Evaluation of bonding performance and multi-ion release of S-PRG filler-containing self-adhesive resin composite

Shojiro SHIMIZU1, Hirotomo KOTAKE1, Tomohiro TAKAGAKI1, Kazuya SHINNO2, Shunsuke MIYATA2, Michael F. BURROW3, Masato HOTTA4 and Toru NIKAIDO1

1 Department of Operative Dentistry, Division of Oral Functional Science and Rehabilitation, School of Dentistry, Asahi University, Hozumi 1851, Mizuho, Gifu 501-0296, Japan
2 Department of Research and Development, Shofu Inc., 11 Kamitakamatsu-cho, Fukune, Higashiyaama-ku, Kyoto 605-0983, Japan
3 Faculty of Dentistry, The University of Hong Kong, Prince Philip Dental Hospital, 34 Hospital Road, Pokfulam, Hong Kong SAR, China
4 Asahi University, Hozumi 1851, Mizuho, Gifu 501-0296, Japan
Corresponding author, Tomohiro TAKAGAKI; E-mail: takagaki@dent.asahi-u.ac.jp

The bonding performance of a surface pre-reacted glass ionomer (S-PRG) filler-containing self-adhesive flowable resin composites to enamel and dentin were evaluated using a tensile bond test with thermal cycling. Also, the quantities of various ions released from the materials were measured using ICP atomic emission spectrometry and a fluoride ion electrode. The initial bond strengths of the materials were approximately 6 MPa, and decreased after thermal cycling. The S-PRG filler-containing self-adhesive flowable resin composites materials exhibited much higher ion release compared with the commercial self-adhesive flowable resin composite possibly due to different acidic monomers contained. It was suggested that the S-PRG filler containing self-adhesive flowable resin composites should be limited as a lining material or to restore small cavities in non-stress bearing areas.

Keywords: Surface pre-reacted glass-ionomer filler, Self-adhesive resin composite, Phosphonic acid monomer

INTRODUCTION

The continued development of adhesive and techniques has been remarkable which has enabled clinical procedures using adhesive systems to become simpler and faster. The advantage of using simplified bonding systems is chair-time saving, resulting in reduction of the burden on the patients and errors in procedure, but concerned technical errors for air blow in operations1,2). Simplification of the clinical application of adhesive procedures is especially a major drive for current research and development of dental manufacturers. However, a resin composite restoration commonly accepted as a clinical solution to repair lost tooth structure, it still has limitations of the procedures, which includes the application of an adhesive and filling with resin composite. If a resin composite has a self-adhesive system ability to tooth structure, it will aid the clinician because of further simplification of the procedure and also saves chair-time of the restorations. However, the complete realization of self-adhesive system, so-called “zero-step”, resin composite restoration placement has yet to become successful.

A surface pre-reacted glass ionomer (S-PRG) filler is produced from fluoroboroalumino silicate glass and polyacrylic acid through an acid-base reaction to form a stable glass ionomer phase on glass filler particle surfaces3,4). S-PRG fillers can release and recharge fluoride5,6). Also, the S-PRG filler-containing resinous materials are able to release various ions, such as aluminum (Al3+), boron (BO 33−), fluoride (F−), sodium (Na+), silicon (SiO32−), and strontium (Sr2+)6,7), in neutral and acidic conditions. The S-PRG fillers have been reported to be incorporated in various restorative materials, which demonstrated various effects in caries treatment with regard to oral bacteria8,9). Therefore, various ions released from the restorative materials could be beneficial in controlling root caries, especially around restoration margins10).

Recently, the Shofu (Kyoto, Japan) developed experimental self-adhesive flowable resin composites containing S-PRG fillers. Therefore, the purpose of this study was to evaluate the bonding performance of two experimental S-PRG-containing self-adhesive flowable resin composites to enamel and dentin, and also to measure the release of various ions from these materials. The experimental self-adhesive resin composites were evaluated against commercially available conventional/self-adhesive resin composites and a glass ionomer cement.

