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Article

Enamel Anti-Demineralization Effect of Orthodontic Adhesive Containing Bioactive Glass and Graphene Oxide: an in-Vitro Study

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Abstract: White spot lesions (WSLs), a side effect of orthodontic treatment, can result in reversible and unaesthetic results. Graphene oxide (GO) with a bioactive glass (BAG) mixture(BAG@GO) was added to Low Viscosity Transbond XT(LV) in a ratio of 1, 3, 5%. The composite's characterization and its physical and biological properties were verified with scanning electron microscopy(SEM) and X-ray diffraction(XRD); its microhardness, shear bond stress (SBS), cell viability, and adhesive remnant index (ARI) were also assessed. Efficiency in reducing WSL was evaluated using antibacterial activity of *S. mutans*. Anti-demineralization was analyzed using a cycle of the acid-base solution. Adhesives with 3 or 5 wt.% of BAG@GO showed significant increase in microhardness compared with LV. The sample and LV groups showed no significant differences in SBS or ARI. The cell viability test confirmed that none of the sample groups showed higher toxicity compared to the LV group. Antibacterial activity was higher in the 48-hour group than in the 24-hour group; the 48-hour test showed that BAG@GO had a high antibacterial effect, which was more pronounced in 5 wt.% of BAG@GO. Anti-demineralization effect was higher in the BAG@GO-group than in the LV-group; the higher the BAG@GO concentration, the higher the anti-demineralization effect.

Keywords: anti-demineralization ; antibacterial effect; white spot lesion; graphene oxide; bioactive glass

1. Introduction

Orthodontic treatment is performed to improve both functionality and aesthetics but undesirable side effects may often occur. White spot lesions (WSLs) are one of the side effects of orthodontic treatment. The white and chalky surface of WSLs is a result of demineralization of the enamel surface. Fejerskov and Kidd defined WSLs as the "first sign of a caries lesion on enamel that can be detected with the naked eye"[1]. The opaque surface of WSLs can be easily detected with the naked eye, and WSLs on anterior teeth is undesirable, because one of the goals of orthodontic treatment is the aesthetic outcome. The main cause of WSLs, or demineralization, is a decrease in intraoral pH due to bacterial activity. Orthodontic fixed appliances create an irregular surface on

teeth, which can then serve as an accumulation site for plaque. *Streptococcus mutans* and *Lactobacilli*, the main pathogens of dental caries, decrease intraoral pH. This effect combined with an irregular enamel surface area and poor oral hygiene during orthodontic treatment, precipitates enamel demineralization. Patient education and regular fluoride application have been utilized to prevent WSLs. Contemporarily, research promulgates supplementation of bonding agents with biomaterials to prevent WSLs, because neither patient cooperation nor additional chair time is necessary. Biomaterials added to bonding agents should be harmless to the human body, shouldn't interfere with the physical properties of bonding agent, and should hinder the growth of bacteria that cause demineralization, by either decreasing the pH or releasing ions to increase the pH. One of the biomaterials being studied contemporarily is BAG, with the basic structure of Si-O-Si, and consisting of CaO, Na_2O, and P_2O_2. BAG functions as a filler and exhibits both an antibacterial function and a buffer effect (by releasing ions when added to resin pastes). In a liquid environment, BAG releases Na^+, $Ca2^+$, and PO_4^{3-} ions and develops into a super saturated ion state. On enamel surfaces, released ions convert precipitated amorphous calcium phosphate layer into apatite. BAG exerts its antibacterial effect by increasing intraoral pH through ion-release, and therefore, compensating for the decrease in pH caused by oral bacteria [2-3]. Graphene and graphene-based materials are recognized as biomaterials in dental fields such as tissue engineering. GO is a carbon-based plate structure, and it has been studied, for an extended period in the tissue engineering field, as an osteoinductive factor [4-5]. The antibacterial effect of GO, especially on dental pathogens, has been discovered recently, and it was shown that GO displayed the highest antibacterial effect when compared to other graphene-based materials such as graphite, graphite oxide, graphene oxide, and reduced graphene oxide [6]. Therefore, the purpose of this study was to develop a composite that combined the antibacterial effect of GO biomaterial and the anti-demineralization effect of BAG, to form an orthodontic bonding adhesive [7], and to investigate the possibility of its clinical application, through antibacterial and acid-base anti-demineralization testing.

2. Materials and Methods

2.1. Synthesis of bioactive glass/graphene oxide

BAG was synthesized with the quick alkali-mediated sol-gel method. The procedure involved mixing and stirring of 2.8 ml of 2M NHO_3 (Samchun, Seoul, Korea), 13.9 ml of distilled water, and 50 ml of ethanol (Samchun, Seoul, Korea) for 30 minutes. The mixture was then spun at 600 rpm under room temperature to produce an aqueous acid solution. A total of 21.6 ml of tetraethyl orthosilicate (TEOS, Sigma-Aldrich, St. Louise, MO, USA) was added to the aqueous acid solution and stirred for 30 minutes under room temperature. A total of 2.2 ml (12.95 mmol) of triethyl phosphate (TEP, Sigma-Aldrich, St. Louise, MO, USA) was added to the solution and stirred for 30 minutes. A total of 14.04 g of $Ca(NO_3)_2{\cdot}4H_2O$ was added to the solution and stirred for 30 minutes to convert the mixture into a transparent sol state. 2M NH_4OH (Samchun, Seoul, Korea) was added to the sol, and a muddler was used to prevent the sol from turning into a bulky gel state. Polycondensation reaction was induced by 24-hour aging in a 60 °C oven, 24-hour drying in an 80 °C oven, washing with distilled water and ethanol, and 4 hours of heat processing in a 600 °C furnace. BAG@GO compound was synthesized with BAG and GO (liquid, 4 mg/ml, Graphenea Inc., Cambridge, MA, USA) by colloidal processing. BAG and GO suspension were prepared using deionized and distilled water as a solvent, respectively, and were sonicated for 2 hours in a bottle containing ice cubes. The concentration of GO (2 ml/ml) and BAG (80 mg/ml) were used to set the weight ratio of BAG and GO to 40:1. After the suspensions were sonicated, GO suspension was combined with BAG suspension through a separatory funnel under 200 rpm of magnetic stirring. A mixture of the suspension was dried for 24 hours in a 65°C vacuum oven, after which, another 2 hours of magnetic stirring was conducted.

