



## An *in vitro* assessment of biaxial flexural strength, degree of monomer conversion, color stability, and ion release in provisional restorations containing Sr-bioactive glass nanoparticles

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### ABSTRACT

This study examined the mechanical and chemical properties of an experimental provisional restoration containing Sr-bioactive glass nanoparticles (Sr-BGNPs) compared to commercial provisional materials. The experimental material (TempS10) contained dimethacrylate monomers with added 10 wt% Sr-BGNPs. The degree of monomer conversion (DC) of self-curing ( $n = 5$ ), biaxial flexural strength (BFS)/modulus (BFM) ( $n = 5$ ), and color changes ( $\Delta E^*_{00}$ ) of materials in red wine ( $n = 5$ ) were determined. Additionally, ion release (Ca, P, and Sr) in water at 2 weeks was examined ( $n = 3$ ). The commercial materials tested included polymethyl methacrylate-based provisional material (Unifast) and bis-acrylic materials (Protemp4 and Cooltemp). TempS10 exhibited a comparable degree of monomer conversion (49%) to that of Protemp4 (60%) and Cooltemp (54%) ( $p > 0.05$ ). The DC of Unifast (81%) was significantly higher than that of other materials ( $p < 0.05$ ). TempS10 showed a BFS (126 MPa) similar to Cooltemp (102 MPa) and Unifast (123 MPa), but lower than Protemp4 (194 MPa). The immersion time for 2 weeks exhibited no detrimental effect on the strength and modulus of all materials. The highest  $\Delta E^*_{00}$  at 24 h and 2 weeks was observed with TempS10, followed by Cooltemp, Unifast, and Protemp4. Only TempS10 showed a detectable amount of Ca (0.69 ppm), P (0.12 ppm), and Sr (3.01 ppm). The experimental provisional resin restoration containing Sr-BGNPs demonstrated polymerization and strength comparable to those of bis-acryl provisional restorations but with the added benefit of ion-releasing properties. However, the experimental material demonstrated unsatisfactory color stability.

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## Introduction

The temporization step with provisional dental restorations is the crucial step in fixed prosthodontic treatments. The most commonly used provisional materials can be divided according to the main resin monomers, such as auto-polymerizing polymethylmethacrylate (PMMA) and bis-acryl composites, such as bisphenol A-glycidyl dimethacrylate (Bis-GMA) and urethane di-methacrylate (UDMA) based materials [1]. The major concern of PMMA is the risk of toxic monomer release and its exothermic reaction during the polymerization [2–4], which could potentially induce inflammation of the pulp-dentin complex. Currently, Bis-GMA-based provisional materials are

widely used due to their ease of placement and high mechanical strength. The concern with Bis-GMA based provisional materials is the risk of contamination with Bisphenol A (BPA), which could cause health concerns related to estrogenic effects [5]. UDMA is commonly used as an alternative base monomer to Bis-GMA. Another potential benefit of using UDMA as the base monomer could be the increase in the degree of monomer conversion for the material [6].

The placement of provisional restorations may require a long temporization period, such as for implant placement. The provisional materials that exhibited an unsatisfactory appearance upon exposure

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to colorants agents may also reduce the patient's comfort [7]. The roughness and low marginal seal of provisional restoration, compared to permanent restorations, may additionally promote bacterial adhesion [8]. This may subsequently compromise the treatment outcome. For patients at high risk for developing periodontal diseases or secondary caries, provisional materials with remineralizing or antibacterial actions may be preferred.

Various ion-releasing fillers that could potentially enhance antibacterial and remineralizing actions for resin-based dental composites have been reported. Bioactive glass is the commonly used additives to enable both remineralizing and antibacterial actions [9, 10]. The previous studies showed that the addition of Sr-bioactive glass promoted the release of essential elements for mineralizing actions such as Ca, P, and Sr [11–13]. A study also reported that Sr inhibited the growth and reproduction, synthesis of cell walls, cell metabolism, and chromosomal replication of bacteria [14]. It was demonstrated that the composites containing bioactive glass enhanced the precipitation of calcium phosphates to a demineralized dentin [15]. Furthermore, the release of ions or particles could inhibit the growth of pathogenic oral microorganisms without causing serious cytotoxic effects [16–18]. However, the addition of the bioactive glass at high concentration demonstrated the negative effects on the mechanical and physical properties of the materials [19].

