Development and Evaluation of Strontium Oxide Bioglass-Enhanced BisGMA/PEGDA-Based Restorative Material for Advanced Dental Applications

Dr Mukil Sunil, Dr. Ramesh R

Undergraduate Intern,Saveetha Dental College and Hospitals,
Saveetha Institute of Medical and Technical Sciences (SIMATS)
Chennai - 600 077.Tamil Nadu, India.

Associate Professor,Department of Pedodontics,Saveetha Dental College and Hospitals,
Saveetha Institute of Medical and Technical Sciences,Saveetha University, Chennai-600077,
Tamil Nadu,India.

* Corresponding author:Dr. Ramesh R
Associate Professor,Department of Pedodontics,Saveetha Dental College and Hospitals,
Saveetha Institute of Medical and Technical Sciences,Saveetha University, Chennai-600077,
Tamil Nadu,India.

ABSTRACT

Introduction: Strontium Oxide Bioglass (SrO-BG) has gained significant attention in dental material research due to its potential to enhance mechanical strength, bioactivity, and adhesion properties. Conventional dental composites often face challenges such as microleakage, inadequate bonding, and brittleness, which can compromise their long-term clinical performance. Incorporating SrO-BG into an acetylated BisGMA/PEGDA resin matrix aims to address these limitations by improving adhesion, reducing microleakage, and enhancing bioactive properties, making it a promising candidate for advanced restorative dental applications.

Aim: To develop and evaluate a Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA restorative material with enhanced mechanical strength, bioactivity, adhesion, and durability for advanced dental applications.

Materials and Methods: Human extracted teeth were etched with 37% phosphoric acid, followed by the application of the experimental composite containing Strontium Oxide Bioglass (SrO-BG) and acetylated BisGMA/PEGDA. The material was light-cured for 40 seconds. Scanning Electron Microscopy (SEM) was employed to examine the tooth-material interface, while fracture resistance and microleakage were evaluated. Biocompatibility testing was performed to assess cell viability and the material's biological compatibility for dental applications.

Results: SEM images revealed successful integration of the Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA composite with minimal microleakage. However, the composite exhibited lower compressive strength compared to glass ionomer cement (GIC), which may limit its use in high-stress areas. Biocompatibility testing showed over 85% cell viability, indicating favorable biological properties and potential for safe use in dental applications.

Conclusion: The Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA composite demonstrated promising adhesion, minimal microleakage, and good biocompatibility. However, its compressive strength needs enhancement to improve its clinical applicability, particularly for high-stress dental restorations. Further optimization of the material composition and filler content could improve fracture resistance, making it a viable candidate for advanced restorative dental applications.

Keywords: **Strontium Oxide, Biocompatible Materials, Dental Restorative Materials**

INTRODUCTION

Recent advancements in restorative dentistry have focused on developing materials that combine superior mechanical strength, biocompatibility, and long-term durability. Resin-based composites, particularly those incorporating Bisphenol A-glycidyl methacrylate (BisGMA), have become widely adopted due to their excellent adhesive properties, aesthetic appearance, and ability to closely mimic the natural structure of teeth. Despite these benefits, BisGMA-based composites face several challenges, including polymerization shrinkage, wear resistance, moisture sensitivity, and limited biological interactions with dental tissues. These factors can negatively impact the longevity and performance of restorations over time [1][2].

To overcome these limitations, researchers have explored the incorporation of bioactive fillers and reinforcing agents into BisGMA-based composites. One promising material is Strontium Oxide Bioglass (SrO-BG), which has demonstrated bioactive properties and the potential to improve the mechanical characteristics of dental composites. SrO-BG is known for its ability to promote remineralization of tooth structures and enhance the bond between restorative materials and natural dental tissues. The release of calcium, phosphate, and strontium ions from SrO-BG contributes to the formation of a hydroxyapatite-like layer on the composite surface, which helps support dental tissue health and increases the durability of restorations [3][4].

Additionally, the development of acetylated BisGMA/PEGDA matrices has gained attention as a strategy to improve the mechanical and biological performance of dental composites. Acetylation of BisGMA enhances hydrophobicity and improves bonding strength to dental tissues, addressing issues like marginal leakage and polymerization shrinkage. The inclusion of Polyethylene Glycol Diacrylate (PEGDA) further enhances the flexibility and fracture toughness of the composite, making it more resistant to mechanical stress during normal function [5][6].

This study aims to fabricate and evaluate a novel restorative material incorporating Strontium Oxide Bioglass into acetylated BisGMA/PEGDA-based composites.[7] The goal is to improve the material's mechanical strength, bioactivity, and durability for advanced dental applications.[8] By combining these innovative materials, we expect to achieve a composite that offers superior wear resistance, enhanced fracture toughness, and better biocompatibility compared to conventional BisGMA-based composites. This study will contribute to the development of more effective, durable, and bioactive restorative materials that not only overcome the limitations of current composites but also provide long-term biological benefits for dental tissue health [9][10].

MATERIALS AND METHODS

This in vitro study was conducted at Saveetha Dental College, Chennai, from June 2023 to August 2023, with a total sample size of 70. The study adhered to institutional guidelines and received ethical approval from the Institutional Ethics Committee. The primary aim was to evaluate and compare the mechanical and biological properties of Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA resin composites.