2.2. Characterization of bioactive glass/graphene oxide

The shape of the sample was analyzed with field-emission scanning electron microscopy (FESEM; SUPRA25; Oberkochen, Germany). XRD pattern of BAG@GO was measured with an automated X-ray powder diffractometer (XRD; Ultima IV, Rigaku, The Woodland, TX, USA) with CuKα radiation of (λ= 1.5409292Å): 40 kV, 40 mA, step size of 0.0010 deg, and a scanning rate of 1.00 deg/sec in the 2θ range of 05 to 85 deg.

2.3. Mechanical properties

2.3.1. Disk preparation for mechanical properties

Disk (5 mm in diameter and 1 mm in height) was used to examine the physical properties of the orthodontic bonding adhesive with BAG@GO. A total of 2 ml of orthodontic bonding adhesive LV (Transbond™ Supreme Low Viscosity Light Cure Adhesive, 3M, Monrovia, CA, USA) with 1, 3, and 5 wt.% of BAG@GO were inserted into a 2-ml Black e-tube. The adhesives with BAG@GO were shaken twice for 20 seconds each with a mixer (ProMix TM, Dentsply Caulk, York, PA, USA). The sample was mixed homogeneously, poured into a brass cast, covered with 0.2 mm thick slide glass, and light-cured with VALO (Ultradent Products, South Jordan, UT, USA) for 20 seconds.

2.3.2. Microhardness

Five disks were examined for each group of adhesives with a different weight percent of BAG@GO. A microhardness tester (MVK-H1, Akashi, Japan) was used to measure hardness Vickers (Hv), applying 200 gf of loading.

2.3.3. Shear bond strength

Five premolars extracted for orthodontic reasons were prepared for each group. This study was reviewed and approved by the Institutional Review Board of Pusan National University Dental Hospital (PNUDH-2016-025). Any tooth with enamel defect, including caries or WSL, was excluded. The surfaces of the teeth where the brackets were intended to be applied, were cleansed with prophylaxis cup and non-fluoridated pumice, washed with water for 10 seconds, and air-dried. 35% phosphoric acid gel (Ultra-Etch, Ultradent, South Jordan, UT, USA) was used to etch the surfaces of the teeth, after 15 seconds, the etchant was washed off with suction, and the teeth surfaces dried. Transbond™ XT Light cure adhesive primer (3M, Monrovia, CA, USA) was applied to the dried teeth surfaces, and gentle air blow was applied for 2 seconds. Premolar brackets (Arista TM, Select dental, USA) were then adhered to the surface, parallel to the long axis of the tooth. Excess of the paste was removed, and the paste was light-cured for 5 seconds from mesial and distal directions. All procedures were performed by the recommended method for Transbond™ XT Primer. Bracket bonded teeth were kept in distilled water for 24 hours, and examined with a universal testing machine (Instron Corporation, Canton, MA, USA) afterwards; the steel rod of the machine was vertically positioned on the bracket on the tooth, and maximum load (N) was measured with crosshead speed of 1 mm/min. Measured load value, N, was divided by 11.83 mm^2 - the surface area of the bracket base, to calculate the bond strength (MPa). Bonding failure of the debonded tooth surface was evaluated with the Adhesive Remnant Index (ARI) using the following standards: 1 – all the adhesive remained on the tooth; 2 – more than 90% of the adhesive remained on the tooth; 3 – from 10 to 90% of the adhesive remained on the tooth; 4 – less than 10% of the adhesive remained on the tooth; and 5 – no adhesive remained on the tooth.

2.4 Biological properties

2.4.1 Cell viability assay

The disk was disinfected in Ethylene oxide(EO) gas, put in a 96 well plate, and radiated with UV light for 100 minutes. Human gingival fibroblasts (HGF-1) (ATCC, Rockville, MD, USA) were

cultured in Dulbecco's modified Eagle's medium (DMEM, Hyclone Logan, UT) with 10% fetal bovine serum (FBS, Hyclone Logan, UT) and 100 IU/mL of penicillin/streptomycin (Hyclone Logan, UT). HGF-1 was evenly divided and injected into 96 well plates containing samples, and the plates were incubated for 24 hours in a 37°C, 5% CO_2 incubator. 5 mg/ml of MTT [3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide] (Sigma-Aldrich, USA) was injected into the cultivated samples. After the samples had undergone 4 hours of reaction in a dark room, the supernatant liquid was removed from the samples, and MTT crystals were dissolved in dimethyl sulfoxide (DMSO, Sigma-Aldrich, USA, 150 μl/well). Absorbance at a wavelength of 620 nm was measured (SunriseTM, TECAN, Switzerland).