This study prepared experimental UDMA-based provisional dental restoration containing Sr-bioactive glass nanoparticles (Sr-BGNPs). The objective of this study was to compare the mechanical/physical properties of the experimental material with commercial provisional materials. The null hypothesis was that the degree of monomer conversion, biaxial flexural strength/modulus, color stability, and ion release of the experimental material should not differ significantly from the commercial materials.

## Materials and methods

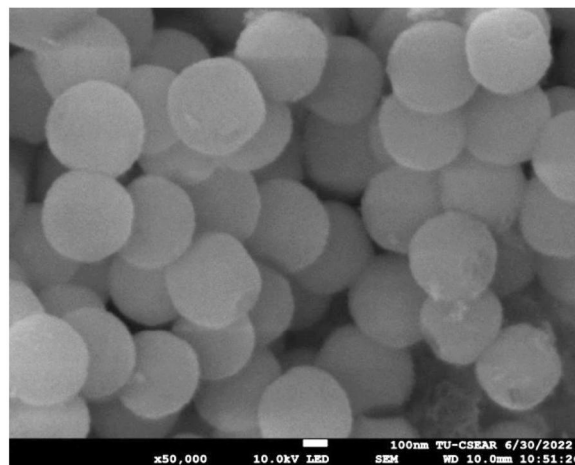
### *Preparation of experimental provisional restoration (TempS10)*

Sr-bioactive glass nanoparticles (Sr-BGNPs) were produced by the sol-gel process. The detail for preparing the particles was provided in the previous study [11]. Briefly, silica nanoparticles were synthesized, followed by ion incorporation using a post-functionalization process. Then, the particles were doped with calcium

(Ca) and strontium (Sr) through the addition of 3.97 g of calcium nitrate tetrahydrate (Sigma-Aldrich, St. Louis, MO, USA) and 10.67 g strontium nitrate (Sigma-Aldrich, St. Louis, MO, USA) at a nominal Si:Ca:Sr molar ratio of 1:0.5:1.5. A heat treatment process at 680 °C (holding time of 3 h) was used to dope the glass particles with Ca and Sr. The elemental composition of the obtained Sr-BGNPs was 81.0 mol% SiO<sub>2</sub>, 14.2 mol% CaO, and 4.8 mol% SrO. The diameter of the particles from the scanning electron microscope (SEM) image was approximately 200–300 nm (Figure 1).

The monomer phase of the experimental provisional material (Table 1) contained 70 wt% urethane dimethacrylate (UDMA, Sigma-Aldrich, St. Louis, MO, USA), 22 wt% triethylene glycol dimethacrylate (TEGDMA, Sigma-Aldrich, St. Louis, MO, USA), 3 wt% 2-hydroxyethyl methacrylate (HEMA, Sigma-Aldrich, St. Louis, MO, USA), 3 wt% 10-MDP (10-methacryloyloxydecyl dihydrogen phosphate, Watson International, Jiangsu, China), and 1 wt% CQ (camphorquinone, Sigma-Aldrich, St. Louis, MO, USA). The initiator and activator paste contained 1 wt% BPO (benzoyl peroxide, Sigma-Aldrich, St. Louis, MO, USA) and 1 wt% DMPT (N-dimethyl-p-toluidine, Sigma-Aldrich, St. Louis, MO, USA), respectively.

The powder phase contained boroaluminosilicate glass (50 nm, 0.7 μm, and 7 μm in diameter, Esstech, Essington, PA, USA) with added 10 wt% Sr-BGNPs. The decision to use 10 wt% was based on the outcomes of similar composite formulations used for preparing core build-up materials [20]. The study demonstrated that adding 10 wt% Sr-BGNPs resulted in superior ion release but with acceptable strength



**Figure 1.** SEM image of Sr-bioactive glass nanoparticles (Sr-BGNPs).

**Table 1.** Composition of commercial materials.

Material	Composition	Lot number	Manufacturer
Experimental material (TempS10)	UDMA, TEGDMA, HEMA, 10-MDP, CQ, BPO, DMPT, borosilicate glass, Sr-bioactive glass nanoparticles	–	–
Protemp4	Ethoxylate bisphenol-A dimethacrylate, silane treated, reaction product of 1,6-diisocyanatohexane with 2-[(2-methacryloyl)ethyl]6-hydroxyhexanone and 2-hydroxyethyl methacrylate, ethanol, 2,2'-[(1-methylethylidene)bis(4,1-phenyleneoxy)]bis-diacetate, benzyl-phenyl-barbituric acid, silane treated silica	7359611	3M ESPE, St. Paul, MN, USA
Cool Temp NATURAL (Cooltemp)	UDMA, diallyl phthalate, Trimethylolpropane triacrylate	L38442	COLTENE, Altstätten, Switzerland
Unifast Trad (Unifast)	<i>Powder:</i> ethyl-methyl methacrylate monomer, polymethylmethacrylate, barbituric acid derivative, organic copper compound, pigments <i>Liquid:</i> methyl methacrylate, N,N-dimethyl-p-toluidine trimethylolpropane, ethylene glycol dimethacrylate	2011171 (powder) 2006031 (liquid)	GC, Tokyo, Japan

compared to formulations containing 5 wt% Sr-BGNPs.