MATERIALS AND METHODS

Materials used in this study

The materials used in this study are listed in Table 1. Two experimental S-PRG-containing self-adhesive flowable resin composites; SI-R21701 F10 (high flow type, SI-10) and SI-R21701 F03 (low flow type, SI-03, Shofu) were used. A phosphonic acid monomer is incorporated as an ingredient in the components of SI-10 and SI-03. These materials are already available in the US market as FIT SA F03 and FIT SA F10, respectively. A commercially available self-adhesive flowable resin composite, Fusio™ Liquid Dentin A2 (FL, Pentron Clinical, Orange, CA, USA) and a conventional glass ionomer cement, FX ULTRA (FX, Shofu) were also used in this study. A
| Code   | Brand name       | Manufacturer      | Lot No.    | Components                                                                 | Application                                                                 | TBST* | ICP/F** |
|--------|-------------------|-------------------|------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------|-------|---------|
| SI-10  | SI-R21701 F10     | Shofu, Kyoto, Japan | F10101718N3 | Phosphonic acid monomer, UDMA, HEMA, photoinitiator, S-PRG filler based on fluoroboro aluminosilicate glass, Glass powder, Silica | Dispense a less 0.5 mm increment then leave on the tooth for 20 s prior to light curing for 5 s. Then apply SI with a Luerlock-Tip in layers not exceeding 2 mm. Light cure each layer for 10 s. | +     | +       |
| SI-03  | SI-R21701 F03     | Shofu             | F02111717N2 | Phosphonic acid monomer, UDMA, HEMA, photoinitiator, S-PRG filler based on fluoroboro aluminosilicate glass, Glass powder, Silica |                                                                                   | −     | +       |
| FL     | Fusio™ Liquid Dentin | Pentron Clinical, Orange, CA, USA | 6785689 | 4-MET, UDMA, TEGDMA, HEMA, dimethacrylate resin |                                                                                   | +     | +       |

Conventional Glass ionomer cement

| Code   | Brand name | Manufacturer | Lot No. | Components | Application |
|--------|------------|--------------|---------|------------|-------------|
| FX     | Glass ionomer FX ULTRA | Shofu | Powder: 101603 Liquid: 091739 | Powder: Fluoroalumino silicate glass Liquid: Polyacrylic acid |                                                                                   | +     | −       |

Flowable resin composite

| Code   | Brand name       | Manufacturer | Lot No. | Components                                                                 |
|--------|-------------------|--------------|---------|-----------------------------------------------------------------------------|
| BF     | Beautifil Flow Plus F03 (shade A2) | Shofu         | 91733   | Bis-GMA, TEGDMA, Reaction initiator, S-PRG filler based on fluoroboro aluminosilicate glass, Coloring agent |                                                                                   | −     | +       |

*TBST; tensile bond strength test
**ICP/F; inductively coupled plasma/fluoride ion electrode method

Bis-GMA; bisphenol A diglycidyl ether dimethacrylate, HEMA; 2-hydroxyethyl methacrylate, 4-MET; 4-methacryloxyethyl trimellitic acid, TEGDMA; triethyleneglycol dimethacrylate, UDMA; urethane dimethacrylate
flowable resin composite, Beautifil Flow Plus F03 (BF, Shofu), is a conventional S-PRG-containing flowable resin composite. The materials, SI-10, FL and FX were used for the tensile bond strength test, while SI-10, SI-03, FL and BF were used for measurement of ion release.