2.4.2 Antibacterial test

Streptococcus mutans (*S. mutans*, KFCC, Korea) used in this research, was incubated with brain heart infusion (BHI) at 37 °C. The disk was disinfected in EO gas, put in 96 well plate, and radiated with UV light for 100 minutes. After *S. mutans* ($1.0X10^5$ CFU/ml) was inserted into the plate, half of the samples were cultured in a 37°C incubator for 24 hours, and the other half for 48 hours. Absorbance at a wavelength of 620 nm was measured (SunriseTM, TECAN, Switzerland).

2.5 Anti-demineralizationtest

Anti-demineralization was examined using the pH cycling method which was introduced by Toda and Featherston [14]. Nine premolars extracted for orthodontic reasons were prepared for each group. Any tooth with enamel defect, including caries or WSLs, was excluded. Each tooth was invested in molded acrylic resin (Caulk Orthodontic Resin, Dentsply Caulk, York, PA). Invested teeth samples were cleansed with prophylaxis cup and non-fluoridated pumice, they were then washed with water for 10 seconds and dried. Only 5 x 5 mm of tooth surface was exposed to the etchant and all other surfaces were protected with tape. The etchant, 35% phosphoric acid gel (Ultra-etch, Ultradent, South Jordan, UT, USA), was applied for 30 seconds and washed off with water for 10 seconds, then the tooth surface was dried. Orthodontic bonding adhesive samples were produced in the same way the disks were made. After the adhesive samples were applied to the exposed teeth surfaces and light-cured for 5 seconds, the tape protecting the unetched surfaces was removed. Teeth samples were stored in distilled water for 24 hours and underwent a 14 day cycle of being submerged in demineralizing solution (Biosesang, Seoul, Korea) for 6 hours, and in anti-demineralizing solution (Biosesang, Seoul, Korea) for 18 hours; the solutions were replaced every 7 days. Each time the samples were moved from one solution to the other, they were washed with distilled water for 1 minute and dried with gentle air. The samples were examined with micro-computed tomography (CT) (InspeXio SMX-90CT Plus Benchtop micro Focus X-ray, Shimadzu, Japan), 90 kV and 109 μA. The micro-CT data was analyzed with image J (National Institutes of Health, Bethesda, MD, USA), with adjustments made according to the scale bar on micro-CT [15]. Brightness histogram was selected as the test standard for identifying sound enamel; enamel tissue with up to 87% brightness was considered sound enamel, and **a**nti-demineralization length was measured from the point where the enamel had a brightness below 87%, to the end point where the sample orthodontic bonding primer had been applied.

2.6 Statistical analysis

Experimental comparison between groups was performed with one-way analysis of variance test (ANOVA) and post-hoc, with Duncan's multiple comparison test; examined properties include microhardness, shear bond strength, antibacterial test, cell viability test, and pH cycle test. ARI was verified with the Kruskal-Wallis test. All statistical analysis was performed with R language program (version 3.5.1; R Foundation for Statistical Computing, Vienna, Austria).

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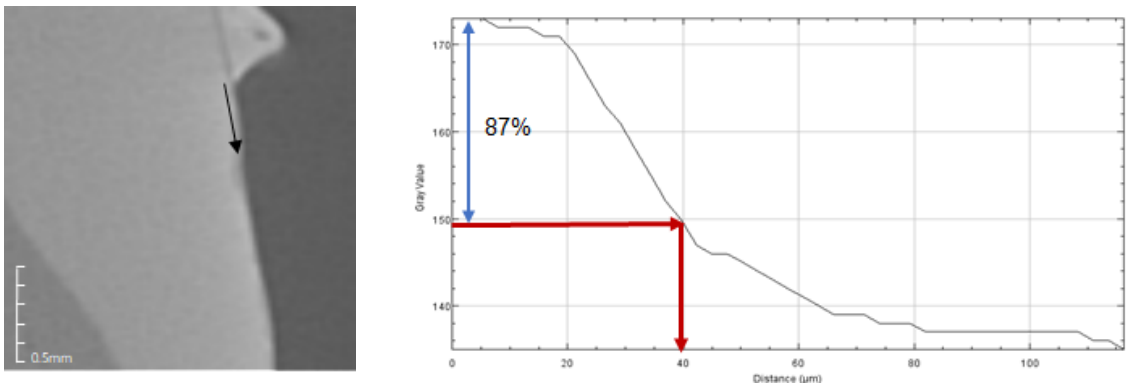

(**a**) (**b**)

Figure 1. Anti-demineralization length analysis method. (a) Micro-computed tomography (CT) slice of ROI (the region of interest) at the center of the lesion perpendicular to the enamel surface. The starting point was the end of the adhesive, black line: the line of ROI from a reference point on the enamel surface; (b) Histogram in ImageJ. Blue arrow: up to 87% level of gray value from the reference point, and red arrow: the distance at the 87% gray value from the reference point.

3. Results

3.1. Characterisation of BAG@GO

BAG synthesized with sol-gel synthesis showed aggregated polygonal structure, similar to other research findings [7]. BAG@GO showed various amorphous GO layers within the BAG structure [8]. XRD patterns of BAG@GO showed combined patterns of both BAG and GO, forming an atypical pattern and a peak at 26.7°(Figure 2).