The initiator paste (contained BP) and activator paste (contained DMPT) were prepared using the powder-to-liquid ratio of 1.7:1 (mass ratio). They were loaded into a double-barrel syringe (medmix Switzerland AG, Haag, Switzerland). The pastes were mixed through a mixing tip with a dispenser. The commercial materials were used as the comparisons (Table 1).

### Assessment of degree of monomer conversion

The degree of monomer conversion ( $n=5$ ) was determined using attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR, Nicolet iS5, Thermo Fisher Scientific, Waltham, MA, USA). The materials were placed on the metal ring (1 mm in thickness and 10 mm in diameter) over the ATR diamond and covered with an acetate sheet. They were covered by a metal plate to prevent exposure to light. The FTIR spectra from 400 to  $400\text{ cm}^{-1}$  were recorded from the bottom surface for 10 min. The test was conducted at room temperature ( $25 \pm 1^\circ\text{C}$ ). DC was calculated using the following equation.

$$\text{DC} = \frac{100(\Delta A_0 - \Delta A_t)}{\Delta A_0} \quad (1)$$

where  $\Delta A_0$  and  $\Delta A_t$  are the height of the peak at  $1320\text{ cm}^{-1}$  (C-O of methacrylate group) [21] above the background level at  $1335\text{ cm}^{-1}$  before curing and at time  $t$ , respectively. The DC was then calculated through the linear extrapolation of late-time DC data versus the inverse of time as it approaches zero (as the inverse of zero is infinity) [22].

### Assessment of biaxial flexural strength (BFS) and modulus (BFM)

BFS and BFM of all materials ( $n=5$ ) were determined under a ball-on-ring testing jig with a mechanical testing frame (AGSX, Shimadzu, Kyoto, Japan). Firstly, disc specimens were prepared according to the protocol of the previous study. The specimens were immersed in 10 ml of deionized water for 24 and 2 weeks in an incubator ( $37^\circ\text{C}$ ). Then, the specimens were placed on the jig under the testing frame. The load cell and crosshead speed for the test were 500 N and 1 mm/min, respectively. The fracture load was recorded (N). The BFS and BFM were calculated using the equation 2 and 3, respectively.

$$\text{BFS} = \frac{F}{d^2} \left\{ (1 + \nu) \left[ 0.485 \ln \left( \frac{r}{d} \right) + 0.52 \right] + 0.48 \right\} \quad (2)$$

$$\text{BFM} = \left( \frac{\Delta H}{\Delta W_c} \right) \times \left( \frac{\beta_c d^2}{q^3} \right) \quad (3)$$

where  $F$  refers to the maximum load (N),  $d$  is the specimen's thickness (m),  $r$  is the radius of circular support (m),  $\nu$  is Poisson's ratio (0.3) [23, 24],  $\frac{\Delta H}{\Delta W_c}$  is the rate of change of load with regard to central deflection (N/m),  $\beta_c$  is the center deflection junction (0.5024) [25], and  $q$  is the ratio of support radius to the radius of the disc. The method for calculating  $\beta_c$  was provided in the previous study [25]. The fracture surface of the representative specimen from each material was sputter-coated with Au (Q150R ES, Quorum Technologies, East Sussex, UK) using a current of 23 mA for 45 s. The fracture surface was then examined under SEM (JSM 7800F, JEOL, Tokyo, Japan).