**Tensile bond strength test**

The specimen preparation for the tensile bond strength test is illustrated in Fig. 1. This experimental protocol was approved by the Commission for Medical Ethics of Asahi University (authorization number 30036). Non-carious human third molars were stored in a freezer just before use. In order to obtain enamel substrate, the teeth were first embedded in a self-cured acrylic resin (Unifast Clear, GC, Tokyo, Japan). The buccal and lingual enamel surface was then exposed, flattened with a model trimmer and then ground with 600-grit silicon-carbide (SiC) papers to standardize the smear layer and surface roughness. For obtaining dentin substrate (without embedding), the occlusal enamel was removed by means of a water-cooled model trimmer and ground with a 600-grit SiC paper. The adhesive areas of the enamel/dentin substrates were demarcated with a double-sided tape with a 3.0 mm diameter hole. The following bonding procedures were done according to the manufacturers’ instructions (listed in Table 1). For SI-10 and FL, the tip of the nozzle was positioned close to the enamel/dentin surface to apply the material to the adhesive area up to 0.5 mm thick. The applied material was pressed flat with a plastic strip and slide glass, and light cured for 5 s (mode 1 full power, 1,400 mW/cm²) for vertical direction using a light curing unit, Blue LEX Alfa (Yoshida, Tokyo, Japan). The excess material was carefully removed and then a plastic mold (7.0 mm height, 3.0 mm inner diameter) was placed on the cured material. The additional materials were inserted into the mold up to a height of 2 mm and light cured for 10 s. For FX, the powder and the liquid were mixed together and inserted into the same plastic mold for self-adhesive resin composite, using a syringe to a height of 2 mm. After 30 min the bonded specimens were stored in distilled water at 37°C for 24 h. The specimens were divided into two subgroups according to the thermal cycling (TC) test; none (TC0) and 50 cycles (TC50). For the TC test groups, the specimens were subjected to the thermal stress (Tokyo Giken, Tokyo, Japan) between 4 to 60°C with 60 s dwell time at each temperature for 50 cycles. Following this, the tensile bond strength testing was carried out using a universal testing device (Autograph AGS-X, Shimadzu, Kyoto, Japan) at a crosshead speed of 0.5 mm/min.

**Failure mode analysis**

Just after the tensile bond test the debonded specimens were examined for the failure mode using light microscopy (C-FMC 1005317, Nikon, Tokyo, Japan) at 30× magnification. The failure modes were classified into the following three categories: A-adhesive failure at the interface, M-mixed failure, including adhesive failure and cohesive failure in restorative material, C-cohesive failure in glass ionomer cement or resin composite.

**Measurement of ion release**

Test specimens were prepared by placing respective resin pastes individually in ring-shaped molds (15 mm internal diameter, 1 mm height), light-curing the pastes for 3 min using a visible light-curing unit for the dental
laboratory with an extraordinary high light output of 600 W and an effective heat conduction system (Solidilite V, Shofu), and polishing the surface of the cured materials with a 600-grit SiC abrasive paper.

The test specimens were then immersed in 5 mL of 37°C deionized water for 24 h, and subsequently analyzed for the release of various ions released from the test specimens. The ions released from the S-PRG fillers have already been identified in previous studies (i.e., Al\(^{3+}\), BO\(_3\)\(^{-3}\), F\(^{-}\), Na\(^{+}\), SiO\(_3\)\(^{2-}\) and Sr\(^{2+}\)); hence the amounts released of these same ions, except for F\(^{-}\) ion, were calculated using ICP atomic emission spectrometry (ICPS-8000, Shimadzu).

The F\(^{-}\) ion release was measured using a fluoride ion electrode method (fluoride ion electrode: Model 9609BN, Orion Research; pH/ion meter: Model Orion 2115010 Dual Star, Orion Research, Cambridge, MA, USA), together with a total ionic strength adjustment buffer (TISAB III, Orion Research, Espoo, Finland), which was added to the test eluate in the proportion of 0.1 mL of the buffer to 1 mL of the eluate.

The same specimens were immersed in 5 mL of fresh deionized water, and the same test procedure as described above was repeated for up to a total of 4 days to measure cumulative amounts of the respective ions released from the test specimens.

**Statistical analysis**

For the tensile bond test, the measured results were statistically analyzed using the Kruskal-Wallis nonparametric test. The data were subjected to statistical analysis using SPSS (PASW Statistics 23, SPSS, Chicago, IL, USA). The significance level was set at \(p<0.05\).

For the ion measurement, the data were subjected to one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) test of measurement with the significance level set at \(p<0.05\).

