three-way analysis of variance (ANOVA) and post-hoc Tukey tests were performed. The significance level was set to 95% ($p < 0.05$). All the statistical analyses were performed using the Stata 17.0 software package (Stata-Corp).

Results

Average interfacial gap (± standard deviation, expressed in µm) at baseline is expressed in Table 2 for each tested RBC and both at the enamel and dentin cervical margins. Variation in the interfacial gap after aging process is reported in Table 3, as the mean difference between after-aging process and baseline values (± standard deviation, expressed in µm).

ANOVA statistics of the baseline results indicated that the employed material and the substrate were significantly influenced the interfacial gap ($p < 0.01$). ANOVA statistics regarding post aging results indicated that the employed material, the substrate and the aging process were significantly influenced the interfacial gap ($p < 0.0053$). Tukey post-hoc tests revealed that at the baseline G2 (Majesty Es Low Flow, Kuraray Noritake) performed significantly better than G1 (Clearfil Es2, Kuraray Noritake) and G3 (Majesty Es Super Low Flow, Kuraray Noritake) and that the dentin margin had a lower ability to maintain the margin sealing. Tuckey post-hoc after aging showed that G2 (Majesty Es Low Flow, Kuraray Noritake) performed significantly better than G1 (Clearfil Es2, Kuraray Noritake), the dentin margin had a lower ability to maintain the margin sealing and the thermomechanical cycling induced a significantly higher gap opening than the thermocycling alone.

Discussion

This research used OCT imaging technology to study how HFRBCs behave at the interface within class V cavities, which are known to be challenging due to their high c-factor and the risk of interface gaps forming [34].