### Assessment of color stability ( $\Delta E^*_{00}$ )

Disc specimens (1 mm thick and 10 mm in diameter) were prepared as described above ( $n=5$ ). The color stability after immersion in red wine was determined using digital spectrophotometry (Easysshade V, VITA Zahnfabrik, Bad Säckingen, Germany) according to a previous study. The color of the specimens was determined before and after being immersed in red wine for 24 h and 2 weeks. The measurement was performed under the luminance of approximately 1,000 Lux over the grey background. The CIELAB coordinates (CIE  $L^*$ ,  $a^*$ ,  $b^*$ ,  $C^*$ , and  $h^\circ$ ) were recorded.  $L^*$ ,  $a^*$ , and  $b^*$  are lightness and values on the red–green and yellow–blue axes, respectively.  $C^*$  and  $h^\circ$  are the chroma and hue angle, respectively. The color change or color stability ( $\Delta E^*_{00}$ ) upon immersion before and after immersion in red wine was calculated using the CIEDE2000 formula (equation 4). The complete formulae were provided in a previous study [26].

$$\Delta E^*_{00} = \left[ \left( \frac{\Delta L'}{K_L S_L} \right) + \left( \frac{\Delta C'}{K_C S_C} \right) + \left( \frac{\Delta H'}{K_H S_H} \right) + R_T \left( \frac{\Delta C'}{K_C S_C} \right) \left( \frac{\Delta H'}{K_H S_H} \right) \right]^{1/2} \quad (4)$$

where  $\Delta L'$ ,  $\Delta C'$ , and  $\Delta H'$  represent the differences in lightness, chroma, and hue, respectively, before and after immersion.  $R_T$  represents a rotation function related to the interaction between the chroma and hue differences in the blue region. Additionally,  $S_L$ ,  $S_C$ , and  $S_H$  are weighting functions, and  $K_L$ ,  $K_C$ ,  $K_H$  are the correction terms for experimental conditions.

### Assessment of ion release

Disc specimens were prepared ( $n=3$ ). They were immersed in 5 ml of deionized water for 4 weeks. Then, the storage solution was collected and mixed with 2 vol% nitric acid. Inductively coupled plasma-optical emission spectrometry (ICP-OES; Optima 8300, PerkinElmer, Singapore) was used to analyze the elemental composition in the solution. The standards for Ca (317.9 nm), P (213.6 nm), and Sr (460.7 nm) were performed using the Environmental standard 26 components (CPAchem, Bogomilovo, Bulgaria). The detection range of Ca, P, and Sr were 0.1–10 ppm, 0.1–10 ppm, and 0.1–50 ppm, respectively.

### Statistical analysis

Data were analyzed with Prism 10 for macOS (GraphPad Software, Boston, MA, USA). Values present in the current study are mean and 95% confidence interval (CI). The normality of data was determined using the Shapiro-Wilk test. Then, data were compared using one-way ANOVA followed by Tukey's test. The significance level was set at  $p=0.05$ . Power analysis was performed using G\*Power version 3.1.9.6 (Heinrich-Heine-Universität Düsseldorf, Dusseldorf, Denmark) to estimate the sample size required by each test. It was estimated that a sample size of  $n=5$  should exhibit power  $> 0.95$  at alpha = 0.05 for One-way ANOVA.

## Results

### Degree of monomer conversion

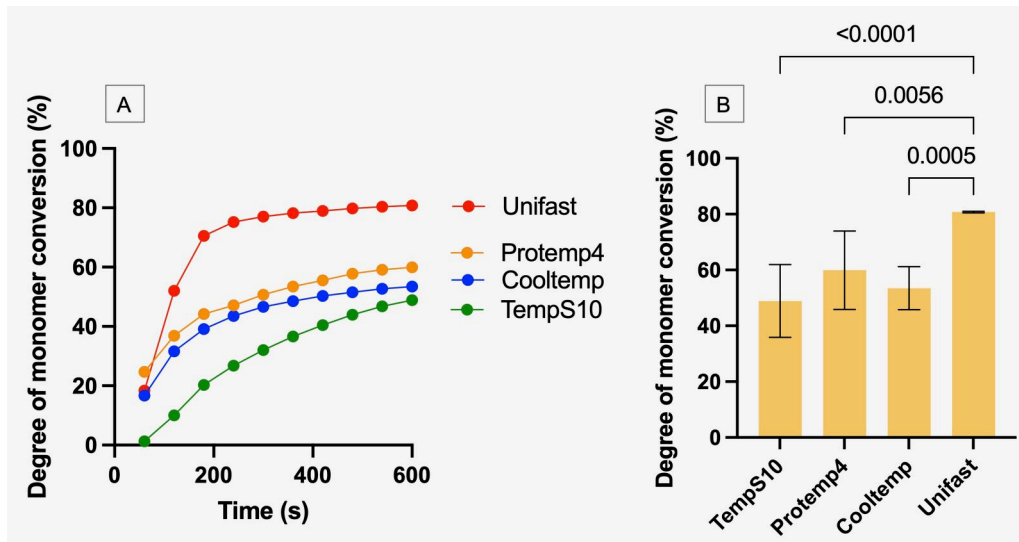
The rapid increase in DC was observed with Unifast, followed by Protemp 4, Cooltemp, and TempS10 (Figure 2A). The calculated DC at the late time of TempS10 ( $48.9 \pm 9.2$ ), Protemp4 ( $60.0 \pm 9.9$ ), and Cooltemp ( $53.4 \pm 5.4$ ) were comparable ( $p > 0.05$ ) (Figure 2B). Unifast exhibited the highest DC ( $80.8 \pm 0.2\%$ ), which was significantly higher than TempS10, Protemp4, and Cooltemp ( $p < 0.05$ ).

