

Physicochemical and mechanical performance of a bioactive resin compared with conventional restorative materials under erosive challenge

Desempenho físico-químico e mecânico de uma resina bioativa em comparação com materiais restauradores convencionais sob desafio erosivo

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ABSTRACT

Objective: To evaluate the physicochemical and mechanical properties of a bioactive resin compared with a conventional resin and a resin-modified glass ionomer cement after an erosive challenge. **Material and Methods:** Thirty specimens (n=10 per material) were prepared and subjected to five daily cycles consisting of immersion in Sprite® (pH 3.6) for 6 hours, followed by storage in artificial saliva for 18 hours. Fluoride release was quantified. Surface hardness and roughness were measured before and after the challenge, whereas sorption and solubility were determined according to ISO 4049. Data were analyzed using one-way ANOVA followed by Tukey's test, paired t-tests, or the Kruskal–Wallis test ($\alpha=0.05$). **Results:** Cumulative fluoride release was 11.60, 12.31, and 0.23 $\mu\text{g F/mL}$ for the bioactive resin, resin-modified glass ionomer cement, and conventional resin, respectively. Release was similar between the bioactive resin and resin-modified glass ionomer cement ($p=0.7008$), and both released more fluoride than conventional resin ($p<0.0001$). Hardness decreased from 92.36 to 78.65 HV for the bioactive resin, from 96.03 to 70.46 HV for the conventional resin, and from 178.09 to 90.88 HV for the resin-modified glass ionomer cement ($p\leq 0.0425$). Hardness loss was similar between the resins ($p=0.7091$) and lower than that of the ionomer cement ($p\leq 0.0061$). Roughness increased in all groups ($p\leq 0.0338$), whereas sorption and solubility did not differ among materials ($p\geq 0.2802$). **Conclusion:** Under these in vitro conditions, the bioactive resin showed mechanical behavior comparable to the conventional resin and fluoride release similar to the resin-modified glass ionomer cement. Further in situ and clinical studies are required.

KEYWORDS

Composite resins; Dental materials; Fluorides; Glass ionomer cements; Tooth erosion.

RESUMO

Objetivo: Avaliar as propriedades físico-químicas e mecânicas de uma resina bioativa em comparação com uma resina convencional e um cimento de ionômero de vidro modificado por resina após um desafio erosivo. **Material e Métodos:** Trinta espécimes (n = 10 por material) foram confeccionados e submetidos a cinco ciclos diários, consistindo em imersão em Sprite® (pH 3,6) por 6 horas, seguida de armazenamento em saliva artificial por 18 horas. A liberação de fluoreto foi quantificada. A dureza e a rugosidade superficiais foram avaliadas antes e após o desafio erosivo, enquanto a sorção e a solubilidade foram determinadas de acordo com a ISO 4049. Os dados foram analisados por ANOVA de uma via seguida do teste de Tukey, testes t pareados ou teste de Kruskal–Wallis ($\alpha = 0,05$). **Resultados:** A liberação cumulativa de fluoreto foi de 11,60, 12,31 e 0,23 $\mu\text{g F/mL}$ para a resina bioativa, o cimento de ionômero de vidro modificado por resina e a resina convencional, respectivamente. A liberação foi semelhante entre a resina bioativa e o cimento de ionômero de vidro modificado por resina ($p = 0,7008$), e ambos liberaram mais fluoreto que a resina convencional ($p < 0,0001$). A dureza diminuiu de 92,36 para 78,65 HV na resina bioativa, de 96,03 para 70,46 HV na resina convencional e de 178,09 para 90,88 HV no cimento de ionômero de vidro modificado por resina ($p \leq 0,0425$). A perda de dureza foi semelhante entre as resinas ($p = 0,7091$) e inferior à do cimento de ionômero de vidro modificado por resina ($p \leq 0,0061$). A rugosidade aumentou em todos os grupos ($p \leq 0,0338$), enquanto a sorção e a solubilidade não diferiram entre os materiais ($p \geq 0,2802$). **Conclusão:** Sob essas condições in vitro, a resina bioativa apresentou comportamento mecânico comparável ao da resina convencional e liberação de fluoreto semelhante à do cimento de ionômero de vidro modificado por resina. Estudos in situ e clínicos adicionais são necessários.