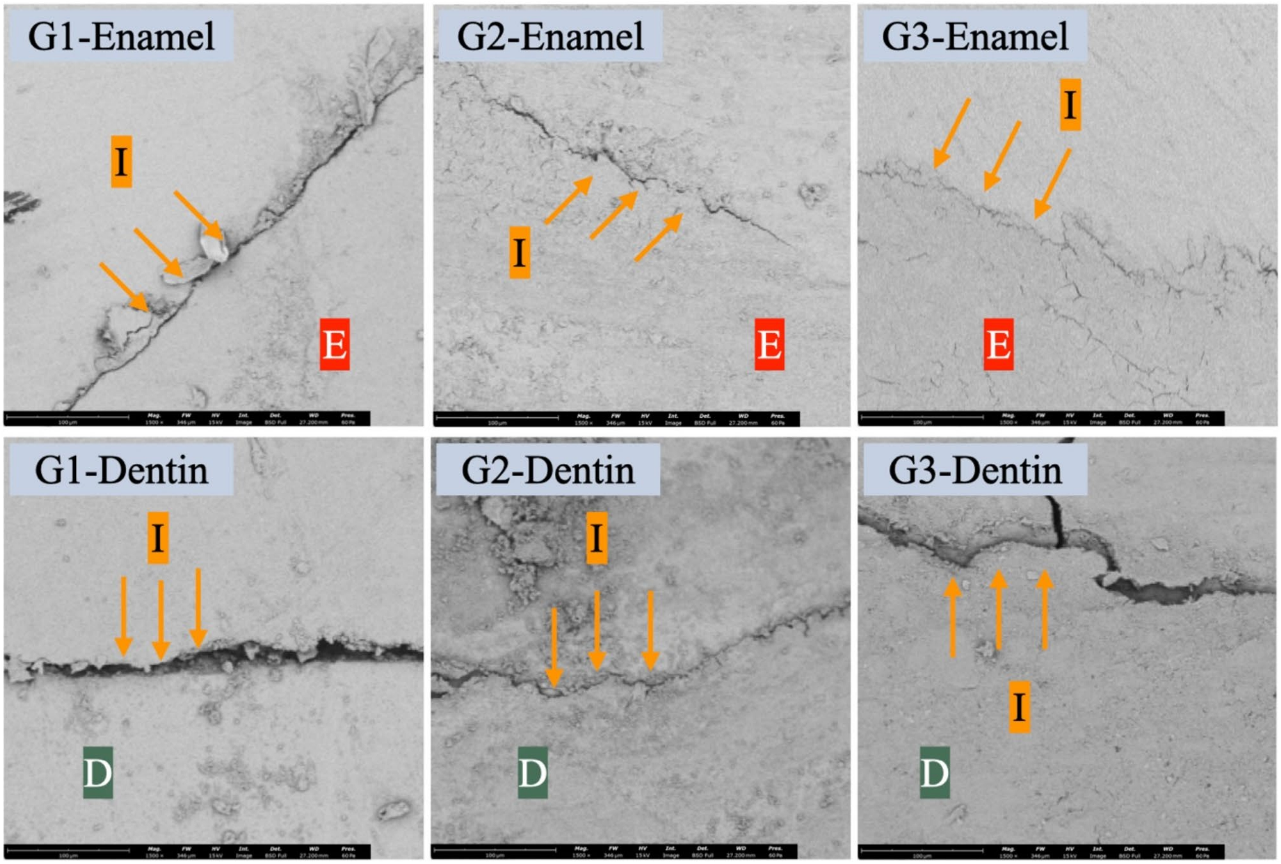

Fig. 4 Representative SEM images from all groups at both the enamel and dentin interfaces. IG: interfacial gap; E: enamel; D: dentin

Table 2 Interfacial gap at baseline (before aging process) expressed in Mm. Equal lower superscript letters indicate no significant differences among the same Raw. Equal upper superscript letters indicate no significant differences among columns ($p < 0.05$)

	Enamel	Dentin
G1	15.12 (±26.19)^{aA}	24.82 (±27.23)^{aA}
G2	2.60 (±5.28)^{aB}	8.82 (±15.71)^{aB}
G3	6.80 (±14.06)^{aA}	22.04 (±38. 66)^{aA}

Class V cavities are tricky for bonding because they often involve sclerotic dentin and lack of enamel at the cervical margin [34, 35]. The study focused on both enamel and dentin substrates and examined the effects of acing degradation.

OCT was chosen because as it has already demonstrated its utility for noninvasive and quantitative detection of gaps at the base of composite restorations [35–37]. Despite some technical limitations in scaling and image fusion, OCT remains valuable due to its ability to produce 2D and 3D images without using X-rays, and its speed and preservation of specimens make it superior to micro-CT in certain aspect [38]. In fact, although micro-CT remains the gold standard for this type of analysis, OCT allows accurate and rapid analysis of non-deep interfaces [39].

From the findings, the first null hypothesis was rejected because G2 demonstrated significantly better interfacial adaptation compared to G1, both at the start and after aging tests. Although not statistically significant, G3

Table 3 Differences between post-aging and basal interfacial gap values expressed in Mm. Equal lower superscript letters indicate no significant differences among the same Raw. Equal upper superscript letters indicate no significant differences among columns ($p < 0.05$)

	Thermal Aging (TC)		Thermomechanical Aging (TMC)	
	Enamel	Dentin	Enamel	Dentin
G1	7.14 (±4.09)^{aA}	12.14 (±5.25)^{aA}	11.01 (±5.71)^{bA}	17.13 (±6.99)^{bA}
G2	5.24 (±2.51)^{aB}	10.43 (±4.11)^{aB}	12.86 (±5.15)^{bB}	9.04 (±3.39)^{bB}
G3	4.51 (±2.39)^{aA}	9.46 (±1.75)^{aA}	11.43 (±2.68)^{bA}	9.60 (±2.68)^{bA}

generally outperformed G1, indicating good interfacial behavior of HFRBCs relative to conventional flowable materials. The results regarding interfacial adaptation can be linked to two key factors: the manipulability of the materials and the polymerization kinetics that produce stresses on the adhesive layer, leading to interfacial gaps [40]. Concerning stress development, the amount of filler and the different monomers in the tested materials could have led to notable differences. Specifically, the HFRBCs evaluated contain a TEGDMA-based organic matrix, unlike G1, which is Bis-GMA based [41]. It is well-known that Bis-GMA features a rigid central core made of a phenyl ring, making it more viscous than TEGDMA, which has a long, linear, and flexible structure [42]. A more mobile and elastic structure results in fewer stresses external to the interfacial area, minimizing subsequent gap creation [43]. Furthermore, the volume of filler content was considerably higher in G2 and G3 (64% and 62% respectively) compared to G1 (30.7%). As reported by Nie et al., the filler volume percentage is the most influential factor on volumetric shrinkage: when it decreases from 68.6 to 33.3%, the volumetric shrinkage increases from 2.55 to 5.20% respectively [11]. Thus, it can be assumed that HFRBCs, due to their specific formulation, likely offer a favorable balance between filler content and monomer polymerization kinetics, displaying positive initial marginal adaptation when applied to class V cavities, while also showing superior manipulability compared to packable RBCs [42].