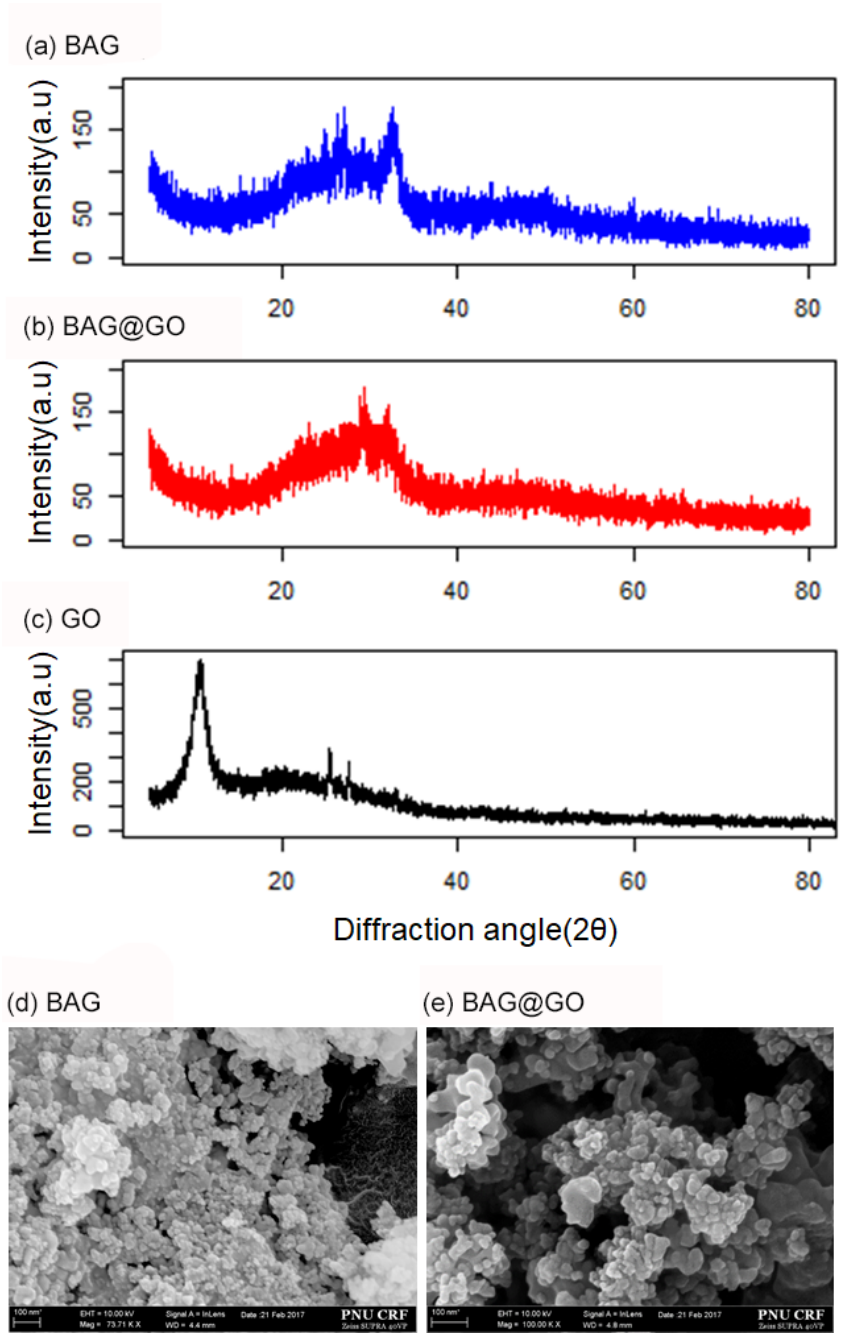

Figure 2. Characterization of BAG, BAG@GO and GO. (a) XRD of BAG, (b) XRD of BAG@GO, (c) XRD of GO, (d) SEM of BAG, and (e) SEM of BAG@GO

3.2 Mechanical Properties

3.2.1 Microhardness

The group with 3 wt.% and 5 wt.% of BAG@GO showed a significant increase in microhardness compared with the group of just LV (Figure 3).