PALAVRAS-CHAVE

Resinas compostas; Materiais dentários; Fluoretos; Cimentos de ionômero de vidro; Erosão dental.

INTRODUCTION

Bioactive materials are designed to interact with the oral environment by releasing ions such as calcium, phosphate, fluoride, zinc, magnesium, and strontium [1-3]. In addition to their biological activity, these materials may contribute to marginal sealing and reduced microleakage [4]. Bioactive resins were developed to combine the esthetic and mechanical properties of resin-based composites with the ion-releasing potential of glass ionomer cements [5]. Accordingly, ion-releasing fillers with different compositions, particle sizes, and concentrations have been incorporated into resin matrices to promote bioactivity while preserving physicochemical stability [6,7].

Among the ions released by bioactive restorative materials, fluoride has received particular attention because of its physicochemical effects on mineralized dental tissues [8-13]. Its availability in the oral environment depends on factors related to the restorative material, including composition, solubility, and permeability, as well as salivary flow and environmental pH [14,15]. Fluoride released by restorative materials may contribute to mineral saturation around restorations, while the ability of some materials to uptake fluoride from external sources and subsequently re-release it may prolong its local availability during repeated acidic challenges [16-19].

However, the same acidic conditions that may stimulate ion release can also promote degradation of restorative materials. Dietary acids, particularly those present in soft drinks and other acidic beverages, are important etiological factors for dental erosion and may compromise the surface integrity and longevity of restorations [20]. Repeated erosive episodes can alter surface hardness, roughness, and overall mechanical performance, and the magnitude of these changes depends on the composition and structure of the restorative material [21]. Acidic exposure may soften the resin matrix, degrade the filler-matrix interface, and dissolve acid-sensitive components, resulting in increased surface roughness and reduced hardness or wear resistance [22]. Glass ionomer-based materials may be particularly susceptible to acid-induced degradation, whereas resin-based materials may exhibit different degrees of matrix softening and filler-matrix degradation [23-25]. Therefore, the clinical value of bioactivity depends not only on ion release but also on the ability of the material

to maintain its physicochemical and mechanical stability under erosive conditions.

Although bioactive resins have been increasingly investigated [26], evidence regarding their behavior under repeated erosive challenges remains limited. In particular, few studies have simultaneously examined fluoride release, surface hardness, roughness, sorption, and solubility under cyclic acidic exposure or directly compared bioactive resins with conventional flowable resins and resin-modified glass ionomer cements. Therefore, the present study aimed to evaluate the physicochemical and mechanical performance of a bioactive resin compared with conventional restorative materials under an erosive challenge.

MATERIAL AND METHODS

Experimental design

This study adhered to the Guidelines for Reporting Pre-Clinical In Vitro Studies on Dental Materials [27]. An in vitro laboratory study was conducted with three categories of restorative materials: bioactive resin (Beautifil Flow Plus, Shofu Inc., San Marcos CA, USA), resin-modified glass ionomer (Ionoseal, Voco GmbH, Cuxhaven, Germany), and a conventional dental resin without bioactive materials as a control group (Opallis Flow, FGM, Joinville, SC, Brazil). The composition of the materials is described in Table I. The materials were subjected to a 5-day erosive challenge protocol, simulating repeated exposure to acidic conditions followed by remineralizing periods in artificial saliva. After this period, fluoride release, as well as the physicochemical and mechanical properties (hardness, roughness, sorption, and solubility), were evaluated.