Regarding the substrate, the study's results align with the literature, as the dentin margins exhibited significantly larger marginal gaps than those in enamel because dentin is a highly hydrophilic tissue that can only be partially dehydrated, making it more challenging to penetrate with hydrophobic adhesives [43]. Indeed, the bonding process with dentin differs from that with enamel due to morphological, histological, and compositional differences; dentin contains a substantial amount of water and organic materials, which impair the bonding mechanism [44].

However, it's vital to emphasize that the substrate is likely a much more critical factor in long-term clinical scenarios not only due to lower bond strength but also due to biochemical and enzymatic deterioration of the hybrid layer [45].

The study's findings also revealed that restorative materials influence the marginal gap values of the enamel and dentin margins.

Regarding the marginal gap values after the aging process, all tested RBCs exhibited minor interfacial degradation without significant differences among the materials but with notable differences between the substrates and the aging process. Specifically, the samples subjected to the thermal aging process demonstrated less interfacial degradation compared to those used in the thermomechanical aging process. The mechanical aging method entails the consistent and repeated application of mechanical forces, intended to simulate the stresses placed on teeth and restorative materials by activities such as chewing or teeth grinding. The method aims to induce changing stresses within the restorative material and the tooth, leading to fatigue breakdown of the restored tooth structure. This could eventually result in failure due to the accumulation of minor and major damage, such as subcritical crack generation, crack propagation, surface irregularities, wear, loss of anatomical shape, marginal breakdown, and fractures [46]. On the other hand, thermal aging is a technique that seeks to challenge and damage the restorations by creating expansion and contraction stresses, caused by alternating immersion in liquid environments with low and high temperatures. Continuous temperature changes could affect the mechanical performance of restorations by straining both the composite material and restored structures, as well as their bonded interface [46, 47].

The results of this study indicated that the combined application of mechanical and thermal cycling (thermomechanical cycling) may cause accelerated mechanical degradation and fatigue of resin composite restorations. Previous studies have questioned the lack of concrete evidence that failures in clinical practice may result from thermal stresses [49], and have also highlighted the uncertainty of whether failure could occur due to flow in one or other of the layers in the bonded structure. The same researchers suggested that immersion during thermal cycling could facilitate the breakdown by hydrolysis of the adhesive bond between the composite and tooth tissue. This reaction might be aided by stress and could serve as a potential mechanism for fatigue failure, but the timing of the reaction could be a relevant condition for further analysis.

The main limitations of this study are associated with certain characteristics of the OCT. Specifically, due to the scanning depth of the OCT, in some specimens, the bottom of the cavity could not be visualized. This might have led to an underestimation of the true marginal gap value, particularly in dentin margins. Further studies using alternative analysis methods or those that also evaluate the presence of internal voids are necessary.

Conclusions

According to the present results, we conclude the following:

- HFRBCs showed promising results in terms of interfacial gap adaptation both at the baseline and after the aging process.

- The presence of a cervical substrate plays a significant role in the tested conditions.
- Compared with thermomechanical aging, thermal caused minor interfacial degradation in all the tested groups.

Flowable composites are relatively new materials and studies in the literature still do not provide conclusive results on their performance, suggesting that long-term clinical trials are necessary.

Abbreviations

RBC	Resin-based composite
HFRBC	Highly-filled flowable resin based composite
Bis-GMA	Bisphenol A-glycidyl methacrylate
TEGDMA	Triethylene glycol dimethacrylate
UDMA	Urethane dimethacrylate
D3MA	1,10-decanediol dimethacrylate
CEJ	Cementoenamel junction
OCT	Optical coherence tomography
TC	Thermocycling challenge
TMC	Thermomechanical cycling challenge

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Author contributions
BP prepared the specimens. VC and RM performed OCT analysis and gap measurement. AC performed statistical analysis. TR performed aging tests. AB and CR wrote the manuscript. VEA protocol definitions. NS supervision and coordination. All authors read and approved the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
ethics approval by the local ethics committee of the Dental School, University of Turin (DS_2021_011).

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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