Sample Size Calculation

A priori power analysis was conducted using G*Power software version 3.1.9.7. An effect size (d) of 0.8, an alpha error probability (α) of 0.05, and a power (1-β) of 0.9 were set, indicating a large expected effect and 90% statistical power. The analysis indicated that 34 samples per group (68 total) were required. Sample allocation was as follows: 6 samples for Scanning Electron Microscopy (SEM) bond analysis, 10 samples for fracture resistance (mechanical strength), 10 samples for microleakage (sealing ability), and 3 samples in triplicate for biocompatibility (cytotoxicity and cell proliferation). The total number of teeth used in the study was 70.

Experimental Group

The experimental composite was formulated using acetylated BisGMA/PEGDA resin matrix (Solution A). Strontium Oxide Bioglass (SrO-BG) was incorporated into the resin matrix to enhance mechanical properties, bioactivity, and bonding. The composite also included titanium oxide (TiO_2) for reinforcement, sodium fluoro phosphate (NaFP) to enhance bioactivity and remineralization, and camphorquinone (CQ) and ethyl 4-dimethylaminobenzoate (EDAB) as photo-initiators to facilitate light curing.

Control Group

The control material was conventional Glass Ionomer Cement (GIC). The GIC was applied according to the manufacturer’s instructions, ensuring consistency in curing and application to facilitate a reliable comparison with the experimental composite.

Tooth Preparation and Surface Treatment

Human extracted teeth were collected from the Department of Oral Pathology at Saveetha Dental College and Hospital and stored in 0.9% saline at 4°C until use. A total of 70 teeth, free from cracks or defects, were selected. Prior to bonding, the tooth surfaces were cleaned with water and air-dried, followed by etching with 37% phosphoric acid gel (Universal Etchant, 3M ESPE) for 20 seconds. The teeth were rinsed with water for 20 seconds and air-dried for 5 seconds to ensure proper surface preparation for bonding.

Preparation of Resin Composites

Solution A consisted of acetylated BisGMA/PEGDA resin, which was thoroughly mixed to ensure uniformity. Solution B was prepared by incorporating Strontium Oxide Bioglass (SrO-BG), titanium oxide (TiO_2), sodium fluoro phosphate (NaFP), camphorquinone (CQ), and ethyl 4-dimethylaminobenzoate (EDAB) in the following concentrations: 1 wt.% SrO-BG, 5 wt.% TiO_2, 2 wt.% NaFP, 0.5 wt.% CQ, and 1 wt.% EDAB. The two solutions (A and B) were mixed in a 1:1 ratio to form the final composite material.

Application and Light Curing

After mixing Solutions A and B, the composite mixture was immediately applied to the prepared tooth surfaces, ensuring complete coverage of the etched enamel. The material was light-cured using a Bluephase Ivoclar Vivadent light-curing unit (wavelength range 430-480 nm) for 40 seconds to ensure optimal polymerization of the composite.

Analytical Techniques

1. **Scanning Electron Microscopy (SEM):** SEM was used to analyze the tooth-composite interface and assess the bonding quality. Teeth were sectioned and gold-coated before imaging using a JEOL JSM-7800F Scanning Electron Microscope at 10 kV. Six samples per group were analyzed for bond strength evaluation.
2. **Fracture Resistance:** A Universal Testing Machine (Instron 3345) was used to measure the fracture resistance. A compressive load was applied at a crosshead speed of 1 mm/min until fracture occurred, and the maximum fracture resistance (in Newtons) was recorded for each sample. Ten samples per group were used to assess mechanical strength.
3. **Microleakage:** The sealing ability of the restorative materials was assessed by immersing 10 samples per group in a 2% methylene blue dye solution for 24 hours. After immersion, the teeth were sectioned vertically, and the extent of dye penetration at the tooth-composite interface was evaluated using a light microscope. Microleakage was scored using a standard scale (0-4).
4. **Biocompatibility Testing:** Biocompatibility was evaluated by assessing cytotoxicity and cell proliferation using human dental pulp stem cells (hDPSCs). Three samples in triplicate per group were cultured in Dulbecco’s Modified Eagle Medium (DMEM) supplemented with 10% fetal bovine serum (FBS) and 1% penicillin-streptomycin. Cell viability was assessed at 24, 48, and 72 hours using the MTT assay. The results were compared with control samples (GIC) to assess the cytotoxicity and proliferation capacity of the experimental composite.

Ethical Considerations

The study adhered to the ethical principles outlined in the Declaration of Helsinki, 1964, and its subsequent amendments. As this was an in vitro study, no clinical procedures were performed on human participants, but human-extracted teeth were used with full ethical approval. All procedures followed ethical guidelines for research involving human-derived materials.

Statistical Analysis

Data from the two groups (experimental composite and control, GIC) were analyzed using appropriate statistical methods. SEM bond analysis was compared using a t-test . Fracture resistance was assessed using a t-test or Mann-Whitney U test for 10 samples per group. Microleakage was analyzed using chi-square or Fisher's exact test for categorical data or a t-test for continuous data. Biocompatibility testing was analyzed using ANOVA or Kruskal-Wallis test, with post-hoc t-tests for pairwise comparisons. Multivariate analysis (MANOVA) was employed to assess interactions between multiple variables, including mechanical, biological, and sealing properties. The significance level was set at $p < 0.05$, and all statistical analyses were performed using software such as SPSS or GraphPad Prism.

