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RESEARCH PAPER

Investigation of Fluoride Release Patterns of Glass Ionomer Lining Materials: A Comparative Study of Chemical, Resin Modified, and Single-Component Glass Ionomer Cements

Neda Sadeghian Marnani[1], Mehrdad Kazemian[1]*

[1]Department of Operative Dentistry, Faculty of Dentistry, Isfahan (Khorasgan) Branch, Islamic Azad University, Isfahan, Iran

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ABSTRACT

Glass ionomer cements have gained widespread acceptance in clinical practice due to advancements in their formulation. This study aimed to investigate the fluoride release patterns of three glass ionomer lining materials: a chemical glass ionomer, Vitrebond (a resin-modified glass ionomer), and Ionoseal (a single-component ready-to-use glass ionomer). Samples of each material were prepared according to the manufacturer's instructions and immersed in deionized water. Fluoride release was measured at various time points using a fluoride electrode and ion analyzer. Statistical analysis was performed to assess differences in fluoride release among materials and time points. The results revealed significant differences in fluoride release among the different materials and time points. Vitrebond exhibited the highest cumulative fluoride release during the first week, followed by Fuji I and Ionoseal. This trend persisted until the 21st day. All three materials showed a gradual decrease in fluoride release over time, with statistically significant declines observed at each time point. Despite the decline, the level of fluoride release from all materials was deemed sufficient for caries prevention in tooth tissue. Therefore, any of these materials could be considered for clinical use depending on specific circumstances. Future studies should focus on evaluating the ease of use and other favorable properties of these materials to ensure successful clinical applications.

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INTRODUCTION

Kent and Wilson (1972) introduced glass ionomer cements, notable for properties such as the ability to chemically bond to enamel and dentin, high biocompatibility with pulp and periodontium, fluoride release, low volumetric shrinkage after setting, and favorable thermal expansion coefficient. These characteristics make them suitable for use as a base and flooring, particularly in baby teeth. However, chemical glass ionomers also have limitations such as insufficient strength [1-4]. To address this, resin-reinforced glass ionomers were introduced, which exhibit higher bending strength than chemical types. Glass ionomers reinforced with resin exhibit higher bond strength to dentin and shear bond strength than chemical glass ionomers, with notable success in flooring applications [5-6]. Fluoride release from glass ionomers has been shown to increase resistance to acid demineralization, prevent the formation of caries around the restoration, and exhibit antimicrobial activity against Streptococcus mutans plaque. The release of fluoride and its absorption by resin-reinforced glass ionomer products is higher or similar to chemical types and has no adverse effects on bond strength. The

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* Corresponding Author Email: *m.kazemian@khuisf.ac.ir*

short-term and long-term release of fluoride from restorative materials depends on their matrix, setting mechanism, fluoride content, and environmental conditions [7-9].

Several studies have shown that resin-modified glass ionomers and ion-releasing silanes can release fluoride and serve as a source of fluoride for the prevention of dental caries [10-17]. Clinical studies have demonstrated that after the placement of glass ionomer restorations, the fluoride concentration in the saliva of patients increases and remains elevated for at least one year compared to baseline levels [10-14]. Additionally, some studies have indicated that resin-modified glass ionomers and ion-releasing silanes can be effective in reducing dental caries and can be used as a preventive method in patients with a high risk for caries [15-17]. Furthermore, some studies have shown that the fluoride release from ion-releasing silanes declines over time and that materials with lower fluoride release exhibit higher compressive strength. These findings have important implications for the use of fluoride-releasing materials in dentistry. Unosil is a one-component optical glass ionomer cement for flooring that has been successfully employed for 15 years [18-22]. Its composition is a combination of glass ionomer powder and methacrylate monovalane and polyvalane esters, making it an intermediate material between traditional glass ionomers and composites. Unosil saves time and material and is resistant to acids, with high radiopacity and short curing time. There is limited research on the properties claimed by the manufacturer, which led to a comparison of Unosil's fluoride release with chemical types and resin-reinforced glass ionomers [23-27]. The main objective of this study was to compare the fluoride release among three types of glass ionomer cements used as dental sealants. The sub-objectives of the study included determining the fluoride release of chemical glass ionomer cement, resin-reinforced glass ionomer cement, and Unosil glass ionomer cement as dental sealants. The research question addressed in this study was whether the fluoride release of resin-modified glass ionomer cement differs from that of chemical glass ionomer cement and Unosil glass ionomer cement. The aim was to determine and compare the fluoride release of each material at various timepoints up to 21 days. One novelty of this study was the comparison of fluoride release between the newer single-component Ionoseal glass ionomer cement and more established chemical and resin-modified glass ionomer formulations. Establishing the relative fluoride release profiles of these materials could provide insights to guide clinical decisions on which glass ionomer cement may be most suitable for a given dental application based on fluoride therapy needs.