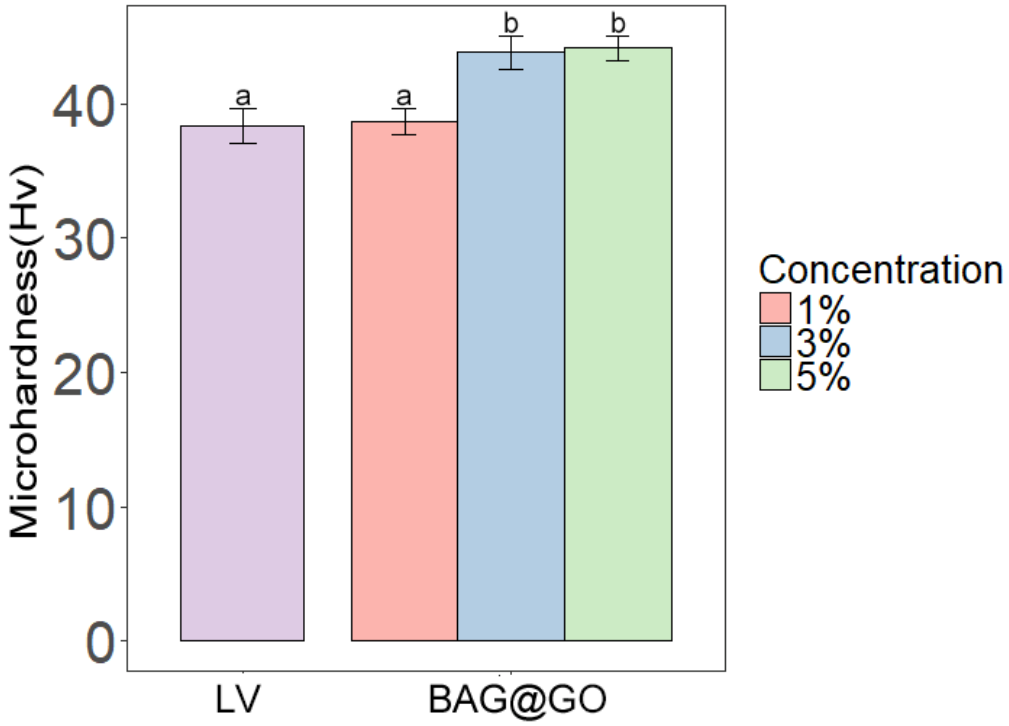

Figure 3. Microhardness comparison of orthodontic bonding paste containing LV and different weight percentages of BAG@GO. The same alphabet indicates no statistically significant difference between the groups ($p < 0.05$) by Duncan's Multiple comparison Test. Error bars were shown ± standard deviation.

3.2.2 Shear Bond Strength

No statistical difference between the LV group and sample group was found in the shear bond strength test. The shear bond strength decreased as the amount of BAG@GO in the sample increased ($p < 0.05$) (Figure 4).

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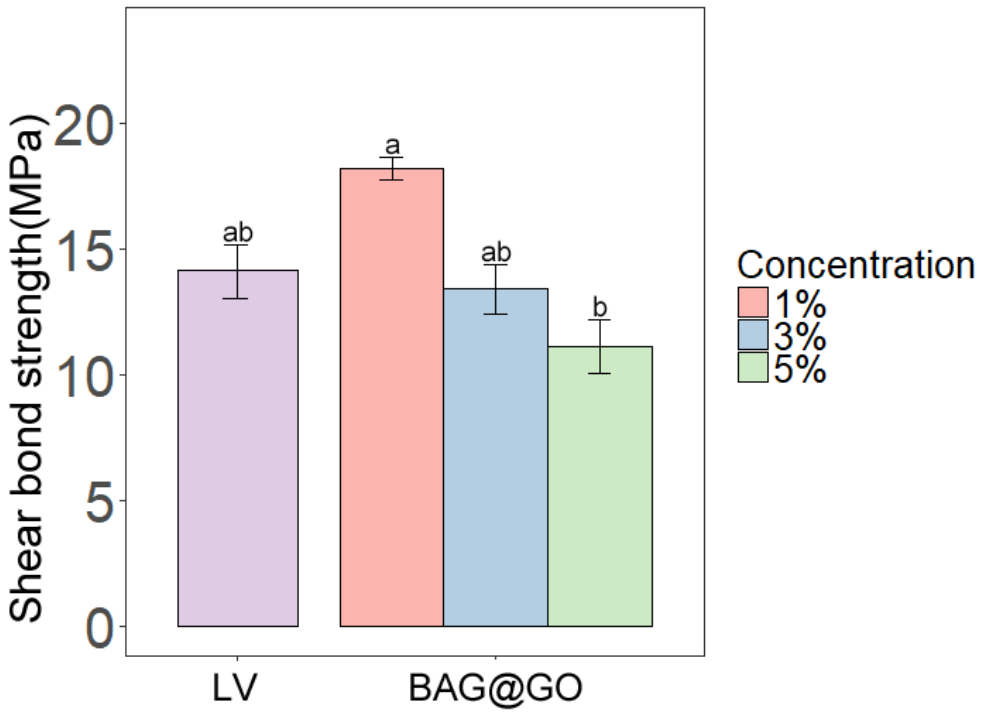

Figure 4. Shear bond strength comparison of orthodontic bonding paste containing LV and different weight percentages of BAG@GO. The same alphabet indicates no statistically significant difference between the groups ($p < 0.05$) by Duncan's Multiple Comparison Test. Error bars were shown ± standard deviation.

3.2.3 Adhesive Remnant Index (ARI) Score

Sample group with BAG@GO did not show any different trend. All groups showed no statistically significant differences ($p < 0.05$) (Table 1).

Table 1. Adhesive Remnant Index (ARI) scores of tested orthodontic bonding adhesives

ARI (%)	LV	BAG@GO			Significant
		1.0%	3.0%	5.0%	
1	0	0	0	0	
2	0	0	0	0	Not significant
3	1	0	1	3	
4	4	5	4	2	
5	0	0	0	0	

The ARI score is not significantly different according to the Kruskal-Wallis test at $\alpha = 0.05$ (n=5). Score 1 – all the adhesive remained on the tooth; score 2 – more than 90% of the adhesive remained on the tooth; score 3 – from 10 to 90% of the adhesive remained on the tooth; score 4 – less than 10% of the adhesive remained on the tooth; score 5 – no adhesive remained on the tooth.

3.3 Biological Properties

3.3.1 Cell Viability test

Cell viability test results after 48 hours were confirmed: control group (sterilized saline) showed significantly higher results when compared to the LV group and the sample groups(1,3,5% BAG@GO group). But the LV group showed no statistically significant difference when compared to 1,3,5% BAG@GO group. Samples with 1 wt.% of BAG@GO showed higher cell viability when compared to samples with 3 and 5 wt.% of BAG@GO. It show that cell viability was higher on more BAG@GO concentration(Figure 5).