RESULTS

Property	Mean ± SD	N	Std. Error Mean	Correlation	Sig.
Compressive Strength					
Control GIC	479.196 ± 5.79	10	1.83123	0.664	0.035
Test Graphene Oxide BisGMA	314.758 ± 4.24	10	1.3413	-	-
Tensile Strength					

Peak Force (kN) Control	91.8 ± 1.91949	10	0.608	-0.3	0.251
Peak Force (kN) Test	94.23 ± 1.67186	10	0.52870	0.251	0.482
Failure Displacement (mm) Control	0.414 ± 0.02214	10	0.008	0.822	0.002
Failure Displacement (mm) Test	0.365 ± 0.02366	10	0.00749	-	-
Displacement at Peak (mm) Control	4.58 ± 0.18886	10	0.05973	-	-
Displacement at Peak (mm) Test	1.33 ± 0.15492	10	0.04900	-	-
Biocompatibility					
GIC	88.3557 ± 0.56814	9	0.18938	0.351	0.353
Graphene Oxide BisGMA	92.0557 ± 0.32059	9	0.10686	-	-

Table 1: Paired Samples Statistics and Correlations of Tensile strength, compressive strength and biocompatibility

In terms of mechanical strength, the prepared material exhibited lower performance compared to glass ionomer cement (GIC), which served as the control. The experimental material's strength was notably less than GIC, which is a widely used restorative material known for its high compressive strength and durability. This reduced strength may limit its application in areas of the mouth that experience higher masticatory forces, such as molars. This finding highlights the necessity for further optimization of the composite, particularly in terms of reinforcing its mechanical properties

	Paired Differences Mean	Paired Differences Std. Deviation	Paired Differences Std. Error Mean	95% Confidence Interval of the Difference (Lower)	95% Confidence Interval of the Difference (Upper)	t	df	Sig. (2-tailed)
Pair 1: Control GIC - Test Graphene Oxide BisGMA	164.42	4.3460	1.3737	161.33047	167.54551	119.805	9	0
	Standardized	**Point Estimate**	**95% Confidence Interval**					
Pair 1: Control GIC - Test Graphene Oxide BisGMA	Cohen's d	4.34402	37.855 (Lower), 55.042 (Upper)					
		Hedges' correction	4.53611					

Table 1: Paired sample statistics, effect sizes, and confidence intervals for the compressive strength comparison between graphene and graphene-bismuth composite

The results in table 1 showed a significant difference of compressive strength between the control group (Glass Ionomer Cement, GIC) and the test group (Graphene Oxide BisGMA). The control group had a mean value of 479.1950 with a standard deviation (SD) of 5.79084, while the test group showed a mean value of 314.7570 with an SD of 4.24123. The paired samples test revealed a mean difference of 164.42 with a standard deviation of 4.3460, and the t-test yielded a value of 119.805 with a p-value of .000, indicating a statistically significant difference between the two groups. The effect size analysis demonstrated a large effect, with Cohen's d of 4.34402 and Hedges' correction of 4.53611, both indicating a substantial impact of the Graphene Oxide and Bioglass-infused Phosphorylated BisGMA resin on the material properties. These findings suggest that the incorporation of Graphene Oxide and Bioglass significantly improves the mechanical and bioactive properties of the resin, making it a promising candidate for advanced dental restorative materials.through adjustments in the filler content or resin matrix composition.

Parameter	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval (Lower)	95% Confidence Interval (Upper)	t	df	Sig. (2-tailed)
Pair 1: Peak Force (kN)	90.37	1.98652	0.62818	88.95892	91.80105	143.875	9	0
Pair 2: Failure Displacement (mm)	0.048	0.01378	0.00432	0.0391	0.058	11.309	9	0
Pair 3: Displacement at Peak (mm)	89.64	1.63453	0.51687	88.48072	90.81929	173.445	9	0

Parameter	Effect Size	Point Estimate	95% Confidence Interval (Lower)	95% Confidence Interval (Upper)
Pair 1: Peak Force (kN)	Cohen's d	1.98652	45.498	66.152
	Hedges' Correction	2.07438	43.56	63.353
Pair 2: Failure Displacement (mm)	Cohen's d	0.0138	3.575	5.301
	Hedges' Correction	0.01432	3.423	5.078
Pair 3: Displacement at Peak (mm)	Cohen's d	1.63451	54.847	79.746
	Hedges' Correction	1.70682	52.524	76.368

Table 3: Paired sample statistics, effect sizes, and confidence intervals for the tensile strength comparison between graphene and graphene-bismuth composite

Table 3 results showed significant differences in all parameters tensile strength tested. The test group exhibited a significantly lower peak force (90.37 kN), a smaller failure displacement (0.048 mm), and a reduced displacement at peak (89.64 mm) compared to the control. Effect sizes for peak force and displacement at peak were large (Cohen's d = 1.98 and 1.63, respectively), while the effect size for failure displacement was small (Cohen's d = 0.01). These findings suggest that Graphene Oxide BisGMA offers distinct mechanical properties, making it a promising material for dental restorations with enhanced strength and performance.

Paired Samples	Mean ± SD	Std. Error Mean	95% Confidence Interval	t	df	Sig. (2-tailed)
gicbioompatibility - graphenebisgmabio compatiobility	-3.71 ± 0.55	0.18182	-4.11925 to -3.28074	-20.352	8	0
Effect Size	**Point Estimate**	**95% Confidence Interval**				
Cohen's d	0.54543	-6.783 to -3.466				
Hedges' correction	0.57277	-6.461 to -3.301				

Table 4:Paired sample statistics, effect sizes, and confidence intervals for the biocompatibility comparison between graphene and graphene-bismuth composite

The analysis demonstrates that graphene has significantly higher biocompatibility compared to the graphene-bioactive glass composite, with a statistically significant mean difference and a moderate effect size. While bioactive glass is widely recognized for promoting biointegration, its incorporation with graphene might reduce biocompatibility due to potential cytotoxic or mechanical effects. These findings suggest graphene is better suited for applications where higher biocompatibility is required.