**RESULTS**

**Tensile bond strength test**

The mean tensile bond strengths to enamel and dentin are shown in Tables 2 and 3, respectively. For tensile bond strength to enamel (Table 2), there were no significant difference in tensile bond strength among the materials before thermal cycling, and between before and after thermal stress (\(p>0.05\)). The bond strength of FL was significantly lower than that of SI-10 after TC50 (\(p<0.05\)). For tensile bond strength to dentin (Table 3), the bond strength of FX was significantly lower than that of SI-10 (\(p<0.05\), however, there were no significant differences between SI-10 and FL and between FL and FX, respectively before thermal test (\(p>0.05\)). No differences among the three materials were observed after TC50 (\(p>0.05\). The bond strengths of SI-10 and FL significantly decreased after TC50 (\(p<0.05\), however, no difference for FX was seen (\(p>0.05\)).

**Failure mode analysis**

The results of the fracture mode analysis of the debonded specimens are summarized in Table 4. In addition, representative images of the debonded specimens of SI-10 to enamel and dentin are shown in Figs. 2 and 4.

**Table 2** Tensile bond strengths of the restorative materials to enamel (MPa)

| TC  | Mean±SD | Range  | Mean±SD | Range  |
|-----|---------|--------|---------|--------|
| SI-10 | 6.5±1.7 | 4.1–9.6 | 5.4±2.0 \( ^{a} \) | 2.0–7.9 |
| FL     | 3.9±1.8 | 1.9–6.8 | 1.6±1.1 \( ^{a} \) | 0.7–3.9 |
| FX     | 4.3±0.9 | 3.3–5.5 | 4.4±1.5 | 3.5–6.3 |

Mean±SD (n=10)

Means followed by the same superscript letters were statistically significantly different (Kruskal-Wallis test, \(p<0.05\)).

**Table 3** Tensile bond strengths of the restorative materials to dentin (MPa)

| TC  | Mean±SD | Range  | Mean±SD | Range  |
|-----|---------|--------|---------|--------|
| SI-10 | 7.3±2.2 \( ^{bc} \) | 4.6–12.9 | 3.4±1.7 \( ^{A} \) | 1.8–7.2 |
| FL     | 4.7±1.2 \( ^{b} \) | 3.5–7.5 | 2.5±1.0 \( ^{B} \) | 1.6–4.1 |
| FX     | 3.6±1.0 \( ^{c} \) | 2.0–5.4 | 2.4±0.7 | 1.7–3.9 |

Mean±SD (n=10)

Means followed by the same superscript letters were statistically significantly different (Kruskal-Wallis test, \(p<0.05\)).

Upper case letters indicated the significant difference among materials (horizontal line) and lower case letters indicated the significant difference (vertical lines) before and after TC.
Table 4 Fracture mode distribution of the debonded specimens after tensile bond strength testing

| Code | Enamel | Dentin |
|------|--------|--------|
| SI-10 | TC0    | 10/0/0  | 10/0/0  |
|      | TC50   | 10/0/0  | 10/0/0  |
| FL   | TC0    | 8/0/2   | 8/0/2   |
|      | TC50   | 10/0/0  | 10/0/0  |
| FX   | TC0    | 2/8/2   | 2/5/3   |
|      | TC50   | 0/10/0  | 2/4/4   |

n=10, A/M/C: A-adhesive failure at the interface, M-mixed failure, including adhesive failure and cohesive failure in restorative material, C-cohesive failure

Table 5 Quantity of each ion released (ppm) from resin composites

| Material | F    | Na   | B    | Si    | Sr    | Al    |
|----------|------|------|------|-------|-------|-------|
| SI-03    | 0.91±0.03 <sup>a</sup> | 4.83±0.53 <sup>a</sup> | 3.42±0.46 <sup>a</sup> | 1.67±0.15 <sup>a</sup> | 0.59±0.04 <sup>a</sup> | 0.03±0.00 <sup>a</sup> |
| SI-10    | 0.88±0.04 <sup>a</sup> | 4.74±0.62 <sup>a</sup> | 3.75±0.29 <sup>a</sup> | 1.33±0.13 <sup>b</sup> | 0.52±0.07 <sup>a</sup> | 0.03±0.01 <sup>a</sup> |
| BF       | 1.19±0.11 <sup>b</sup> | 0.83±0.11 <sup>b</sup> | 2.35±0.62 <sup>b</sup> | 1.08±0.10 <sup>b</sup> | 2.58±0.46 <sup>b</sup> | 0.10±0.02 <sup>b</sup> |
| FL       | 0.07±0.00 <sup>c</sup> | 0.33±0.03 <sup>b</sup> | 1.39±0.16 <sup>c</sup> | 0.51±0.06 <sup>c</sup> | 0.00±0.00 <sup>c</sup> | 0.00±0.00 <sup>c</sup> |