### Biaxial flexural strength (BFS) and modulus of elasticity (BFM)

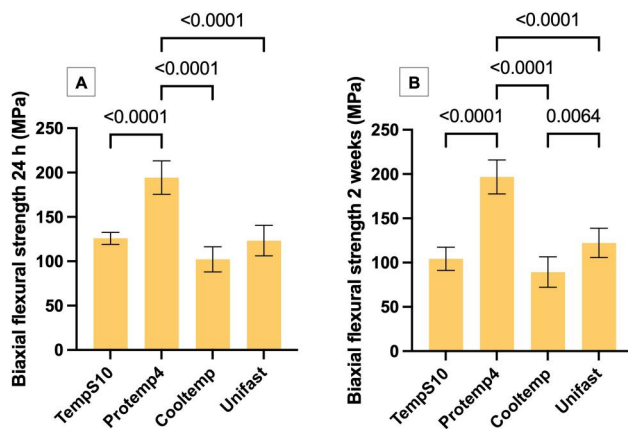
The highest BFS at 24 h was detected from Protemp4 ( $194 \pm 17$  MPa) (Figure 3A), which was significantly higher than that of TempS10 ( $126 \pm 6$  MPa) ( $p < 0.01$ ), Cooltemp ( $102 \pm 12$  MPa) ( $p < 0.01$ ), and Unifast ( $123 \pm 15$  MPa) ( $p < 0.01$ ). The BFS of TempS10 was comparable to that of Cooltemp and Unifast ( $p > 0.05$ ). The BFS at 2 weeks of all materials was comparable to the value at 24 h ( $p > 0.05$ ) (Figure 3B). The higher BFS after immersion in water for 2 weeks was obtained from Protemp4 ( $196 \pm 14$  MPa) followed by Unifast ( $122 \pm 12$  MPa), ProtempS10 ( $104 \pm 9$  MPa), and Cooltemp ( $89 \pm 12$  MPa), respectively.

For BFM at 24 h, the highest modulus was observed with TempS10 ( $2.7 \pm 0.2$  GPa), which was significantly higher than that of Protemp4 ( $1.9 \pm 0.4$  GPa), Cooltemp ( $1.3 \pm 0.1$  GPa), and Unifast ( $1.3 \pm 0.4$  GPa) ( $p < 0.05$ ) (Figure 4A). Furthermore, no significant difference between the BFM of each material at 24 h and 2 weeks was detected ( $p > 0.05$ ). The highest BFM at 2 weeks was observed with





**Figure 2.** (A) DC of all Materials upon time for 600 s. (B) The extrapolated late-time DC of all materials. Lines indicate  $p < 0.05$ .

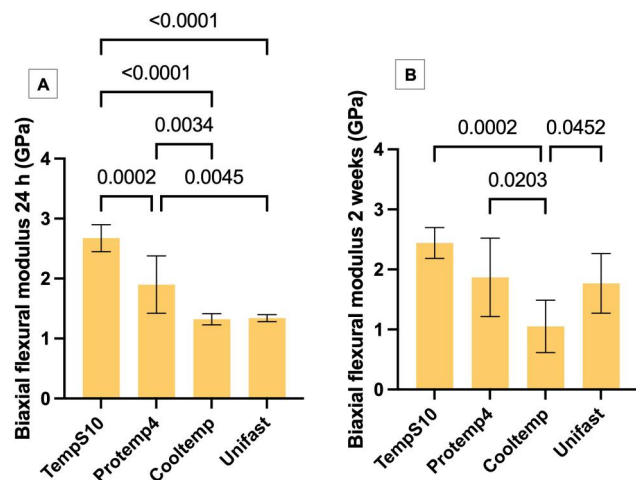


**Figure 3.** Biaxial flexural strength (BFS) of all Materials after immersion in deionized water for (A) 24 h or (B) 2 weeks. Error bars are 95% CI ( $n = 5$ ). Lines indicate  $p < 0.05$ .