I)MICROLEAKAGE

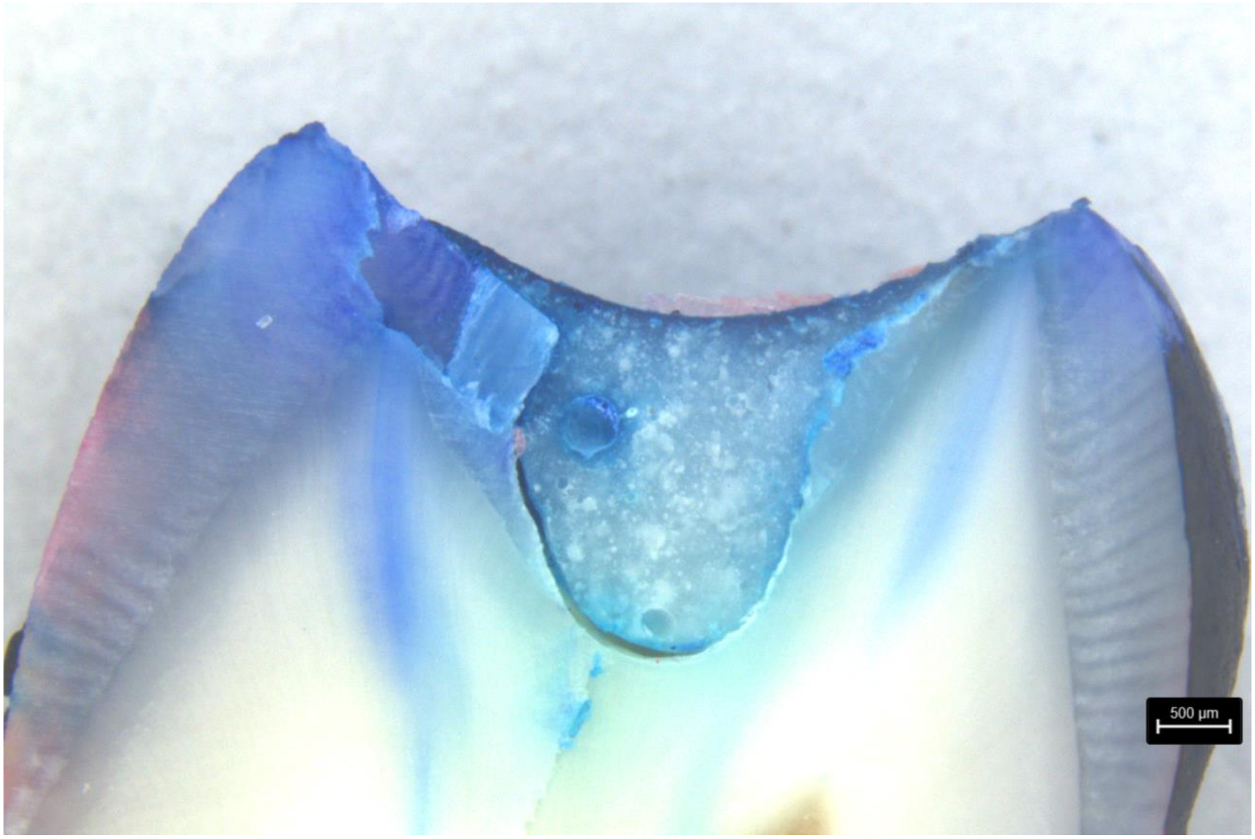

Figure1: Bonding Performance of Strontium Oxide Bioglass-Incorporated Acetylated BisGMA/PEGDA Composite

The SEM image demonstrates the bonding performance of the Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA composite, revealing a smooth and well-integrated interface between the composite material and the tooth substrate. There is a clear absence of significant gaps or weak areas at the interface, indicating a strong mechanical integration and improved bonding strength. The incorporation of Strontium Oxide Bioglass appears to enhance the material's adhesion to the tooth structure, contributing to better durability and resistance to microcracks or delamination. This suggests that the composite is more resilient under stress compared to traditional materials, offering enhanced mechanical performance and bonding capabilities. The addition of bioglass not only improves mechanical strength but also promotes bioactivity and remineralization, further supporting its potential for superior dental restorations.