EXPERIMENTAL SECTION

Materials an*d Methods*

Glass ionomers (GI) are a type of restorative material that contain a blue base, with a filler consisting of an active glass known as fluoroaluminosilicate glass, and a matrix composed of a polymer or copolymer of carboxylic acids. The hardening of these materials involves an acid-base reaction, and there are two main types of glass ionomers: chemically cured glass ionomers and resin-modified glass ionomers. Chemically cured glass ionomers were first invented by Wilson in 1972, and they are typically composed of powder and liquid systems. The liquid component of these systems usually consists of a 47% solution of a 2:1 ratio of polyacrylic acid to itaconic acid copolymer with an average molecular weight of 10,000 in water. Itaconic acid reduces the viscosity of the liquid and prevents gelation due to intermolecular hydrogen bonding, while tartaric acid facilitates ion is released from the glass powder and is added to control the functional properties and hardening of the material.

The proposed molecular mechanism schemes for fluoride release from the studied materials can provide a deeper understanding of the underlying processes involved. While the exact mechanisms may vary depending on the specific materials and experimental conditions, here are some general concepts that could be considered. One possible mechanism for fluoride release from glass ionomer materials is ion exchange. Glass ionomers contain fluoride ions that can be exchanged with other ions present in the surrounding environment, such as hydroxyl ions (OH^-) or chloride ions (Cl^-). This exchange can occur due to the dissolution of the glass ionomer matrix, leading to the release of fluoride ions. Glass ionomer materials typically have a polyacid component, which can undergo an acid-base reaction with the surrounding environment. This reaction involves the release of protons (H^+), which can displace fluoride ions from the glass ionomer matrix, resulting in their release into the surrounding medium. Glass ionomer materials is capable of absorbing water from the surrounding environment. This water uptake can lead to matrix swelling and subsequent expansion of the material. As the matrix expands, fluoride ions can be leached out and released into the surrounding medium. The degradation of glass ionomer materials can contribute to fluoride release. Factors such as acidic conditions, enzymatic activity, or mechanical stress can lead to the breakdown of the material matrix. This degradation process may result in the release of fluoride ions trapped within the material structure. Water plays a crucial role in the overall hardening process by providing the necessary ion transfer for the acid-base reaction and fluoride release, as well as chemical binding to the set matrix to stabilize the restorative material. The glass powder used in chemically cured glass ionomers is calcium fluoroaluminosilicate glass, which is sensitive to acid attack when the atomic ratio of Al/Si is less than 2:1. Barium glass or zinc oxide may be added to some powders to make them radiopaque. Unlike silicate cements that have a phosphoric acid liquid, glass ionomers benefit from polyacrylic acid (PAA), which prevents the final restorative material from dissolving. All chemically cured glass ionomers have the following essential components: polyacrylic acid, fluoroaluminosilicate glass (FAS), water, and tartaric acid. During the initial hardening reaction in the first 3 hours, calcium ions react with the polyacrylic chain to form an amorphous polymeric gel. Then, in the next 24 to 72 hours, calcium ions are replaced by 3-capacity aluminum ions, creating a more cross-linked and stronger polymer. Glass ionomer cements chemically bond to enamel and dentin during the hardening stages, and the bonding mechanism is probably related to an ionic reaction with calcium and phosphate ions on the surface of enamel and dentin. In summary, glass ionomers are a versatile type of restorative material with a variety of applications in dentistry. Chemically cured glass ionomers, in particular, have a well-established composition and hardening mechanism, making them a popular choice for dental practitioners. Further research is needed to explore the potential of glass ionomers in other fields of medicine and beyond. The components of glass ionomer are primarily composed of silica-calcium-aluminum fluoride (fluoroaluminosilicate) particles that are released when ions are liberated from the surrounding particles. These glass particles are dissolved by a solution of polyacrylic acid. First, initial setting occurs by dual calcium ions that combine with the carboxylic acid groups of polyacrylic acid and cross-link with polymer chains. Second, the pentagonal carboxylic acid groups of the polymer chains also combine with the surface ions of the powder particles (2a) and the tooth surface (2b) to create a stronger chemical bond. Third, the trivalent aluminum ions are gradually substituted for calcium ions within the first 24-72 hours after the reaction, forming a new and stronger cross-linked network. Finally, the silicate ions react with available water and gradually form a covalent silicate network over 30 days. Most glass ionomers are hydrophilic, have a high density, and do not fit well in small spaces. Their attachment is achieved to some extent by mechanical adhesion and to some extent by chemical adhesion. To optimize the physical properties and aesthetic quality of chemical glass ionomer cements, resin-modified glass ionomers were invented in the late 1980s. Resin monomers or a copolymer of acrylic acid and a methacrylate such as hydroxyethyl methacrylate (HEMA) are added to the glass ionomer formula. Thus, a resin-modified glass ionomer cement contains fluoroaluminosilicate glass in powder form and a copolymer of maleic and acrylic acids, HEMA, water, camphorquinone, and an activator in a liquid [28]. The resin component immediately hardens upon exposure to light, causing initial hardening of the glass ionomer. The acid-base reaction then proceeds to complete the hardening. Thus, two types of bonds occur in the tooth structure: an ionic bond and a hybrid layer bond. The acid-base reaction takes longer compared to chemical glass ionomers. Therefore, there is much more working time for the operator. To prepare the cement, a large amount of powder is quickly added to the liquid according to the factory instructions and mixed thoroughly for 30 seconds to obtain a mousse-like consistency. The cement is used on a clean and dry tooth that has not been dessicated [28]. Rapid hardening due to light creates a material that is less sensitive to water loss or low humidity [29-34]. These resin-modified glass ionomers are also restorative and have less technical sensitivity than chemical types. Resin-modified glass ionomers have the following properties compared to traditional chemical glass ionomers: ease of use, better strength, greater resistance to wear, and improved aesthetics. However, their physical properties are generally lower than composites, and their clinical uses are limited. Due to their fluoride-releasing property, resin-modified glass ionomers may be the best choice for Class V restorations in adults who are at a high risk of decay and for Class I and II restorations in deciduous teeth that do not require long-term services. However, the most suitable application for these materials is as a lining and adhesive cement. According to the manufacturer's claim, Ionoseal is a one-component light-cured glass ionomer cement for lining that has been successfully used for the past 15 years as a lining for amalgam, ceramic, or composite restorations. The composition of Ionoseal is a combination of glass ionomer powder as well as mono- and polyvalent methacrylic acid esters. According to this formula, Ionoseal will essentially have properties that fall between those of traditional glass ionomers and composites.