TempS10 ( $2.4 \pm 0.2$  GPa), followed by Protemp4 ( $1.9 \pm 0.5$  GPa), Unifast ( $1.8 \pm 0.4$  GPa), and Cooltemp ( $1.1 \pm 0.3$  GPa), respectively (Figure 4B). The fracture surface of all TempS10, Protemp4, and Cooltemp revealed fillers with polymer matrix. Voids or dislodgement of glass fillers were detected with Cooltemp (Figure 5). Additionally, the agglomeration of Sr-BGNPs was observed on the fracture surface of TempS10.

### Color stability ( $\Delta E^*_{00}$ )

The  $\Delta E^*_{00}$  at 24h was detected with TempS10 ( $3.8 \pm 0.4$ ), whilst the lowest value was detected from Unifast ( $0.6 \pm 0.2$ ) (Figure 6A). The  $\Delta E^*_{00}$  of TempS10 was significantly higher than Unifast, Protemp4 ( $0.9 \pm 0.2$ ), and Cooltemp ( $2.0 \pm 0.5$ ) ( $p < 0.05$ ). A significant increase of  $\Delta E^*_{00}$  at 2 weeks was detected with all materials ( $p < 0.05$ ). The highest



**Figure 4.** Biaxial flexural modulus (BFM) of all Materials after immersion in deionized water for (A) 24 h or (B) 2 weeks. Error bars are 95% CI ( $n = 5$ ). Lines indicate  $p < 0.05$ .

color change at 2 weeks was obtained from TempS10 ( $26 \pm 5$ ), which was significantly higher than Protemp4 ( $2.8 \pm 0.1$ ), Cooltemp ( $1.7 \pm 1.5$ ), and Unifast ( $4.3 \pm 0.9$ ) ( $p < 0.05$ ) (Figure 6B). The color change of Unifast was comparable to that of Protemp4 ( $p = 0.837$ ), but these values were significantly lower than that of Cooltemp ( $p < 0.05$ ).

### Ion release

The concentrations of Ca, P, and Sr observed with PT, CT, and UF were below than that of the working range of the instrument. For TempS10, the Ca, P, and Sr concentrations in water at 2 weeks were  $0.69 \pm 0.10$  ppm,  $0.12 \pm 0.02$  ppm, and  $3.01 \pm 1.09$  ppm, respectively.

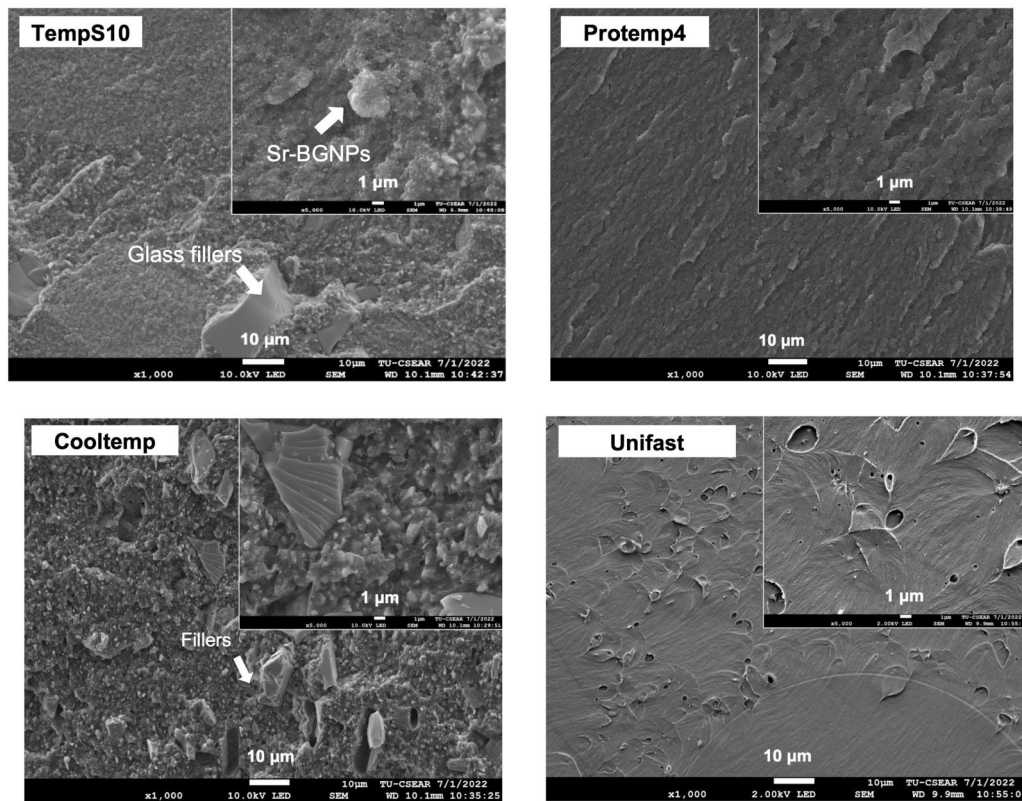


Figure 5. SEM Images of the fracture surface of the representative specimen after BFS testing at 2 weeks.