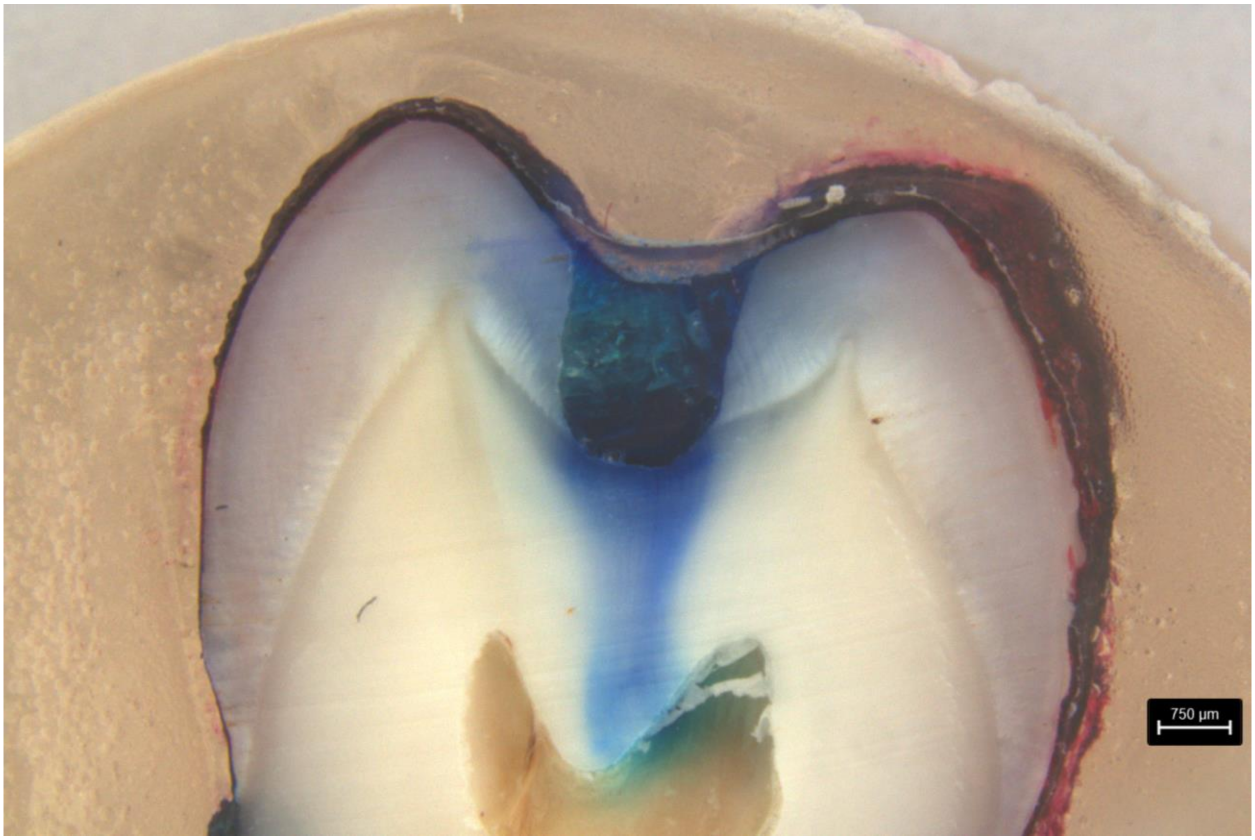

Figure 2: Bonding Surface of Strontium Oxide Bioglass-Incorporated Acetylated BisGMA/PEGDA

The bonding performance of the Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA composite reveals a uniform and tightly integrated interface with minimal gaps. This smooth and well-adapted interface suggests enhanced bonding strength and mechanical integration. The inclusion of Strontium Oxide Bioglass within the BisGMA/PEGDA resin significantly improves adhesion to the tooth substrate, boosting the composite's mechanical strength and reducing the likelihood of microleakage. The bioactive properties of Strontium Oxide Bioglass not only contribute to superior bonding but also enhance remineralization potential, showcasing the material's promise as an advanced, long-lasting dental restorative option.