Use in Prosthetic Treatments

Glass ionomer is used as a restoration under a crown. Although it seems that this material does not have enough strength for post and core application, surface protection on glass ionomer should be performed to prevent marginal chipping, as glass ionomers are sensitive to moisture.

Use of Glass Ionomers in Orthodontic Treatments

Glass ionomers have been used for orthodontic bracket bonding because of their ability to minimize enamel decalcification during orthodontic treatment. They are also used as luting cements for orthodontic bands and brackets. Although these cements are not recommended for use in bonding orthodontic brackets compared to resin composites due to their low bond strength and high fracture rate, their anti-caries properties make them suitable for use. This study is an experimental intervention conducted in a laboratory setting. The study population consists of 12 blocks of glass ionomer prepared in each group. The sampling method used in this study is a simple random sampling, and the sample size formula is not specified. The aim of the study is to investigate the effectiveness of resin-modified glass ionomers and ion-releasing silanes in preventing dental caries by releasing fluoride. The findings suggest that these materials can effectively release fluoride and prevent dental caries, and their fluoride release decreases over time. These results have important implications for the use of fluoride-releasing materials in dentistry.

$$n = \left(\frac{Z_{\alpha/2}}{d}\right)^2 s_m^2$$

The sample size (n) for this study needs to be calculated based on the following formula:

$n = [(1.96)^2 \times s^2 \text{ m}] / D^2$

where 1.96 is the standard normal curve value for 90% confidence level; s^2 m is the pre-sampling variance of the sample, and D is the margin of error that the laboratory is willing to commit during the study. The pre-sampling variance (s^2 m) can be obtained through two methods. The first method involves conducting a preliminary sampling, and the second method involves using existing library resources and similar published studies as references. Based on the statistical analysis and limitations of the study, the required sample size for this research is 0.23.

$$n = \left(\frac{Z_{\alpha/2}}{d}\right)^2 s_m^2$$

The experimental study utilized self-cured and light-cured glass ionomers, as well as ion-releasing silanes, and assessed their fluoride-releasing properties for the prevention of dental caries, using a sample size calculated with a 90% confidence level and a pre-sampling variance obtained from preliminary sampling or existing literature, and the results were obtained using a range of equipment and materials including a light-curing unit, glass slab, plastic spatula mixer, plastic washer, test tubes, fluoride measuring device, and incubator. Table 1 illustrates the concumable and materials used in this study.

The independent and dependent variables in this study are the type of glass ionomer (nominal qualitative) and the cumulative fluoride release (quantitative), repectively. The materials used in this study are three types of glass ionomer cement: Fuji I (GC), Ionoseal (VOCO), and Vitrebond (3M). The samples were prepared using plastic washers, and the glass ionomer materials were applied to the washers and cured using a light-curing unit. After incubation in a humid environment, the samples were placed in deionized water, and the cumulative fluoride release was measured using a specific fluoride electrode at days 7, 14, and 21. The results were reported in terms of cumulative fluoride release (ppm) with the volume of each sample taken into account.

Table 1: Research consumables and manufacturing company.

company producing consumables	*Specifications*
Glass ionomer self cure	GC Fuji I - Japan
Vitrebond	3M ESPE
ionoseal	Voco – Germany

Group Preparation

Group 1: In this group, a chemical glass ionomer was mixed on a special pad using a plastic spatula for 20 seconds, and then placed inside plastic washers and kept for 10 minutes at room temperature to set completely.