Preparation of the blocks

Data obtained from a pilot study were used for the a priori sample size calculation, with fluoride release ($\mu\text{g F/mL}$) defined as the primary outcome. The calculation considered an estimated standard deviation of $0.45 \mu\text{g F/mL}$ and a minimum detectable difference of $0.65 \mu\text{g F/mL}$ between the restorative materials. This difference corresponded to a standardized mean difference of 1.44 and was considered the smallest scientifically relevant difference for distinguishing the fluoride-release behavior of the materials under the experimental conditions.

Table 1 - Composition and manufacturer of bioactive composite resins, glass ionomer cements and the control group supplied by each manufacturer

Identification	Material/Manufacturer	Composition
Bioactive Resin	Beautifil Flow Plus. Shofu Inc., San Marcos CA, USA (Batch : 112016)	Bisphenol A-glycidyl methacrylate (15–25%), Triethylene glycol dimethacrylates (12–14%), Aluminofluoro-borosilicate glass (50–60%), Al ₂ O ₃ (1–2%), Camphorquinone.
Conventional Resin (Control Group)	Opallis Flow FGM, Joinville, SC, Brazil (Lot : 010322)	Barium-aluminum silicate, nanoparticulate silicon dioxide, TEGDMA, Bis (EMA), Bis(GMA)], camphorquinone, co-initiators, preservatives and pigments.
Resin Modified Glass Ionomer Cement	Ionoseal. Voco GmbH, Cuxhaven, Germany (Lot: 2233538)	Fluoroaluminosilicate glass, Bis-GMA, 1,6-hexanediylbismethacrylate 5%-10%, TEDMA 2.5%-5%

Considering three experimental groups, a significance level of 5%, and a statistical power of 80%, a minimum sample size of 30 specimens was required, with 10 specimens allocated to each material. A split Teflon matrix with six circular perforations was used to produce specimens measuring 4 mm in diameter and 2 mm in thickness. Each restorative material was manipulated in a laboratory environment, with a controlled temperature ($26 \pm 1^\circ\text{C}$). The material was applied using a handling spatula in a single portion inside the matrix. Immediately after material insertion, the specimen was covered with a polyester strip (Quimidrol, SC, Brazil) and a glass plate ($15 \times 7 \times 6$ mm) to flatten the surface and to remove excess material due to pressure. The resins were photoactivated for the time recommended by the manufacturers using a photopolymerizer (Optilight LD MAX, GNATUS, Ribeirão Preto, SP, Brazil) under a polyester strip. The photopolymerizer had been previously tested with a radiometer and the dimensions of the test specimens were checked using a digital caliper (Ortocentral®, stainless steel, 150 mm). The specimens were stored individually for 24 hours at 37°C in 100% humidity in a biochemical oxygen demand oven (SPLabor, São Paulo, SP, Brazil). Afterward, the specimens underwent finishing and polishing procedures with discs with decreasing abrasiveness (Sof-lex Pop On, 3M ESPE, St. Paul, MN, USA) under low speed with the discs being discarded after each use.

Erosive challenge protocol

A modified erosive challenge model described by Rebelato et al. [28] was used. The protocol consisted of five consecutive cycles designed to simulate repeated exposure to dietary acids. Each specimen was individually

immersed in 1 mL of an acidic solution (Sprite®, pH 3.6) and incubated at 37°C for 6 hours. After acid exposure, the specimens were rinsed with distilled water and transferred to 1 mL of artificial saliva, where they were incubated at 37°C for 18 hours to simulate remineralizing conditions. Both the acidic solution and artificial saliva were renewed daily for each specimen at the beginning of their respective exposure periods. The artificial saliva composition was as follows: 0.33 g KH_2PO_4 , 0.34 g Na_2HPO_4 , 1.27 g KCl, 0.16 g NaSCN, 0.58 g NaCl, 0.17 g CaCl_2 , 0.16 g NH_4Cl , 0.2 g urea, 0.03 g glucose, and 0.002 g ascorbic acid [29].