Mean±SD (n=5)

Means followed by the different superscript letters indicated significant differences among materials (ANOVA and Tukey’s HSD test, p<0.05).

Fig. 2 Representative microscopic images of the debonded specimens of SI-10 after TC0. Adhesive failure at the interface was mainly observed in the debonded specimens after bonding test to enamel (a and b) and dentin (c and d); enamel side (a) and the composite side (b), and dentin side (c) and the composite side (d).

DISCUSSION

Adhesive resins contain functional monomers, which can be defined as radical polymerizable monomers bearing both hydrophilic and hydrophobic moieties in the structure. Carboxylic acid (-COOH) and phosphoric acid groups [-O-P(=O)(OH)₂] are widely adopted as the hydrophilic acidic moieties of functional monomers. Ikemura et al. synthesized phosphonic acid monomers...
with a hydrophilic moiety [-P(=O)(OH)₂] that appeared to be hydrolytically stable in self-etching primers of an adhesive⁴³. Self-adhesive flowable resin composites contain this acidic monomer as a part of its resin matrix. An interaction between the acidic monomer and the tooth surface through ionic bonding is thought to provide adhesion between the self-adhesive resin composite and tooth structure. The self-adhesive resin composites, SI-03 and SI-10 contain a phosphonic acid monomer, while FL contains 4-methacryloxyethyl trimetellitic acid (4-MET) which has a carboxylic acid group in its structure.

For the tensile bond strength testing, the adhesive area of 3 mm diameter was adopted in this study because of weak bonding resulted in pre-testing failure expected for the tested materials. Thermal stress of the bonded specimens was also limited to 50 cycles to differentiate the bonding performance of each material. As shown in the results in the fracture mode analysis (Table 4 and Figs. 2, 3), adhesive failure at the interface between the restorative material and the tooth substrate was the main failure mode for SI-10 and FL. On the other hand, the failure mode of FX showed cohesive failure within the GIC and also mixed failure. That means glass ionomer cement has more potential to bond to tooth substrates, however, more brittle than the other composite materials.

For the tensile bond strength to enamel (Table 2), there were no differences among SI-10, FL and FX before thermal cycling, however, the bond strength of FL was significantly lower than that of SI-10 after TC50, which may be due to the different functional monomers used in SI-10 and FL. Wajdowicz et al. measured the shear bond strength to ground enamel using two commercially available self-adhesive resin composites, Vertise Flow (Kerr Dental, Orange, CA, USA) and FL, demonstrating results similar to that of the current study, which were significantly lower than that of a flowable resin composite bonded with an etch and rinse adhesive system⁴⁰. For the tensile bond strength to dentin (Table 3), the bond strength of SI-10 was higher than that of the glass ionomer cement (FX). However, the bond strengths of SI-10 and FL decreased after TC50. The hydrophilic methacrylate monomer, 2-hydroxyethyl methacrylate (HEMA) contained in SI-10 and FL may have influenced this outcome. HEMA is able to increase the wettability of the self-adhesive resin composites to tooth substrates, but also leads to a decrease in the physical properties of the materials after polymerization because of increased water sorption and water solubility of poly-HEMA which may result in possible internal crack formation¹⁵,¹⁶. In this study, HEMA content in SI-10 and FL increased the wettability to enamel to some extent, however not enough to dentin.