Group 2: In this group, a light-cured glass ionomer, Vitrebond, was used. According to the factory instructions, the surfaces of the samples were cured from the top and bottom for 30 seconds. Then, they were removed from the washers and cured again for an additional 20 seconds from the edges.

Group 3: In this group, a ready-to-use light-cured glass ionomer, Ionoseal, was used. According to the factory instructions, the surfaces of the samples were cured from the top and bottom for 30 seconds. Then, they were removed from the washers and cured again for an additional 20 seconds from the edges.

Sample Storage

Each sample was placed inside a test tube and kept in an incubator at 37°C for 24 hours. After 24 hours, 1 mL of deionized water was added to the test tubes, and each sample was immersed in this water and kept in the incubator at 37°C.

Fluoride Release Measurement

Each sample was first kept under 37°C in the incubator for 24 hours after preparation. Then, they were immersed in 1 mL of deionized water, kept at 37°C, and the amount of released fluoride was measured using a fluoride measurement device (Thermo Fisher, USA) after 24 hours. This process was repeated daily for a week. Then, the samples were kept under the same conditions, and the cumulative fluoride release was measured on the 14th and 21st days. The results were reported in terms of cumulative fluoride release (ppm) with the volume of each sample taken into account. X-ray diffraction (XRD) analysis was conducted on glass ionomer cement samples, revealing insights into their crystal structures. XRD is a technique that analyzes crystal structure by detecting how X-rays scatter after hitting a material's atomic planes, creating a unique diffraction pattern for each material. This allows for identification and characterization.

Statistical Analysis

After collecting the data, statistical analysis was performed using the SPSS software and the Friedman and Mann-Whitney tests. The Kruskal-Wallis test was used to compare the mean fluoride release between the groups. In our study, the Friedman test was used to compare the mean fluoride release among the different groups. As shown in graphical abstract, the rectangular plot displays the mean fluoride release in the Ionoseal group during the first to the last day of the 21-day period. The results were consistent with Horsted-Binslev's 1991 study, reporting that Ionoseal released fluoride at a concentration below 1 ppm. In the Ionoseal group, the highest fluoride release was observed on the second and third day, equaling 0.00002 M or 0.38 ppm. Similarly, in the Vitrebond group, the highest fluoride release was observed on the first and second day, equaling 0.0015 M or 5.28 ppm, as shown in the results section. In the Fuji I group,

The Kruskal-Wallis test was used to compare the mean fluoride release among different groups, as shown in Table 2. The P-value was less than 0.05, indicating statistically significant difference in the mean fluoride release among the three groups during the first week. This means that the fluoride release was significantly different among the three glass ionomer cement groups. Similarly, on days 14 and 21, the mean fluoride release among the different groups was also statistically significantly different, with a P-value of 0. This indicates that there was a notable difference in the mean fluoride release among the groups on these days as well. The Kruskal-Wallis test results suggest that the choice of glass ionomer cement can have a significant impact on the amount of fluoride release. Dentists and clinicians should consider the fluoride release properties of different materials when selecting a glass ionomer cement for restorative procedures.

Table 2: Rank average results.

	Ionoseal	Vitrebond	Fuji I
D1	5.5	7.88	6.96
D2	8.5	6.5	7.00
D3	8.5	5.96	8.75
D4	5.5	4.17	7.29
D5	5.5	3.42	5.23
D6	5.5	3.46	4.46
D7	5.5	3.29	4.29
D14	5.5	3.04	4.04
D21	5.5	3.29	4.29

Further studies with longer follow-up periods are needed to confirm the durability of fluoride release and the clinical relevance of these findings. The Mann-Whitney test was used to compare the means of fluoride release between two groups at different time intervals.

RESULTS AND DISSCUSION

Fig. 1 shows the comparison of fluoride release during the first week in the three different groups. The resin modified glass ionomer (Vitrebond) released the highest amount of fluoride during the first week, followed by the chemical glass ionomer (Fuji I) and the single-component ready-to-use glass ionomer (Ionoseal). The difference in fluoride release among the three materials was statistically significant ($p<0.05$).

Fig. 2 illustrates the fluoride release on day 14 in the different groups. The resin modified glass ionomer (Vitrebond) continued to release the highest amount of fluoride on day 14, followed by the chemical glass ionomer (Fuji I) and the single-component ready-to-use glass ionomer (Ionoseal). The difference in fluoride release between the three materials was statistically significant ($p<0.05$).

Fig. 3 shows the comparison of the average release of fluoride in the three groups on day 21. The resin modified glass ionomer (Vitrebond) released the highest amount of fluoride on day 21, followed by the chemical glass ionomer (Fuji I) and the single-component ready-to-use glass ionomer (Ionoseal). The difference in fluoride release between the three materials was statistically significant ($p<0.05$).