Analysis of resin properties

Fluoride release

At the end of each 6-hour acidic exposure and each 18-hour artificial saliva period, the respective solutions were collected separately for fluoride analysis and replaced with fresh solutions for the subsequent phase. A 0.1-mL volume of Total Ionic Strength Adjustment Buffer III was added to 1 mL of each collected sample. Fluoride concentration was determined using a fluoride ion-selective electrode (Orion 9606, Orion Research Inc., USA) coupled to a potentiometer while the solution was continuously stirred. A calibration curve ranging from 0.025 to 16 $\mu\text{g F/mL}$ was prepared before the measurements.

The fluoride released into each aliquot was calculated by multiplying the measured fluoride concentration ($\mu\text{g F/mL}$) by the volume of the collected solution (1 mL). Cumulative fluoride release for each specimen was calculated as the sum of the fluoride released into the acidic solution and artificial saliva during all five experimental cycles and was expressed as $\mu\text{g F/specimen}$.

Hardness

Initial surface hardness was measured using a Durimet4 microhardness tester (Leitz, Wetzlar, Germany), with five indentations made using a Vickers tip under a 50 grams-load for 5 seconds at different regions of each specimen. After completing the erosive challenge, the specimens were measured again to determine the final hardness using the same parameters. The percentage loss of surface hardness was calculated using the following calculation:

$$\left[\frac{\left(\frac{\text{Initial hardness} - \text{Final hardness}}{\text{Initial hardness}} \right)}{1} \right] \times 100 \quad (1)$$

Roughness

Surface roughness was measured using a rugosimeter (Surfcorder SE 1700, Kosakalab, Tokyo, Japan) equipped with a diamond tip (V500 sensitivity), which traversed the specimen surface and recorded measurements every 0.250 mm, totaling 1.250 mm (five measurements) at a speed of 0.100 mm/second. Three measurements were taken on each specimen, and the average of these values was calculated. Roughness was assessed both before and after erosive challenge using the same parameters.

Sorption and solubility

Following the ISO 4049 standard, the specimens were stored in a glass desiccator (Vidrolabor, Campinas, SP, Brazil) with blue silica gel (QuimisulSC, Joinville, Santa Catarina, Brazil). After 24 hours, the specimens were weighed on an analytical balance (Shimadzu, Barueri, SP, Brazil) to obtain their stable initial weight. This process was repeated every 24 hours until a constant mass (m_1) was observed. Once the initial mass stabilized, the diameter and thickness of the specimens were measured with a digital caliper (DIGIMESS, São Paulo, Brazil; ± 0.001 mm). The diameter was measured at two perpendicular points, and the average diameter was calculated. The thickness was measured at four equally spaced points along the center of each specimen, and the average thickness was calculated. The volume (V) of each specimen was calculated using the formula $V = \pi \times r^2 \times h$, where r is the average radius (diameter/2) and h is the average thickness.

After determining the volume, the specimens underwent to the erosive challenge. Following this process, the specimens were removed with tweezers, washed thoroughly with distilled water, dried with an absorbent paper towel, kept at room temperature for 15 seconds, and weighed again to obtain the mass after immersion in the solutions (m_2). The specimens were then returned to their tubes and stored in a desiccator with silica gel. During dehydration, measurements were performed using the same methodology described for the 24-hour cycles to obtain the reconditioned constant mass, denoted as m_3 .

Sorption and solubility were expressed as $\mu\text{g}/\text{mm}^3$ and calculated using the following equations: Sorption = $(m_2 - m_3)/V$ and Solubility = $(m_1 - m_3)/V$, where m_1 is the constant mass before immersion (μg), m_2 is the mass immediately after the erosive challenge (μg), m_3 is the reconditioned constant mass after the final desiccation period (μg), and V is the specimen volume (mm^3).