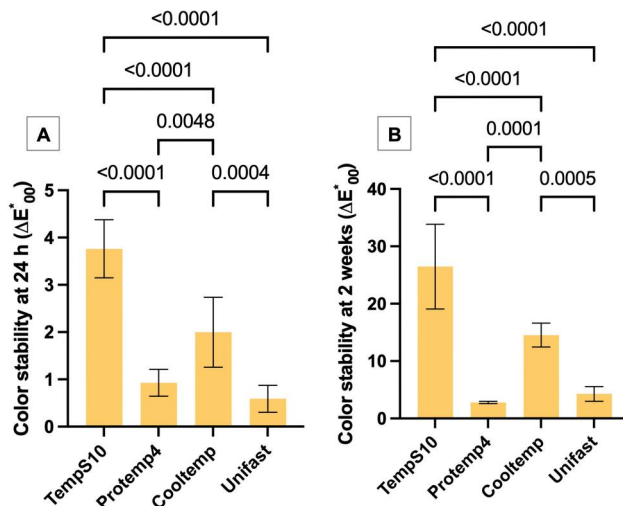


Figure 6. Color change ( $\Delta E^*_{00}$ ) of all materials after immersion in red wine for 24 and 2 weeks.

## Discussion

It was expected that the addition of Sr-bioactive glass nanoparticles may promote the release of essential ions, which could potentially enhance the remineralizing actions of the materials [11, 27]. This study, therefore, examined the physical and mechanical properties of experimental resin composites containing Sr-bioactive

glass nanoparticles for provisional restorations (TempS10). The experimental material demonstrated a degree of monomer conversion (DC) and strength comparable to those of commercial bis-acryl provisional materials, but with the added benefit of ion release. However, the color stability of TempS10 was significantly lower than that of other commercial materials. Hence, the null hypothesis was partially rejected.

The DC results obtained from the commercial materials were similar to those reported in the previous study [28]. DC observed for each material was primarily influenced by the composition of the monomer system present in the material. The high DC, as observed with Unifast, is usually associated with a high exothermic reaction, which could potentially affect the dentin-pulp complex. A study reported that the peak temperature recorded with at the center and peripheral areas of PMMA disc specimen were  $73.9 \pm 8.6^\circ\text{C}$  and  $59.2 \pm 5.3^\circ\text{C}$ , respectively [29]. It was also demonstrated that PMMA polymerization induces a significant temperature increase ( $4\text{--}5^\circ\text{C}$ ) in dentine, which was higher than that ( $1\text{--}3^\circ\text{C}$ ) observed with bis-acryl materials [3].

It should be mentioned that the actual composition and concentration of each commercial product were not obtained from suppliers, thus limiting the direct

comparison with the experimental material. A high DC for resin composite-based materials may be partially correlated with a low risk of toxic monomer release. A study indicated a strong inverse correlation between the increase in DC (from 22.4 to 46.5%) and the amount of monomers eluted from the resin composites [30]. Given that the DC of composite provisional materials in the current study was approximately higher than 50%, this may suggest the low risk of toxic monomer release. However, elution studies and cytotoxicity tests should be employed in future studies.

The strength observed in commercial materials was slightly higher than the reported value in the published study (Protemp4 = 113 MPa, Unifast = 64 MPa) [31, 32]. This discrepancy might be attributed to variations in testing protocols used across different studies. For instance, the specimens in the current study were tested at the initial time point and did not undergo thermally accelerated aging. This may not represent the long-term service simulation, which was considered as the limitation of the current study. Additionally, the current study allowed the specimen to be set for 24 h before immersion. This could subsequently increase the degree of polymerization and the observed mechanical strength of the specimen.