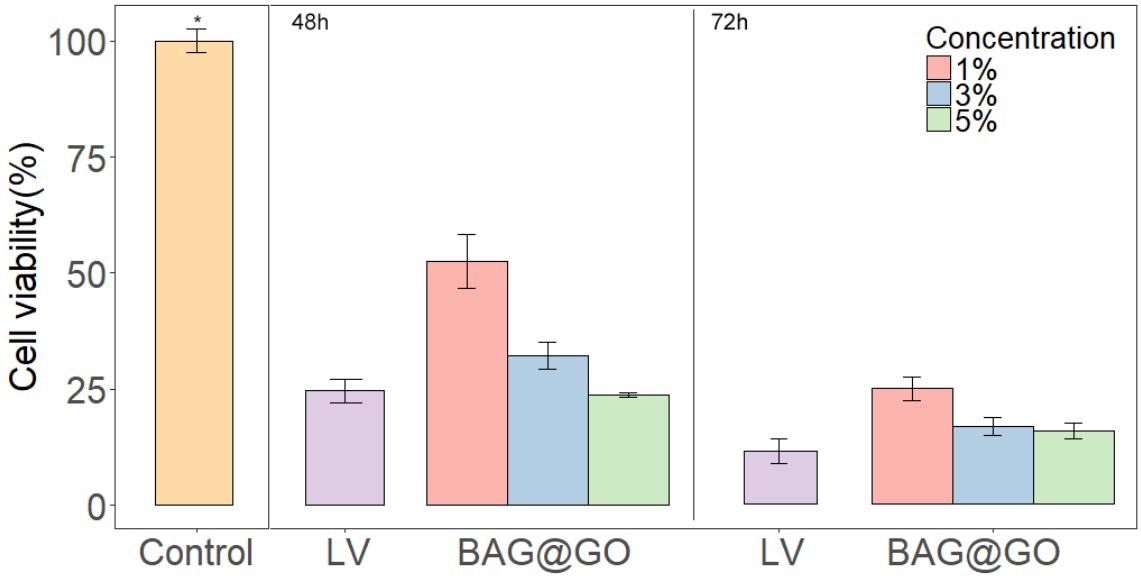

Figure 5. Cell viability test by HGF cytotoxicity on cured LV and BAG@GO containing orthodontic bonding paste. Cell viability test results after 48 and 72 hours are shown. The same alphabet indicates no statistically significant difference between the groups ($p < 0.05$) by Duncan's Multiple comparison Test. Error bars were shown ± standard deviation.

3.3.2 Antibacterial Properties

With respect to antibacterial effect, sample groups with BAG@GO showed a significantly higher antibacterial effect compared to the control group (containing nothing) and the LV group. All groups within 48 hours of the reaction, showed higher antibacterial effect than groups with just 24 hours of the reaction. The sample group with 5 wt.% of BAG@GO showed the highest antibacterial effect. Groups with 24 hours of the reaction did not show any correlation between the concentration of BAG@GO and antibacterial effect, while groups with 48 hours of the reaction showed antibacterial effect proportional to the concentration of BAG@GO (Figure 6).

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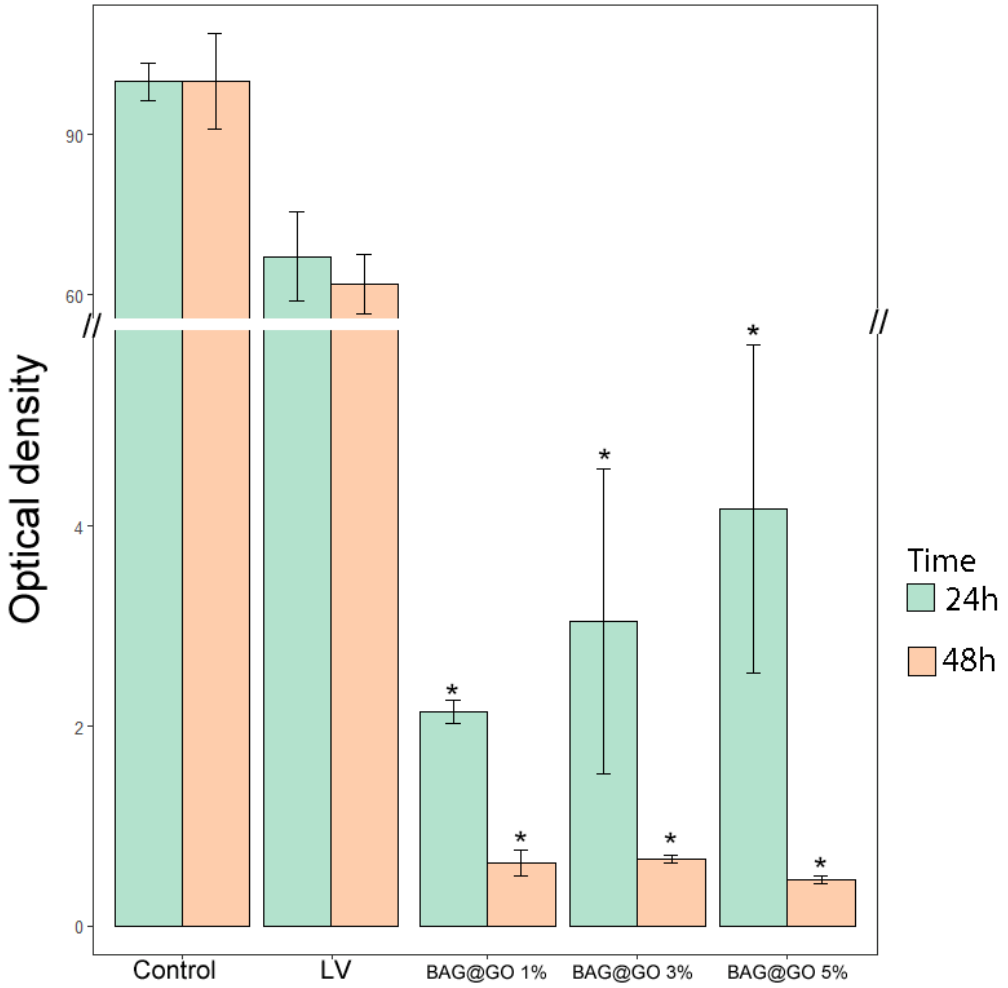