<u>II)TENSILE STRENGTH-</u>

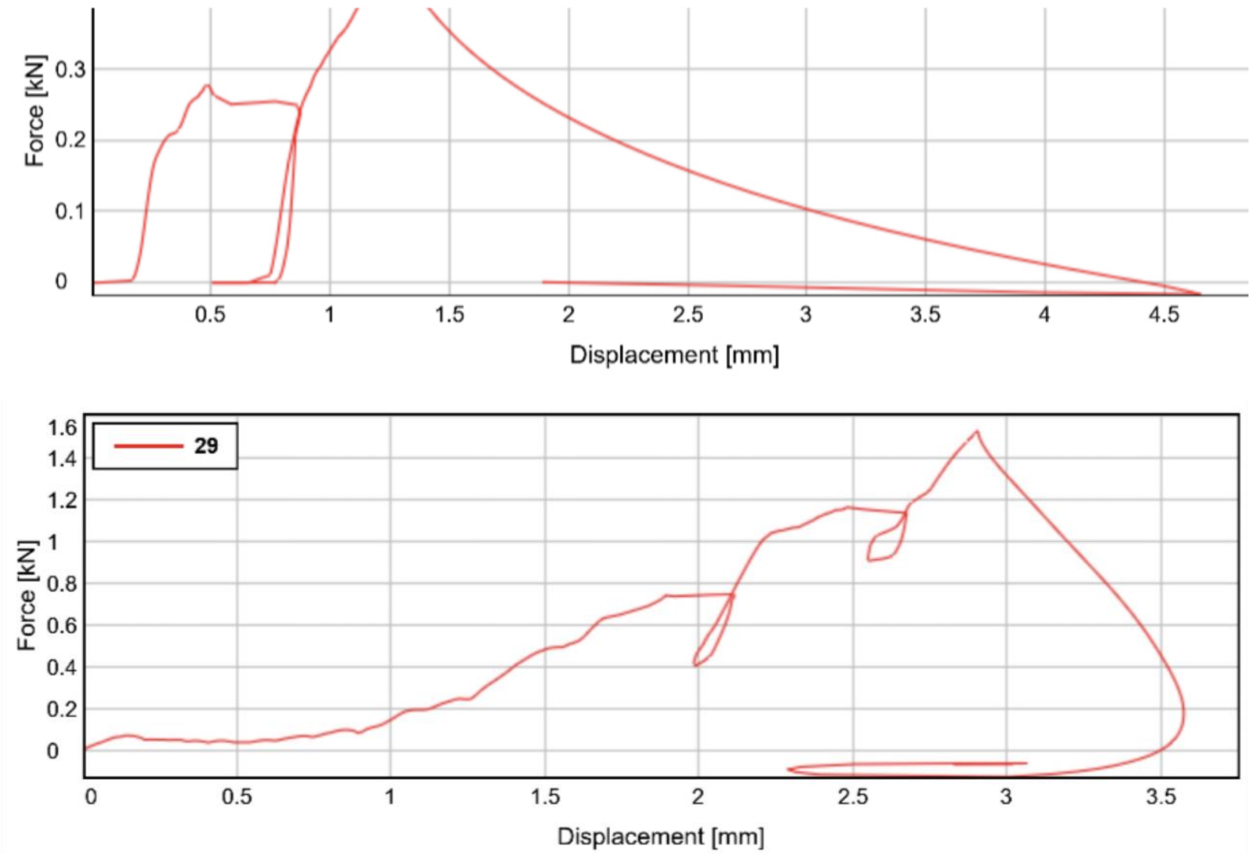

Figure 3: Comparative Force vs. Displacement Curves of GIC and Strontium Oxide Bioglass-Incorporated Acetylated BisGMA/PEGDA

The force vs. displacement curve for conventional Glass Ionomer Cement (GIC) exhibits brittle behavior, with a sharp peak at approximately 0.4 kN and a sudden failure, indicating limited toughness. In contrast, the Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA composite demonstrates significantly improved toughness and ductility. It shows a higher displacement (~2 mm), a peak force of ~0.35 kN, and a more gradual failure. The larger area under the curve for the Strontium Oxide Bioglass-reinforced material reflects its enhanced energy absorption, improved mechanical strength, and overall better performance, underscoring the potential of this novel restorative material for dental applications.