The addition of filler particles with a diameter in micron size (7  $\mu\text{m}$ ) and sub-micron sizes (0.7  $\mu\text{m}$ , 500 nm) could lead to the high stiffness observed with TempS10. Furthermore, the estimated filler load of TempS10 (~63 wt%) was also higher than that of commercial materials such as Protemp4 (24–45 wt%) [33]. The combination of glass of various sizes and nanoparticles was also expected to enhance the filler packing [34]. The agglomeration of Sr-BGNPs in some areas was observed with TempS10, which could negatively affect the strength of the material. It was speculated that the smooth fracture surface of Protemp4 may be attributed to the effective dispersion of small glass fillers (50 nm) [35], leading to efficient stress transfer and increased mechanical strength in comparison to other materials [36, 37]. However, the minimum flexural strength required by ISO 10477-2018 (Polymer-based crown and veneering materials) was 50 MPa [38]. The results from the current study suggest that the experimental material still meets the requirement of the standard. Future work should employ a longer immersion time or use an accelerating protocol to compare the long-term mechanical performance of the materials. This may ensure

the durability of the material when a long-term temporization period is needed.

The major limitation of experimental material in the current study is its low color stability. It was reported that viewers can detect color differences as small as  $\Delta E^*_{00}=0.8$ , while the acceptable threshold is  $\Delta E^*_{00}=1.8$  [39]. The results from the current study indicated that Protemp4 and Unifast exhibited color stability in an acceptable range after immersion in red wine at 24 h immersion. The monomer and fillers systems contained in materials influenced the color stability of resin-based materials [40]. Furthermore, it may be possible that the color stability of materials is associated with the surface roughness, which leads to the increase in the accumulation of pigments. A previous study showed that the Protemp4, which contained only nanosized filler, exhibited the lowest surface roughness compared with other materials [41]. This could explain the low  $\Delta E^*_{00}$  observed in Protemp4 in the current study. The low color stability of TempS10 and Cooltemp could be due to the containing of large glass fillers, which may increase the surface irregularities that could promote the deposition of pigments. It is also possible that the release of Sr-BGNPs from the surface of experimental provisional material may enhance surface irregularities. The use of large fillers may additionally result in poor wear resistance. The crack propagation at the interface of filler and matrix leads to the loss of filler particles [42]. This should be examined using surface roughness studies such as atomic force microscopy or profilometry in future work. A previous study also suggested that the chemical reaction between ions due to the dissolution of bioactive glass and components in beverages could contribute to the increase in color changes of composites containing bioactive glass [43]. The elution of components such as fillers and monomers also affected color stability of the materials, this should be further examined using HPLC in future study.

The release of essential elements such as Ca, P, and Sr from the experimental material was expected to encourage remineralization for the demineralized dentin [10, 12]. The previous study proposed that Sr may enhance the acid resistance of dental hard tissue *via* the transformation of hydroxyapatite to Sr-substitute apatite, which may help promote antibacterial action [44]. The greater strontium release than other ions could be because they dissolve from the doped area, while the release of calcium and phosphorous involves dissolving from the glass network. The limitation of this study was the absence of an

experimental control (i.e. the formulation without any additive), which could influence the accurate determination of the beneficial effects of Sr-BGNPs.

The concentration of calcium released from TempS10 was still lower than that of commercially available hybrid resin composite used for restoration (~1–2 ppm, ACTIVA BioActive-Restorative, Pulpdent, Watertown, MA, USA) [45, 46]. The concentration of all ions released was also lower than that observed with resin-based composite used in orthodontic adhesives in the previous studies [11, 47]. An explanation could be that the materials prepared in the earlier studies contained a highly soluble monocalcium phosphate monohydrate (MCPM, solubility = 783 g/L, Ca/P ratio = 0.5) [48, 49]. Combining MCPM with bioactive glass nanoparticles may enhance the water sorption [50] and accelerate glass degradation, but this could also reduce the color stability and strength of the materials. It should be emphasized that the current study is an *in vitro* study. The need for further assessment of dentin remineralization using the suggested methods [10], such as XRD, FTIR, or Raman spectroscopy, should be confirmed in future work prior to assessment in *in vivo* studies.

## Conclusion

Considering the limitations imposed by the study methods, it could be concluded that experimental material containing Sr-BGNPs showed a comparable degree of monomer conversion and mechanical strength to commercial resin composite-based provisional materials. The experimental materials showed lower color stability but could provide the release of essential ions for mineralization, such as Ca, P, and Sr. This was expected to promote remineralizing actions for the material.

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## Author contribution

Conception: PP, CP, and PN; methodology: PP, CP, and PN; data analysis: NS, HC; manuscript preparation: NS, HC, CP, PN, and PP; review and editing: PN and PP.

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## Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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