Figure 6. The difference in antibacterial properties between cured LV and BAG@GO orthodontic bonding pastes at 24 hours. An asterisk (*) indicates statistically significant differences between the control and LV groups ($p < 0.05$) by Duncan's Multiple Comparison Test. Error bars were shown ± standard deviation.

3.4 Anti-demineralizationTest

All sample groups with BAG@GO showed statistically significant higher anti-demineralization effect than the LV group, and anti-demineralization effect was proportional to the concentration of BAG@GO (Figure 7).

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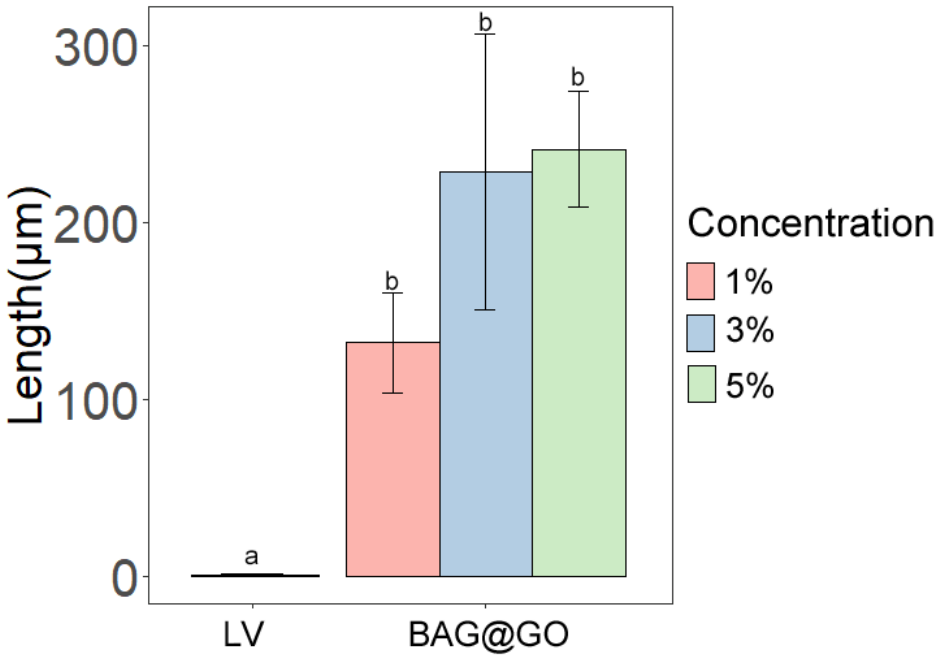

Figure 7. Anti-demineralization length comparison of orthodontic bonding paste containing LV and BAG@GO by Image J analysis. The same alphabet indicates no statistically significant difference between the groups ($p < 0.05$) by Duncan's Multiple Comaprison Test. Error bars were shown ± standard deviation.