Statistical analysis

The response variables were analyzed to determine whether they met the assumptions of equality of variance and a normal distribution of errors using Shapiro-Wilk test. Daily fluoride release was analyzed using a three-way mixed-design analysis of variance (ANOVA), considering material, solution, and time as factors. The main effects of material, solution, and time, as well as their interactions were evaluated. All main effects and interaction terms were statistically significant ($p < 0.0001$). Tukey's multiple-comparisons test was used to identify differences among the levels of the factors when significant effects or interactions were detected. Cumulative fluoride release, represented by a single value for each specimen, was analyzed using one-way ANOVA followed by Tukey's post hoc test. Cumulative fluoride release was calculated as a single value for each specimen and analyzed using one-way ANOVA followed by Tukey's post hoc test. Surface hardness and roughness were compared among materials using one-way ANOVA followed by Tukey's test, and pre- and post-challenge measurements within each material were compared using paired t-tests. Sorption and solubility data were analyzed using the Kruskal-Wallis test. Statistical analysis was performed using GraphPad Prism 10.0 (GraphPad Software, San Diego, CA, USA). A p -value of < 0.05 was considered statistically significant.

RESULTS

Table II presents the fluoride release of the restorative materials under acidic and artificial saliva conditions throughout the experimental period. Three-way mixed-design ANOVA revealed significant main effects of material, solution, and time on daily fluoride release ($p < 0.0001$). Significant material $\times$ solution, material $\times$ time, solution $\times$ time, and material $\times$ solution $\times$ time interactions were also observed ($p < 0.0001$), indicating that the fluoride release pattern over time depended on both the restorative material and the immersion solution. Tukey's multiple-comparisons test was used to identify the specific differences presented in Table II. On the first day of exposure to the acidic medium, the bioactive resin (Beautifil) exhibited the highest fluoride release ($4.63 \mu\text{g}$ fluoride/mL) among the materials evaluated ($p < 0.0001$), followed by a gradual reduction over time. From the second day onward, the resin-modified glass ionomer cement (Ionoseal) released significantly more fluoride than the other materials under acidic conditions ($p \leq 0.0011$). In artificial saliva, Beautifil showed higher fluoride release than Ionoseal during the first three days ($p \leq 0.0469$). As expected, the conventional resin (Opallis) did not release fluoride under either experimental condition.

For both fluoride-releasing materials, fluoride release was significantly higher under acidic conditions than in artificial saliva, up to day 3 for Beautifil and throughout the experimental period for Ionoseal ($p \leq 0.0280$).

Table III summarizes the physicochemical and mechanical properties of the materials before and after the erosive challenge. Ionoseal exhibited the highest initial surface hardness, with a significant difference compared with the other materials ($p < 0.0001$). After the erosive challenge, all materials showed a significant reduction in surface hardness ($p \leq 0.0425$). No significant differences were observed in initial or final surface roughness among the materials ($p \geq 0.2136$); however, surface roughness increased significantly after the erosive challenge for all groups ($p \leq 0.0338$). Sorption and solubility values remained similar among the materials after exposure to the erosive challenge ($p \geq 0.2802$).

Figure 1 illustrates the cumulative fluoride release following the erosive challenge. At the end of the experimental period, Beautifil and Ionoseal exhibited significantly higher cumulative fluoride release than the conventional resin ($p < 0.0001$), with no significant difference between the two fluoride-releasing materials ($p = 0.7008$).