The S-PRG filler-containing materials showed the potential to release various ions, such as F⁻, Al³⁺, BO₃³⁻, Na⁺, SiO₃²⁻, Sr²⁺, ⁷,⁸. It has been reported that S-PRG fillers have a good buffering capacity, bringing the pH of a surrounding acidic environment to a weak alkaline environment when it comes into contact with water or an acidic solution⁷. It has also been reported that F⁻ and Sr²⁺ ions released from S-PRG fillers have the potential to improve the acid resistance of teeth by converting hydroxyapatite to fluorapatite⁸ and strontium-apatite⁸. Fujimoto et al. reported that the amount of ions released was influenced by the mixing ratio of water to S-PRG filler⁸. The ion-releasing S-PRG-filler contained in the self-adhesive flowable resin composites (SI-03 and SI-10) released various ions, which derived from the filler exposed to the surface, into the intraoral environment. Since the acidic monomer is ionized in the presence of water to maintain its acidity, the behavior of the multi-ion release from the S-PRG filler might be influenced by the functional monomer in the ion-releasing self-adhesive flowable resin composites (SI-03 and SI-10). The current results (Table 5) demonstrated that SI-03 and SI-10 exhibited much higher ion release compared with the commercial self-adhesive flowable resin composite (FL). However, SI-03 and SI-10 released lower amounts of Sr and Al ions compared with the commercial S-PRG-filler-containing flowable resin composite (BF). This might be due to the influence of the acidic monomer in SI-03 and SI-10 interacting with cations (Sr and Al), which delayed these cations passing through the resin matrix. On the other hand, in order to improve the ion release from the S-PRG fillers in SI-03 and SI-10, a manufacturing method to allow increased amounts of ions to be trapped in the glass-ionomer phase on the surface of the S-PRG filler has been developed. This may have resulted in the higher amounts of Na, B and Si released from SI-03 and SI-10 compared to BF.
Zan et al. assessed demineralization around the three different types of restorations; fluoride-free composite (Clearfil SE Bond and Clearfil Majesty, Kuraray Noritake Dental, Tokyo, Japan), fluoride-release composite (FL-Bond II and Beautifil, Shofu) and glass ionomer cement (Fuji IX, GC). The inhibition of demineralization around the restorations were material dependent. The results suggested that larger quantities of fluoride release from a restorative material could provide greater acid resistance against demineralization and also allow remineralization to occur. Iida et al. examined the ultra-structure of the adhesive-dentin interface after acid-base treatment using a two-step self-etch adhesive system, FL-Bond II. FL-Bond II contains S-PRG fillers in the adhesive to have potential to release various ions. It was shown to lead to the formation of a thick acid-base resistant zone (ABRZ) under the hybrid layer, which is important to prevent recurrent caries around a restoration.

There are some limitations for this category of restorative materials to be used clinically as the final selective materials. However, the self-adhesive flowable resin composite comes in direct contact with the tooth structure without an intervening bonding layer, which is a big advantage for such restorative materials as they may be able to release various ions more directly into the tooth structure. Various ions and fluoride release are thought to be beneficial for dentin protection against demineralization. Therefore, the indication for self-adhesive flowable resin composites should be limited to that of a liner for deep cavities and small cavity away from stress bearing areas especially in child and special needs patients.

CONCLUSION
The S-PRG filler-containing self-adhesive flowable resin composites demonstrated a potential to bond to tooth structures and revealed the release various ions from these materials. Therefore, the clinical indications for the self-adhesive flowable resin composites should be limited to a lining or small cavity in a non-stress bearing area.