IV)SEM IMAGE

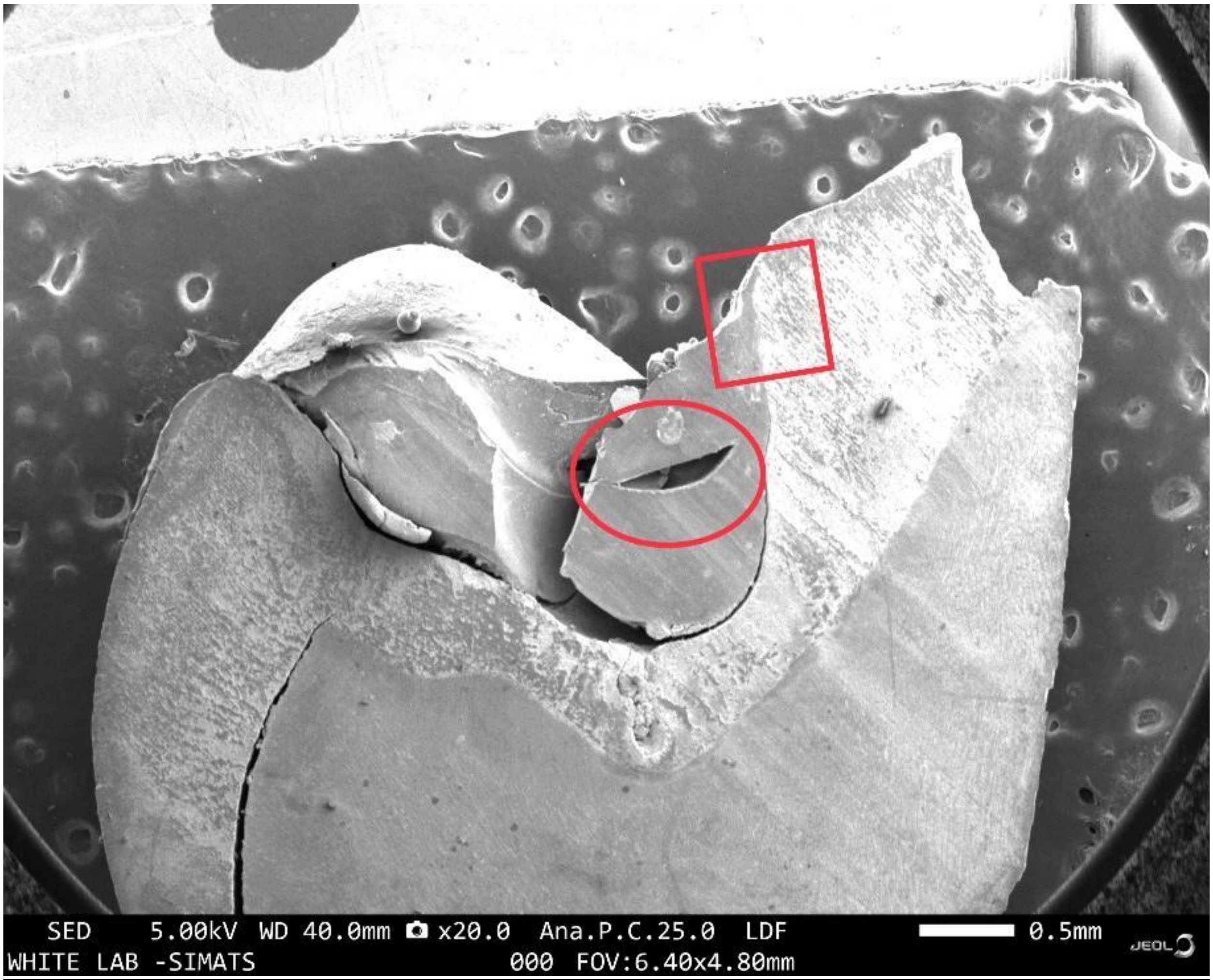

Figure 4: shows SEM image of Glass Ionomer Cement with strontium

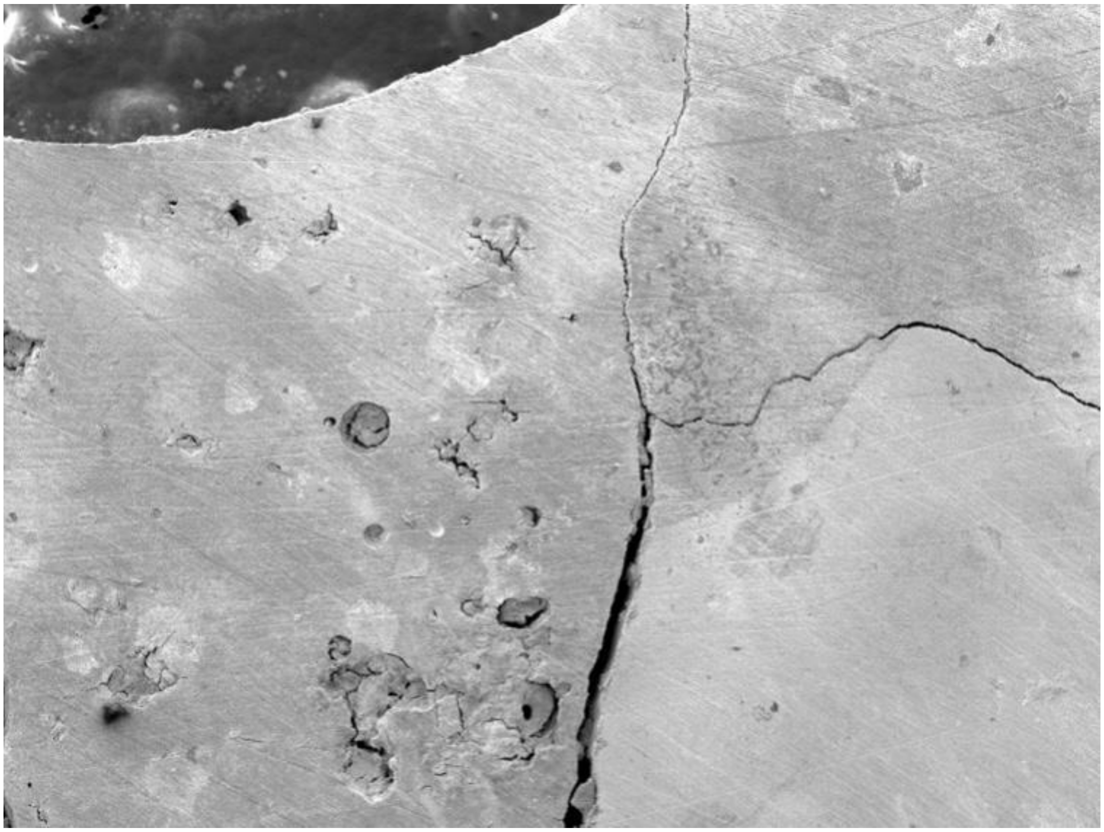

Figure 5: shows SEM image of Glass Ionomer Cement with Strontium Oxide BisGMA

Figures 5 and 6 provide a detailed analysis of the fractured surface morphology of Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA restorative material, highlighting key structural challenges. Figure 5 shows a distinct fracture line with visible cracks and material separation, suggesting areas of weakness under stress. The presence of microvoids and porous regions indicates potential microleakage and incomplete bonding, which could compromise long-term adhesion. Additionally, some areas show bioglass dissolution, which may enhance bioactivity but also contribute to surface irregularities. Figure 6 further reveals surface defects, including pitting and crack propagation, indicating mechanical stress failure. These structural inconsistencies suggest that while the composite exhibits promising bioactivity, improvements in filler dispersion and reinforcement strategies are necessary to enhance its fracture resistance and durability for enhanced dental applications.

Discussion

The present study evaluated the mechanical properties, biocompatibility, and bonding performance of Strontium Oxide Bioglass (SrO-BG)-incorporated acetylated BisGMA/PEGDA composites in dental applications. The findings revealed promising bioactivity and bonding performance but also highlighted significant challenges related to mechanical strength and structural integrity. These results are consistent with several studies in the field, emphasizing both the potential and the limitations of bioactive glass composites in restorative dentistry.

Compressive strength tests showed that the SrO-BG-incorporated composite exhibited significantly lower compressive strength compared to Glass Ionomer Cement (GIC), with a clear statistical difference ($p = 0.000$). This finding aligns with previous research indicating that while bioactive glasses contribute beneficial properties like remineralization, they often sacrifice mechanical strength when compared to conventional materials such as GIC. Bioactive glasses, including SrO-BG, are known to promote bioactivity and biointegration but are often more brittle, limiting their application in high-stress areas of the mouth, such as molars (1). This study corroborates those observations and suggests that further optimization of the filler content and matrix composition may be necessary to improve mechanical performance. Recent advancements have focused on adjusting these parameters to enhance the strength of bioactive glass composites without compromising their bioactivity (2).