Table II - Mean (SD) of fluoride release ($\mu\text{g F/ml}$) from studied materials according to solution and time ($n=10$)

Time	Sprite®			Saliva		
	Beautifil	Opallis	Ionoseal	Beautifil	Opallis	Ionoseal
Day 1	4.63 (0.97) aA	0.04 (0.01) bA	2.70 (0.64) cA	1.14 (0.44) aA*	0.02 (0.01) bA	0.37 (0.16) cA*
Day 2	1.74 (0.62) aB	0.03 (0.01) bA	2.46 (0.49) cA	0.56 (0.29) aB*	0.02 (0.01) bA	0.34 (0.11) cA*
Day 3	1.08 (0.39) aC	0.02 (0.01) bA	2.45 (0.68) cA	0.51 (0.19) aB*	0.02 (0.01) bA	0.33 (0.10) cA*
Day 4	0.61 (0.25) aCD	0.02 (0.01) bA	1.64 (0.28) cB	0.46 (0.18) aB	0.02 (0.01) bA	0.31 (0.06) aA*
Day 5	0.52 (0.25) aD	0.02 (0.01) bA	1.50 (0.32) cB	0.35 (0.15) aB	0.02 (0.01) bA	0.21 (0.05) aA*

Different lowercase letters indicate significant differences among materials within the same solution and time point. Different uppercase indicate significant differences among time points within the same material and solution. An asterisk indicates a significant difference between solutions within the same material and time point. Comparisons were performed using Tukey's multiple-comparisons test following three-way repeated-measures ANOVA (material $\times$ solution $\times$ time), with the significance level set at 5%.

Table III - Mean (SD) of hardness (HV), roughness (μm), sorption ($\mu\text{g/mm}^3$) and solubility ($\mu\text{g/mm}^3$) of studied materials ($n=10$)

Materials	Hardness		Roughness		Sorption	Solubility
	Initial	Final	Initial	Final		
Beautifil	92.36 (15.41) a	78.65 (20.45)*a	0.08 (0.04) a	0.18 (0.13)* a	0.07 (0.01) a	0.03 (0.01) a
Opallis	96.03 (26.92) a	70.46 (7.61)*a	0.09 (0.05) a	0.28 (0.20)* a	0.15 (0.20) a	- 0.04 (0.20) a
Ionoseal	178.09 (41.01) b	90.88 (25.18)*a	0.13 (0.12) a	0.40 (0.39)* a	0.07 (0.01) a	0.04 (0.03) a

Different lowercase letters indicate statistical difference between materials (ANOVA, $p < 0.05$) and the asterisk indicates difference between each material before and after the erosive challenge (t test, $p < 0.05$).

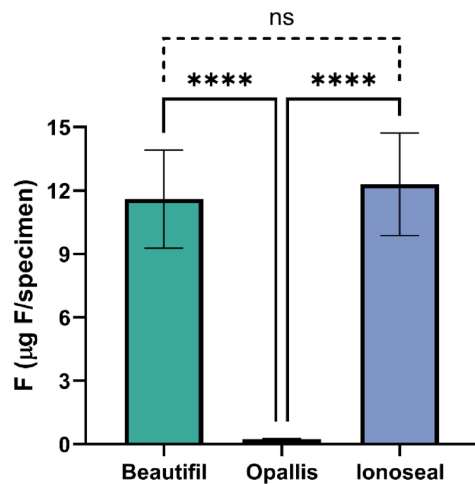


Figure 1. Cumulative fluoride release after pH cycling according to the materials studied (n=10), **** indicates statistical difference between groups ($p < 0.0001$), ns indicates no statistical difference between groups ($p = 0.7008$), and the vertical bar indicates the standard deviation.

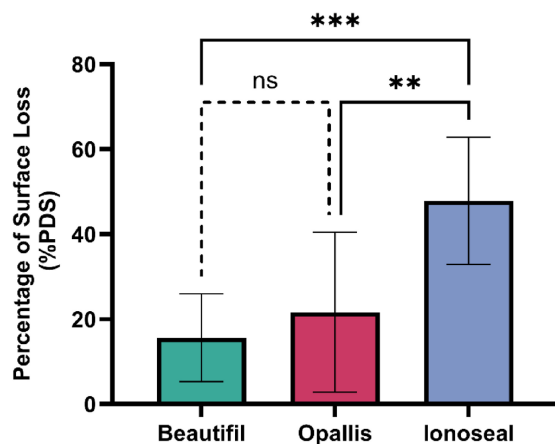


Figure 2. Percentage of surface hardness loss (%PDS) according to the materials studied (n=10), ** and *** indicates statistical difference between groups ($p = 0.0061$ and $p = 0.0009$, respectively), ns indicates no statistical difference between groups ($p = 0.7091$), and the vertical bar indicates the standard deviation.