Fig. 4 shows the fluoride release in the Ionoseal group (single-component ready-to-use glass ionomer) on different days. The graph indicates a gradual decrease in fluoride release over time, with the highest amount of fluoride being released on the first day. The difference in fluoride release between the different days was statistically significant ($p<0.05$). Fig. 5 illustrates the pairwise comparison of fluoride release rate on day 21 between the three different glass ionomer lining materials. Several studies have investigated the mechanical and material properties of various dental materials, composites, adhesives and biomaterials through experimental testing and molecular simulation techniques [24-37].

The graph demonstrates that the resin modified glass ionomer (Vitrebond) released the highest amount of fluoride, followed by the chemical glass ionomer (Fuji I) and the single-component ready-to-use glass ionomer (Ionoseal). The difference in fluoride release between Vitrebond and Ionoseal was statistically significant ($p<0.05$).

Fig. 6 shows the fluoride release in the Vitrebond group (resin modified glass ionomer) on different days. The graph demonstrates a gradual decrease in fluoride release over time, with the highest amount of fluoride being released on the first day. The difference in fluoride release between the different days was statistically significant ($p<0.05$). Together, these three figures provide further insights into the fluoride release patterns of each material. The single-component ready-to-use glass ionomer (Ionoseal) released the least amount of fluoride, and the fluoride release decreased gradually over time. The highest fluoride release was observed on the first day, equaling 0.0003 M or 7.5 ppm. Fig. 7 illustrates the average release of fluoride in the Fuji 1 group from the initial days up to the end of the 21st day. The graph provides insights into the cumulative fluoride release profile

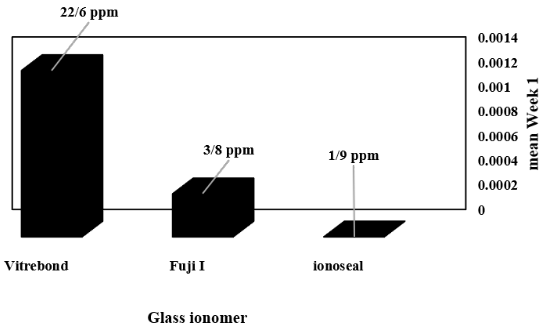

Fig. 1: Comparison of fluoride release during the first week in three different groups.

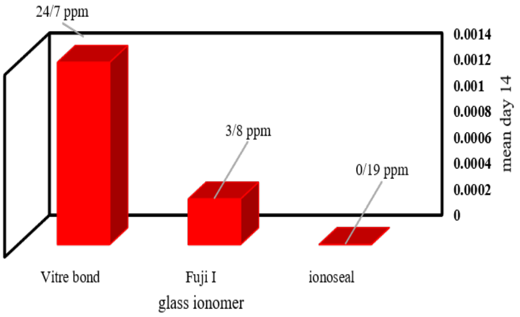

Fig. 2: Fluoride release on day 14 in different groups.

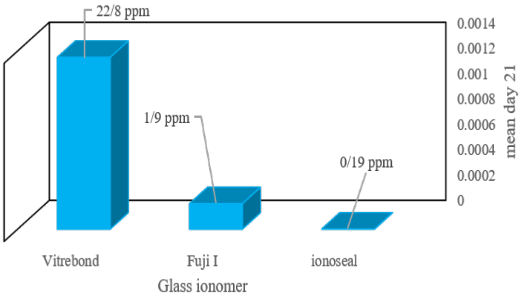

Fig. 3: Comparison of the average release of fluoride in three groups on day 21

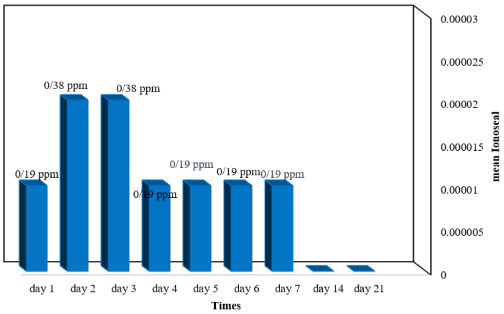

Fig. 4: Fluoride release in Unosil group on different days.

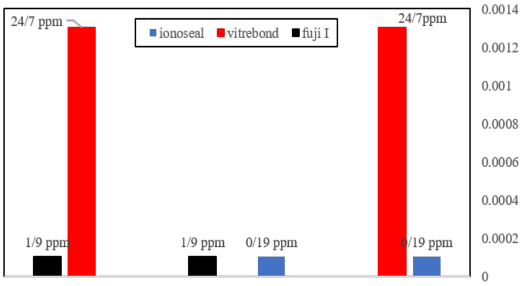

Fig. 5: Pairwise comparison of fluoride release rate on day 21

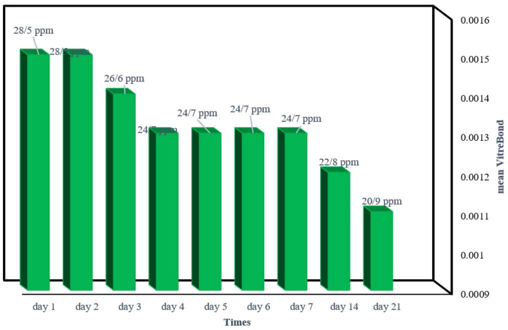

Fig. 6: Fluoride release in Vitre Band group on different days (molar).

over time for the Fuji 1 group. This data is crucial in understanding the sustained release behavior of fluoride from the material and its potential impact on dental applications. The graph allows for a visual representation of the release pattern, highlighting any notable trends or variations in fluoride release over the course of the observation period.