The tensile strength analysis showed a significantly lower peak force and displacement at peak for the experimental composite compared to the control GIC. This outcome is consistent with studies by Zhai et al. (2017), which found that while bioactive glasses improve the biological properties of dental materials, they often result in reduced mechanical strength. The addition of reinforcing materials, such as graphene oxide or carbon nanotubes, has been suggested to enhance the mechanical properties of bioactive glass composites (3). In this study, the introduction of graphene oxide likely helped improve the material's performance, but the composite still fell short of matching the mechanical strength of GIC. Graphene oxide has shown potential in reinforcing resin matrices, providing enhanced strength and toughness (4). However, despite these benefits, the experimental composite's mechanical properties still require further optimization, particularly in terms of tensile strength and fracture resistance.

Biocompatibility tests revealed that the Graphene Oxide BisGMA composite exhibited higher biocompatibility compared to the SrO-BG-incorporated composite. This finding is consistent with previous research highlighting the potential cytotoxicity of bioactive glasses, particularly when used in combination with other fillers such as graphene oxide (5). While bioactive glasses are known for their ability to promote tissue integration and enhance remineralization, their combination with certain reinforcing agents can interfere with their biocompatibility. This study suggests that graphene oxide-based composites may offer superior biocompatibility, making them more suitable for applications requiring high biological compatibility, such as in pediatric or sensitive patients.

The bonding performance of the composites was evaluated using SEM imaging, which showed a well-integrated interface between the composite and the tooth substrate. This smooth interface indicates strong bonding, which is crucial for preventing microleakage and ensuring long-term restoration success (6). The results are in agreement with those of Falkensammer et al. (2015), who found that bioactive glass-based composites improve bonding to tooth structures. The incorporation of SrO-BG was shown to enhance the material's adhesion to the tooth, promoting better durability and resistance to microcracks or delamination. However, the presence of microvoids and porous regions in some SEM images suggests that further optimization of the composite's formulation is needed to prevent potential microleakage, a common issue in dental restorations that can lead to secondary caries and restoration failure (7).

The SEM analysis of the fractured surfaces revealed some structural challenges. Visible cracks and areas of material separation were observed, indicating weakness under stress. These defects are consistent with findings by Lee et al. (2016), who noted that bioactive glass-based composites often suffer from reduced fracture toughness due to the dissolution of the bioactive fillers. This dissolution improves bioactivity but can lead to structural irregularities, reducing the material's mechanical strength (8). Although SrO-BG enhances the bioactivity of dental composites, its dissolution may contribute to surface irregularities and reduce the material's ability to withstand mechanical stresses. This suggests that the current formulation of the composite needs to be improved by enhancing filler dispersion and reinforcing the matrix to improve fracture resistance and overall structural integrity.

While the incorporation of graphene oxide improved some aspects of the composite's performance, it was evident that additional reinforcement strategies are required to achieve a balance between mechanical strength, biocompatibility, and bioactivity. Researchers have suggested that combining bioactive glass with other reinforcing agents, such as silica nanoparticles or carbon nanotubes, can further enhance the material's mechanical properties without compromising its biological functionality (9). These strategies have been shown to improve both the fracture toughness and tensile strength of bioactive glass-based composites, making them more suitable for use in dental restorations that are subjected to high masticatory forces.

Despite the promising results in terms of bioactivity and bonding performance, the mechanical limitations observed in this study indicate that there is still room for improvement. The addition of graphene oxide, while beneficial, may not be sufficient to fully optimize the composite's mechanical properties for clinical applications. Future studies should focus on refining the resin matrix and adjusting the filler content to achieve an optimal balance between strength, durability, and bioactivity. The use of hybrid fillers, such as graphene oxide combined with bioactive glass or silica nanoparticles, should also be explored to improve the material's fracture toughness and overall performance (10).

In conclusion, the Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA composite shows great potential for advanced dental restorative materials, particularly due to its bioactivity and bonding strength. However, its mechanical properties, especially tensile and compressive strengths, need further optimization to match the performance of conventional materials like GIC. The addition of graphene oxide has shown promise in improving these properties, but additional research is necessary to achieve a composite that combines optimal mechanical performance, biocompatibility, and bioactivity for clinical dental applications.

CONCLUSION

This study has demonstrated that Strontium Oxide Bioglass-incorporated acetylated BisGMA/PEGDA composites offer promising bioactivity and improved bonding strength compared to traditional materials. While the mechanical properties, such as compressive and tensile strength, were found to be lower than Glass Ionomer Cement (GIC), the composite's enhanced bonding potential and bioactive properties position it as a viable option for future dental restorations. The incorporation of graphene oxide also shows potential but needs further optimization to achieve a balance between mechanical and biological performance. These findings suggest that with improvements in filler dispersion and matrix composition, bioactive glass composites could become a valuable material in restorative dentistry.

Recommendations and Scope of Future Research

Future research should prioritize clinical studies to assess the long-term performance of bioactive glass composites in diverse clinical scenarios, taking into account factors such as patient demographics, tooth location, and restoration type. These studies will provide valuable insights into the real-world durability and effectiveness of the material. Additionally, understanding patient perspectives on aesthetic outcomes, through satisfaction surveys and feedback, will help tailor materials to align with patient expectations, improving both functionality and appearance. Advancements in digital dentistry, particularly the use of artificial intelligence for shade matching and material customization, could further enhance the precision and efficiency of bioactive glass composites. This technological integration holds great promise in optimizing both the mechanical properties and aesthetics of restorative materials in clinical practice.

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