Figure 2 presents the percentage of surface hardness loss after the erosive challenge. No significant difference was observed between Beautifil and Opallis resins ($p = 0.7091$); however, both materials exhibited significantly lower surface hardness loss than Ionoseal ($p \leq 0.0061$).

DISCUSSION

Exposure to acidic challenges is a well-recognized factor affecting the surface integrity and longevity of restorative materials. In the present study, the bioactive resin demonstrated cumulative fluoride release comparable to that of a resin-modified glass ionomer cement when subjected to an erosive challenge (Figure 1).

Under acidic conditions, fluoride release may increase local fluoride availability and contribute to maintaining mineral saturation around the tooth–restoration interface [30]. Nevertheless, this ion-releasing behavior should not be interpreted as direct evidence of protection against dental erosion or improved restoration longevity. From this perspective, bioactive resins may act as modifiers of the local chemical environment under erosive conditions, although the clinical relevance of this effect remains to be established [31].

The highest fluoride release from the bioactive resin was observed during the first day of exposure to the acidic medium (Table II), followed by a gradual decrease over time. This release pattern resembles the initial burst effect classically described for glass ionomer cements [19,32], which is attributed to the rapid dissolution of fluoride-containing phases upon acid contact. The present findings indicate that Beautifil exhibits similar fluoride-release behavior under erosive conditions, suggesting that acidic exposure may enhance ion diffusion from the bioactive resin matrix. Both fluoride-releasing materials exhibited greater fluoride release in the acidic solution than in artificial saliva, reinforcing the influence of environmental pH on fluoride availability [33]. However, fluoride release alone does not guarantee clinical protection against erosive tooth wear or greater restoration longevity. Such outcomes also depend on the material's resistance to softening, roughening, hydrolytic degradation, and mechanical wear, as well as patient-related factors such as salivary flow, buffering capacity, frequency of acid exposure, and oral hygiene practices.

The erosive challenge employed in this study was based on exposure to a carbonated soft drink (Sprite®), selected due to its low pH and high consumption frequency [28]. This approach enhances the clinical relevance of the model, as dietary acids from soft drinks represent a major etiological factor for dental erosion and may also compromise the surface properties of restorative materials [25,28]. In such conditions, restorative materials are repeatedly exposed to acidic environments that may accelerate surface degradation, highlighting the importance of evaluating their physicochemical and mechanical behavior under erosive challenges [25].

One of the main challenges in the development of bioactive resins is achieving a balance between ion release and mechanical stability, particularly under acidic conditions that may exacerbate

material degradation [34]. Although bioactive materials have been extensively investigated for their potential benefits, evidence regarding their performance under erosive challenges remains limited. The present findings indicate that the bioactive resin maintained mechanical behavior comparable to that of a conventional flowable resin while releasing fluoride under acidic conditions. These characteristics may be potentially relevant for patients subjected to recurrent extrinsic acid exposure, such as individuals with a high intake of soft drinks, sports drinks, citrus beverages, or other acidic dietary products. They may also be relevant in situations involving intrinsic acid exposure, including gastroesophageal reflux disease or recurrent vomiting. However, because the present study was conducted *in vitro*, these possible clinical advantages remain hypothetical and should be confirmed in *in situ* and clinical investigations [35].