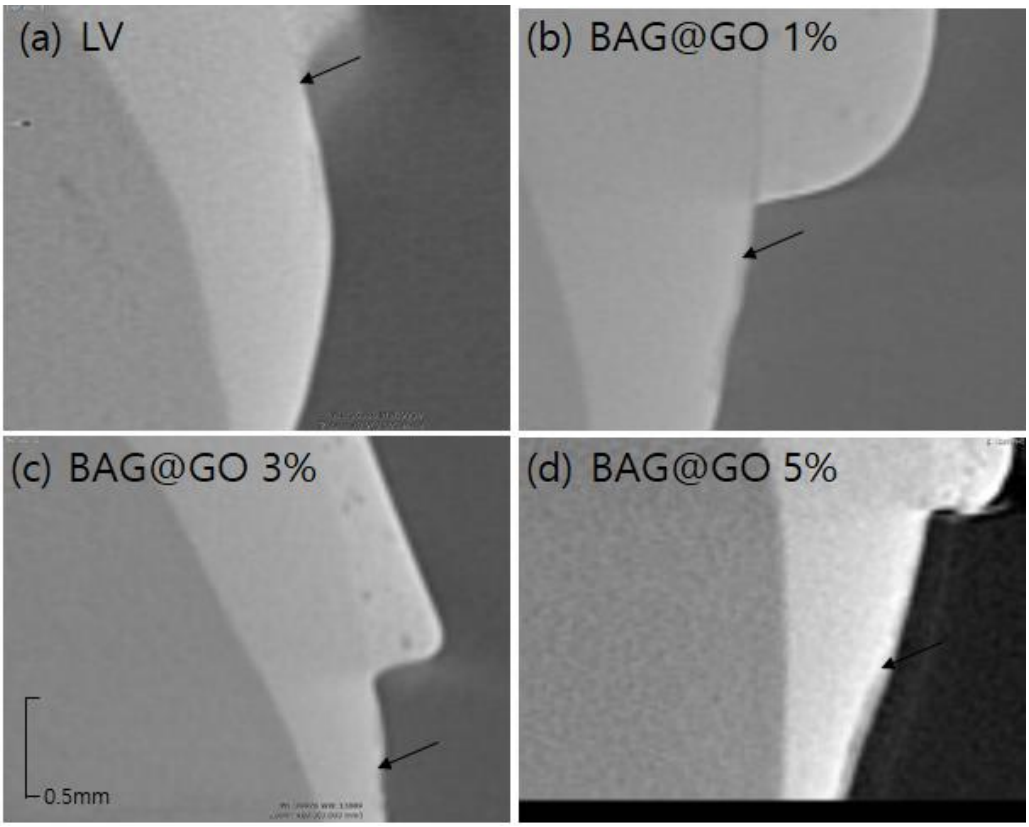

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Figure 8. Anti-demineralization point (black arrow) of the LV and BAG@GO orthodontic bonding adhesive via CBCT. (a) LV, (b) 1 wt.% of BAG@GO, (c) 3 wt.% of BAG@GO, and (d) 5 wt.% of BAG@GO.

4. Discussion

WSLs are side effects of orthodontic treatment that significantly affects one of the most important orthodontic treatment purposes: aesthetics. WSLs preventive treatment that requires patient cooperation is unpredictable, and clinical fluoride application or prosthodontic treatment requires additional expense and chair time, making it difficult for orthodontists to perform effectively. Research is currently targeted at different methods of mixing biomaterials with bonding materials, to prevent WSLs. These biomaterials act as fillers and therefore, do not interfere with the physical properties of the resin adhesive[7-8].

In this study, an orthodontic adhesive with 1 wt.% of BAG@GO showed no statistically significant difference in micro-hardness when compared to existing orthodontic adhesives, but those with 3 wt.% or 5 wt.% of BAG@GO showed a significant increase in micro-hardness. This result corresponds with the results of the research performed by Lv et al; composite with graphene nano sheet and 0.5 wt.% or 1.0 wt.% of HA showed 30–40% increase in microhardness, and PMMA with 0.5, 1.5, 2.0 wt.% of nano-GO showed an increase in Vicker's hardness [9-10]. This is because the stable layer structure of GO acts as an effective filler in the material, subsequently increasing the microhardness.

Shear bond strength of the the LV group showed no statistically significant difference compared with the BAG@GO group, while adhesives with 1 wt.% of BAG@GO showed slight increase in shear bond strength; the increased SBS is due to physical interlocking because BAG or BAG@GO adhesives creates a tough, irregular surface (300 – 400 nm) [10]. The surface irregularity also hinders crack propagation in the material by functioning as an interlocking bridge between cracks. The adhesive group with 5 wt.% of BAG@GO showed lower SBS, but this result was not statistically significant. This may be attributable to a decrease in brightness resulting in a lower curing rate; in clinical use, a longer curing time is necessary when this material is applied.

All sample groups containing BAG@GO showed a statistically significant increase in antibacterial activity, compared with the control group (sterilized water) and the LV group. The 48 hour-group showed higher antibacterial effect than the 24 hour-group, implying higher effectiveness of BAG@GO samples over time. Bioactive glass exerts antibacterial activity by decreasing PO_4, and therefore inhibiting bacterial metabolism, subsequently arresting enamel demineralization and decreasing the incidence of WSLs [11]. GO demonstrates its antibacterial activity via two main mechanisms: by generating reactive oxidative stress [12], GO nanosheet causes damage to the cell membrane and therefore interferes with bacterial metabolic activity [13]; and by trapping and isolating the bacterial cell surface from the environment and thus blocking the membrane activity site [14]. These mechanisms both decrease cell metabolic activity, therefore with time, its antibacterial effect increases. This supports the result that 48 hour-group of BAG@GO shows higher antibacterial activity than 24 hour-group. Research shows that GO is effective against dental pathogens, as well as general bacteria [6, 9].

Chemical anti-demineralization effect through pH cycle was higher in sample groups with BAG@GO than the control group, a higher anti-demineralization effect was observed as the concentration of BAG@GO increased. This is because the chemical anti-demineralization effect is a result of the buffering effect of ions released by BAG, which prevents a decrease in intraoral pH [15].

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The group with 1 wt.% of BAG@GO showed high efficacy, whereas groups with 3 wt.% and 5 wt.% of BAG@GO did not show any statistically significant difference.

The grain size of BAG remains limited because graphene hinders the growth of BAG grain, allowing the grain to have more exposed contact surface with bodily fluids and to release more ions [16-17]. Sample groups with more than 3 wt.% of BAG, however, are less affected by the size of the BAG grains because the difference in the amount of released ions increases.

In conclusion, combining BAG@GO with orthodontic adhesives will decrease WSLs because of the ion-releasing effect of BAG and the antibacterial activity of GO, and will be clinically acceptable considering the results obtained for the cell viability and mechanical properties of the samples. Orthodontic treatment, however, requires more than a year of device application. Therefore, long-term experimental results and in vivo testing in conditions similar to that found in the oral environment will be required.

5. Conclusions

An orthodontic adhesive containing BAG@GO showed antibacterial and anti-demineralization effects, is biologically safe, and exhibits good mechanical properties for clinical use.

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