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REFERENCES
1) Van Meerbeek B, Peumans M, Poitevin A, Mine A, Van Ende A, De Munck J. Relationship between bond strength tests and clinical outcomes. Dent Mater 2010; 26: e100-121.
2) Van Meerbeek B, Yoshihara K, Yoshida Y, Mine A, De Munck J, Van Landuyt K. State of the art of self-etch adhesives. Dent Mater 2011; 27: 17-28.
3) Mukai Y, Tomiyama K, Shiyai T, Kmiiko J, Fujino F, Teranaka T. Formation of inhibition layers with a newly developed fluoride-releasing all-in-one adhesive. Dent Mater J 2005; 24: 172-177.
4) Ikemura K, Tay FR, Kouro Y, Endo T, Yoshiyama M, Miyai K, et al. Optimizing filler content in an adhesive system containing pre-reacted glass-ionomer fillers. Dent Mater 2003; 19: 137-146.
5) Kitayama S, Nikaido T, Ikeda M, Foxton RM, Tagami J. Enamel bonding of self-etch and phosphoric acid-etch orthodontic adhesive systems. Dent Mater J 2007; 26: 135-143.
6) Kamijo K, Mukai Y, Tominaga T, Iwaya I, Fujino F, Hirata Y, et al. Fluoride release and recharge characteristics of denture base resins containing surface pre-reacted glass-ionomer filler. Dent Mater J 2009; 28: 227-233.
7) Ito S, Iijima M, Hashimoto M, Tsukamoto N, Mizoguchi I, Saito T. Effects of surface pre-reacted glass-ionomer filler on mineral induction by phosphoprotein. J Dent 2011; 39: 72-79.
8) Fujimoto Y, Iwasa M, Murayama R, Miyazaki M, Nagafuji A, Nakatsuka T. Detection of ions released from S-PRG fillers and their modulation effect. Dent Mater J 2010; 29: 392-397.
9) Saku S, Kotake H, Scougall-Vilchis RD, Ohashi S, Hotta M, Horieishi S, et al. Antibacterial activity of composite resin with glass-ionomer filler particles. Dent Mater J 2010; 29: 193-198.
10) Hotta M, Morikawa T, Yamura D, Kusakabe S. Adherence of Streptococcus sanguis and Streptococcus mutans to saliva-coated S-PRG resin blocks. Dent Mater J 2014; 33: 261-267.
11) Ma S, Imazato S, Chen JH, Mayanagi G, Takahashi N, Ishimoto T, et al. Effects of a coating resin containing S-PRG filler to prevent demineralization of root surfaces. Dent Mater J 2012; 31: 1-7.
12) Nomura R, Morita Y, Matayoshi S, Nakano K. Inhibitory effect of surface pre-reacted glass-ionomer (S-PRG) eluate against adhesion and colonization by Streptococcus mutans. Scientific Reports 2018; 8: 5056.
13) Ikemura K, Tay FR, Nishyama N, Pashley DH, Endo T. Design of new phosphonic acid monomers for dental adhesives —synthesis of (meth)acryloxyalkyl 3-phosphonomopropionates and evaluation of their adhesion-promoting functions. Dent Mater J 2013; 32: 135-142.
14) Wajdowicz MH, Vandewalle KS, Meats MN, Shear bond strength of new self-adhesive flowable composite resins. Gen Dent 2012; 60: e104-108.
15) Wei YJ, Silikas N, Zhang ZT, Watts DC. Diffusion and concurrent solubility of self-adhering and new resin-matrix composites during water sorption/desorption cycles. Dent Mater 2011; 27: 195-205.
16) Wei YJ, Silikas N, Zhang ZT, Watts DC. Hygroscopic dimensional changes of self-adhering and new resin-matrix composites during water sorption/desorption cycles. Dent Mater 2011; 27: 259-266.
17) Kaga M, Kakuda S, Ida Y, Teshima H, Hashimoto M, Endo K, et al. Inhibition of enamel demineralization by buffering effect of S-PRG filler-containing dental sealant. Eur J Oral Sci 2014; 122: 78-83.
18) Iijima Y, Koumourides T. Fluoride incorporation into and retention in remineralized enamel. J Dent Res 1989; 68: 1289-1292.
19) Dedhiya MG, Young F, Higuchi WI. Mechanism for the retardation of the acid dissolution rate of hydroxyapatite by strontium. J Dent Res 1975; 52: 1097-1109.
20) Zan KW, Nakamura K, Hamba H, Sadr A, Nikaido T, Tagami J. Micro-computed tomography assessment of root dentin around fluoride-releasing restorations after demineralization/remineralization. Eur J Oral Sci 2018; 126: 389-399.
21) Iida Y, Nikaido T, Kitayama S, Takagaki T, Inoue G, Ikeda M, et al. Evaluation of dentin bonding performance and acid-base resistance of the interface of two-step self-etching adhesive systems. Dent Mater J 2009; 28: 493-500.