Regarding mechanical performance, Ionoseal exhibited higher initial surface hardness than the resin-based materials, consistent with previous studies reporting superior hardness values for glass ionomer-based materials [36,37]. However, after the erosive challenge, the resin-modified glass ionomer showed greater surface hardness loss than both resin-based materials. The bioactive resin exhibited surface hardness loss comparable to that of the conventional resin, indicating that the incorporation of ion-releasing fillers did not adversely affect its resistance to erosive degradation. These findings are in agreement with previous reports suggesting that materials capable of releasing multiple ions may still maintain adequate mechanical stability over time [38].

Water sorption and solubility are additional factors that may influence the degradation of restorative materials, particularly under acidic conditions. Water diffusion into the resin matrix can promote hydrolytic degradation, leading to reductions in hardness and other mechanical properties [39,40]. Increased sorption and solubility may also compromise esthetic stability and long-term performance by facilitating microcrack formation and material weakening [41-43]. In the present study, no significant differences in sorption or solubility were observed among the materials. Negative solubility values were observed for Opallis resin. This finding may result from water retained within the polymer network, water uptake exceeding the mass of leached components, or hydrolytic reactions involving inorganic fillers, thereby masking the actual material loss.

Therefore, these values should be interpreted as low apparent solubility under the experimental conditions rather than as complete insolubility.

All materials evaluated in this study were low-viscosity restorative materials. Due to their lower filler content and reduced elastic modulus, flowable materials may act as an “elastic layer,” absorbing stresses generated by polymerization shrinkage and occlusal loading [44]. The bioactive resin exhibited surface hardness values comparable to those of the conventional flowable resin while also releasing fluoride under acidic conditions. This combination of properties suggests potential applicability as a base or liner in Class I and II restorations, including clinical situations involving recurrent acid exposure. Nevertheless, fluoride release should be regarded as an additional material characteristic rather than evidence, by itself, of anti-erosive efficacy or improved clinical longevity.

Surface roughness is a critical parameter in the context of erosive degradation, as increased roughness may accelerate wear and compromise the esthetic and functional longevity of restorations. In the present study, all materials exhibited surface roughness values below the critical threshold for bacterial retention prior to the erosive challenge. Although surface roughness increased after acidic exposure, no significant differences were observed among the materials (Table III). Notably, the bioactive resin was the only material that maintained roughness values below the critical threshold of 0.2 μm after the erosive challenge. Increased roughness has been associated with enhanced wear, reduced color stability, and greater susceptibility to surface degradation, which are particularly relevant concerns under erosive conditions [45-47].

Some limitations of this study should be acknowledged. Although *in vitro* models allow for strict control of experimental variables, they cannot fully reproduce the complex oral environment, where factors such as salivary flow, pellicle formation, and biofilm interactions may influence erosion and material degradation [34]. In addition, the inclusion of other bioactive restorative materials and complementary mechanical tests, such as flexural strength and fracture toughness, could provide a more comprehensive understanding of material behavior under erosive challenges. Therefore, caution is warranted when extrapolating these findings to clinical conditions, and further *in situ* and clinical studies are necessary to confirm the performance of bioactive resins in erosive environments [48,49].

CONCLUSION

Under *in vitro* erosive conditions, the Beautifil bioactive resin demonstrated physicochemical and mechanical performance comparable to that of the conventional flowable resin, while exhibiting fluoride release similar to a resin-modified glass ionomer cement. These findings suggest that this bioactive resin maintains stable surface and mechanical properties under acidic challenges and may represent a viable restorative option in clinical situations involving exposure to erosive environments. However, as these results are limited to the experimental conditions of this study, further *in situ* and clinical investigations are needed to confirm its performance in the oral environment.

Data availability

Data available upon request for the authors.

Author's Contributions

GV: Conceptualization. LR: Methodology. GV, LR: Formal Analysis. LR, EP: Data Curation. GV: Supervision.

LR, EP: Writing – Original Draft Preparation. GV, LR: Writing – Review & Editing.

Conflict of Interest

No conflicts of interest declared concerning the publication of this article.

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