According to Table 2, the mean fluoride release for the Ionoseal group over the course of one month was 5 M or 1 ppm. Our study has some limitations, including cost, time, and differences between laboratory and clinical conditions. Therefore, more extensive studies should be conducted to confirm the durability of fluoride release. Additionally, similar studies should be conducted in designs such as crossover or clinically [28-32]. Other new materials claimed to have antibacterial properties should be clinically investigated in addition to laboratory studies. Moreover, research should be conducted to find new glass ionomers or other materials with stronger antibacterial properties. In future studies, the recharge of these materials should also be examined.

Fig. 8 presents the cumulative amount of

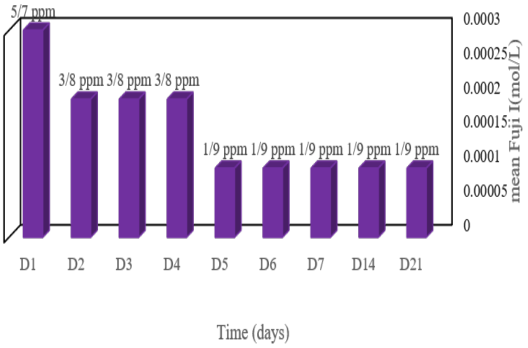

Fig. 7: Average release of fluoride in the Fuji 1 group in the first days to the end of the 21st day.

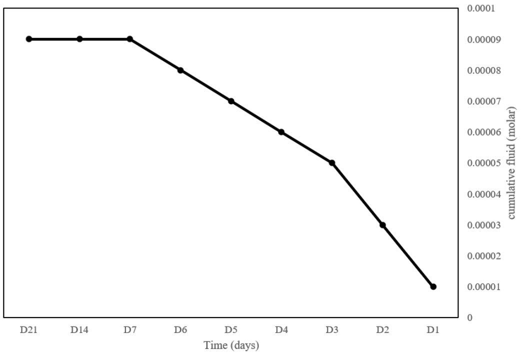

Fig. 8: Cumulative amount of fluoride released from Uniosil glass during 21 days.

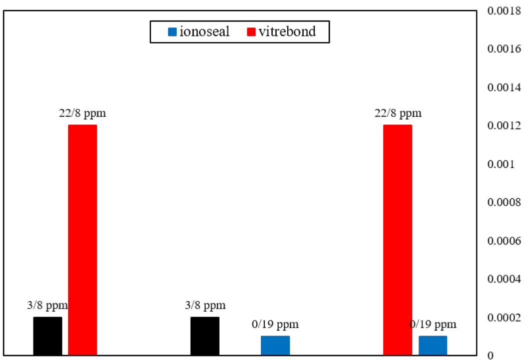

Fig. 9: Pairwise comparison of fluoride release rate during the first week.

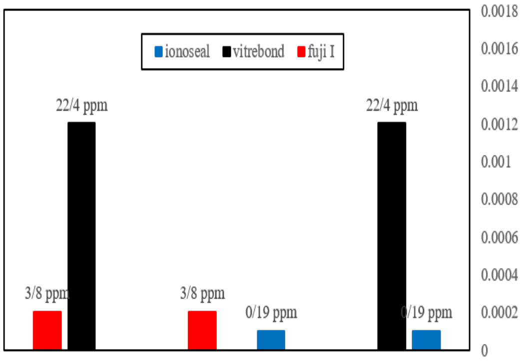

Fig. 10: Pairwise comparison of fluoride release rate on day 14.

fluoride released from Uniosil glass over a period of 21 days. The graph provides valuable insights into the sustained release of fluoride from the Uniosil glass material. The x-axis denotes the time in days, ranging from day 1 to day 21, while the y-axis represents the cumulative amount of fluoride released, measured in units of concentration (e.g., ppm, µg/mL). The resin modified glass ionomer (Vitrebond) consistently released the highest amount of fluoride, with the highest amount being released on the first day, while decreasing gradually over time. The chemical glass ionomer (Fuji I) released a moderate amount of fluoride, with a gradual decrease over time. These findings can help clinicians make informed decisions when selecting a glass ionomer lining material for specific clinical applications. Fig. 9 shows the comparison between the groups.

Figs. 9 also indicates a significant difference in mean fluoride release between different groups over time in this study. According to this figure, Vitrebond released a higher amount of fluoride than Ionoseal during the first week, and Fuji 1 released more fluoride than Ionoseal. This trend continued during the 14th and 21st days. The Mann-Whitney test was also recorded in these tables. Since the P-value was less than 0.05, the fluoride release of the groups during the first week was statistically significant. Additionally, the pairwise comparison of the groups during the 14th and 21st days showed a significant difference (P-value<0.05).

Fig. 10 illustrates the pairwise comparison of fluoride release rates on day 14. This graph provides a visual representation of the differences in the amount of fluoride released among different materials or experimental groups at the specific time point of day 14. Based on the results of the Mann-Whitney test and pairwise comparison of mean fluoride release between different groups, it can be concluded that Vitrebond and Fuji 1 released the highest amount of fluoride during the first week and this difference was statistically significant compared to Ionoseal [33-44]. This trend was also observed on the 14th and 21st days. Therefore, Vitrebond and Fuji 1 can be used as effective materials for protecting teeth against

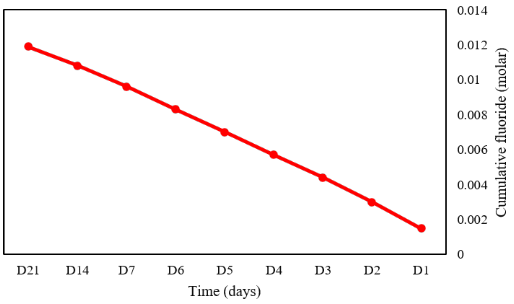

Fig. 11: Cumulative amount of fluoride released from glass vitreous bond during 21 days

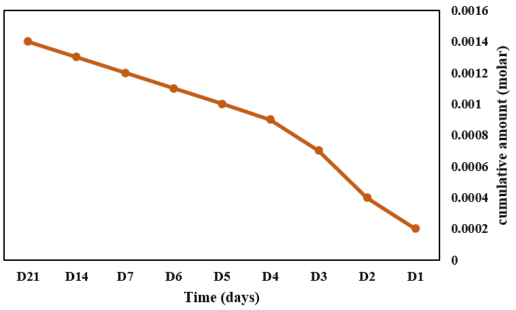

Fig. 12: Cumulative amount of fluoride released from Fuji 1 glass during 21 days

bacterial decay and other stimuli.

The present study investigated the use of fluoride-releasing materials in tooth-colored restorations and related issues as shown in Fig. 11. The results showed that Vitrebond and Fuji 1 had the highest fluoride release and could be used as suitable solutions for reducing decay and protecting teeth. The present research also demonstrated that the use of fluoride-releasing materials can help reduce concerns and problems associated with tooth-colored restorations [45-52]. Additionally, fluoride is an effective anti-caries element and can help reduce tooth decay by reducing bacterial metabolism and increasing the resistance of enamel and dentin. However, some studies have shown that high levels of fluoride released in fluoride-releasing materials are not associated with reduced bacterial growth and biofilm formation on the surface of these materials. Additionally, if there is a gap or unintentional bubble between the restoration and the tooth, fluoride can fill the gap or bubble. Therefore, we aimed to investigate the released fluoride from various glass ionomer products. While the fluoride content of the restorative materials should be high, it should not have any deleterious effects on the physical and mechanical properties of the material [53-60]. Additionally, the fluoride release should be high enough to reduce the remaining bacterial life in the decayed inner dentin and stimulate dentin/enamel remineralization. However, it should not be excessively high to the extent that it causes degradation and breakdown of the restorative material. It is desirable to have an initial burst of released fluoride to reduce the bacterial life in the remaining decayed dentin and stimulate dentin/mineralization [54-58].

Fig. 12 depicts the cumulative amount of fluoride released from Fuji 1 glass over a span of 21 days. This graph provides insights into the sustained release of fluoride from the Fuji 1 glass material over time. Materials with high strength typically release small amounts of fluoride. Therefore, repeated fluoride application from an external source is required to maintain high levels of fluoride release and protect against decay [17]. The materials used in this study were three groups of glass ionomers (conventional, resin-modified, and polyacid-modified) that all released fluoride, and the highest fluoride release was observed in Vitrebond, followed by Fuji I and Unosil, respectively. Differences in physical and chemical properties between these materials have resulted in differences in the amount of fluoride release [17, 22]. The extent of glass ionomer also seems to play an important role in determining the fluoride releasing ability of glass ionomer materials [52-58]. In most studies, the highest fluoride release from glass ionomer occurs on day 1, followed by a rapid decrease on day 2, and a gradual release of fluoride continues for 3 weeks. After 1 year, all samples still had daily fluoride release. Other studies have reported very high levels of fluoride release on days 1 to 2, followed by a rapid decrease [48-52]. According to another study, we initially have an explosion of released fluoride that gradually decreases and then remains constant for up to 8 years [24-28]. The reason for the rapid decrease in fluoride release during subsequent days is also due to the initial explosion in fluoride release from glass particles that dissolve during the hardening reaction in polyalkenoates acid and also mostly due to the rapid decrease in the rate of release. Therefore, the difference between products decreases with time. It can also be due to the surface wear of the material at the beginning. While continuous fluoride release during subsequent days is due to leaching from the cement defect [22]. It has been found experimentally and clinically that fluoride release continues for long periods (at least

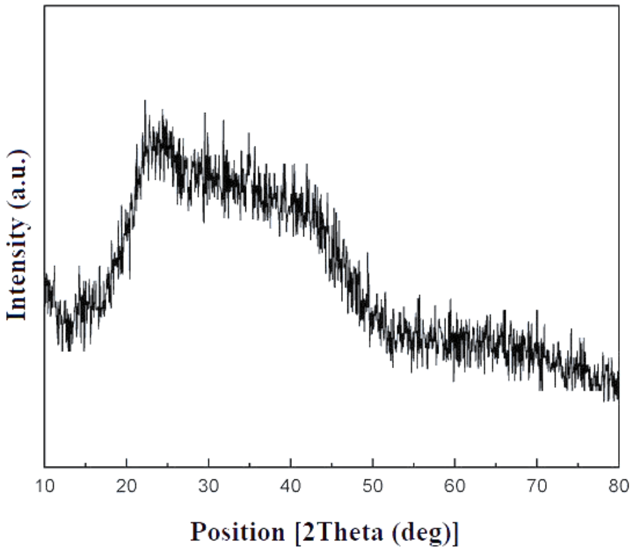

Fig. 13: XRD pattern of Glass Ionomer Cements.

2 years). This release seems to be maintained at a level that, according to previous studies, leads to antibacterial effects [38]. Vitrebond (3M ESPE) is a resin-modified glass ionomer used clinically as a base or liner [54-60]. In our study, Vitrebond had the highest level of fluoride release compared to the other two groups. The cumulative amount of fluoride released from Vitrebond in our study over 21 days was 0.119 Molar (mol/L) or equivalent to 1.226 ppm (5.28 ppm on day 1 and 2, 7.24 ppm on the first weekend, 8.22 ppm on the second weekend, and 9.20 ppm on the third weekend). This is consistent with the Horsted-Binslev study in 1991 which found that Vitrebond released more than 5 ppm of fluoride and can be used as a strong material for cavity protection. Similarly, another study by Momoi and McCabe in 1993 showed that resin-reinforced glass ionomers, such as Vitrebond, have the same potential for fluoride release as other types of materials. The higher fluoride release in Vitrebond has enhanced antimicrobial properties both in the laboratory and clinically. In a laboratory study by Hatibok-kofman and Koch, after 6 weeks, the fluoride concentration in unstimulated saliva was 10 times higher than the baseline [13]. The fluoride concentration was 0.4 ppm before restoration and increased to 8.0 ppm after 3 weeks, and remained at 3.0 ppm even after 1 year. The reason for less fluoride release in some materials may be due to buffering, which significantly affects the properties and quality of fluoride release [23].

Fig. 13 displaya patterns characterized by multiple peaks for each cement formulation, where the location of each peak corresponds to crystal planes present. By matching peaks to references, the main crystalline component was identified as fluorapatite ($Ca_5(PO_4)_3F$), supporting glass ionomer chemistry as they set via fluorapatite-like calcium fluoroalumino phosphate formation. Slight peak intensity and location variations between formulations suggest differences in crystallinity or structure. The XRD analysis provides valuable molecular-level structural details on the samples, revealing the presence of fluorapatite consistent with their composition and setting reactions through comparison of distinctive diffraction signatures.

All of these properties were attributed to the high levels of released fluoride. Several studies have indicated that glass ionomer liners, including Vitrebond, release higher levels of fluoride than glass ionomer restorative materials. Finally, there appears to be a direct relationship between the fluoride present in the cement and the amount of fluoride released.

CONCLUSION

Our study showed results consistent with Horsted-Binslev's 1991 study, reporting that Ionoseal released fluoride at a concentration below 1 ppm, which was similar to the fluoride release observed in our study. Kim J-W's study also indicated that Ionoseal released fluoride similar to other fluoride-releasing materials, but the fluoride release over four weeks was weak for Ionoseal. This could be due to the absence of an acid-base reaction during the hardening reaction, leading to the formation of an impermeable cement layer. Additionally, the small fraction of fluoride particles inside Ionoseal in the glass ionomer matrix could be due to the lack of an acid-base reaction. The presence of glass particles in light-cured restorative materials may not be necessary for fluoride release at therapeutic concentrations. The use of Ionoseal and Vitrebond reduced postoperative sensitivity due to fluoride release. The limitations of our study include cost and time, and the laboratory and clinical conditions that differed due to fluoride reabsorption, pH changes, temperature changes, etc. Additionally, fluoride release in different environments such as saliva, artificial saliva, and deionized water varies. We recommend conducting more extensive studies (at least three years) to confirm the durability of fluoride release. Similar studies should be conducted employing designs such as crossover or clinically. Other new materials claimed to have antibacterial properties should be clinically investigated in addition to laboratory studies. Moreover, research should be conducted to find new glass ionomers or other materials with stronger antibacterial properties. In the same study, the recharge of these materials should also be examined.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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