Saudi Dental Journal (2019) 31, 367–374

King Saud University

Saudi Dental Journal

www.ksu.edu.sa
www.sciencedirect.com

ORIGINAL ARTICLE

An improved dental composite with potent antibacterial function

Rashed Almousa [a,c], Xin Wen [a], Gregory G. Anderson [b], Dong Xie [a,*]

[a] Department of Biomedical Engineering, Purdue School of Engineering and Technology, Indiana University-Purdue University at Indianapolis, Indianapolis, IN, USA
[b] Department of Biology, Purdue School of Science, Indiana University-Purdue University at Indianapolis, Indianapolis, IN, USA
[c] Department of Medical Equipment Technology, College of Applied Medical Science, Majmaah University, Almajmaah, Riyadh 11952, Saudi Arabia

Received 12 February 2019; revised 21 March 2019; accepted 21 March 2019
Available online 26 March 2019

KEYWORDS

Composite;
Antibacterial;
Bacterial viability;
Mechanical strength

Abstract A new BisGMA-based antibacterial dental composite has been formulated and evaluated. Compressive strength and bacterial viability were utilized to evaluate the formed composites. It was found that the new composite exhibited a significantly enhanced antibacterial function along with improved mechanical and physical properties. The bromine-containing derivative-modified composite was more potent in antibacterial activity than the chlorine-containing composite. The modified composites also exhibited an increase of 30–53% in compressive yield strength, 15–30% in compressive modulus, 15–33% in diametral tensile strength and 6–20% in flexural strength, and a decrease of 57–76% in bacterial viability, 23–37% in water sorption, 8–15% in shrinkage, 8–13% in compressive strength, and similar degree of conversion, than unmodified composite. It appears that this experimental composite may possibly be introduced to dental clinics as an attractive dental restorative due to its improved properties as well as enhanced antibacterial function.
© 2019 The Authors. Production and hosting by Elsevier B.V. on behalf of King Saud University. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Antibacterial dental restoratives are clinically attractive because they can prevent or decrease secondary caries formation and thus reduce patents' visits to dental offices as well as their expenses (Nedeljkovic et al., 2015; Demarco et al., 2015; Forss and Widstrom, 2004; Manhart et al., 2002; Deligeorgi et al., 2001). Secondary caries are mainly produced by tooth demineralization because of the attack of plaque-causing bacteria such as *Streptococcus mutans* and *lactobacillus* in fermentable food debris, especially carbohydrates, at the cavity preparation and the restoration interface (Manhart et al., 2002). Secondary caries formation is known to be the

* Corresponding author at: Department of Biomedical Engineering, Purdue School of Engineering and Technology, Indiana University-Purdue University at Indianapolis, 723 West Michigan Street, SL-220E Indianapolis, IN 46202, USA.
E-mail address: dxie@iupui.edu (D. Xie).
Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.sdentj.2019.03.009
1013-9052 © 2019 The Authors. Production and hosting by Elsevier B.V. on behalf of King Saud University.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

primary reason to dental restorative failure (Nedeljkovic et al., 2015; Demarco et al., 2015; Forss and Widstrom, 2004; Manhart et al., 2002; Deligeorgi et al., 2001). Although dental materials scientists have made tremendous efforts at enhancing antibacterial functions of dental restoratives, most have been focusing on developing formulations that can release or slow-release low molecular weight antibacterial compounds or ions. Such compounds or ions include but are not limited to antibiotics, chlorhexidine, silver, zinc and iodine (Craig and Power, 2002; Wiegand et al., 2007; Osinaga et al., 2003; Takahashi et al., 2006; Yamamoto et al., 1996). However, release/slow-release strategies can suffer from gradual reduction in mechanical or other properties of the material, short-term release but long-term run-out, and potential toxicity of the compounds or ions to surrounding tissues (Craig and Power, 2002; Wiegand et al., 2007; Osinaga et al., 2003; Takahashi et al., 2006; Yamamoto et al., 1996). Incorporating antibacterial compounds or ions into restorative formulations by covalent linkages is a more effective approach than release or slow-release schemes. One typical example is to incorporate organic quaternary ammonium salts into polymers or restoratives (Cherchali et al., 2017; Gottenbos et al, 2002; Huang et al., 2018; Thebault et al., 2009; Imazato et al., 1995; Murata, 2007; Lu et al., 2007). It was found that the quaternary ammonium salt-containing materials exhibited a broad spectrum of antimicrobials and were also able to kill or inhibit bacteria which have resistance to other kinds of cationic antibacterial compounds (Lee et al., 2004). The examples of using these compounds for dental materials include adding polymerizable dodecyl pyridinium bromide methacrylate in composites (Murata, 2007), using ethyl cetyl ammonium chloride methacrylate in bonding agents (Li et al., 2009a,b), adding polyethylenimine quaternary ammonium nanoparticles to dental composites (Beyth et al, 2006), and incorporating polymerizable quaternary ammonium bromide derivatives with different chain lengths into glass-ionomers (Xie et al., 2011). The results from these studies showed that all the quaternary ammonium salt-modified dental restoratives exhibited significant antibacterial activities. Recently furanone-derivatized compounds have shown strong antitumor (Jung et al., 1990; Jones and Young, 1968) and antibacterial functions (Lattmann et al., 2005). These derivatives were also incorporated into dental glass-ionomer cements and the outcomes are very promising (Weng et al., 2012). The formulated cements showed a significant bacterial inhibition comparable to those formulated with the quaternary ammonium salt derivatives (Xie et al., 2011). In this study we tethered 2(5H)-furanone-based compounds onto a common and popular liquid dimethacrylate which is often used for dental application, incorporated the formed derivatives into a dental composite formulation, and evaluated the antibacterial, mechanical and physical properties of the formulated composites.

2. Materials and methods

2.1. Materials

Bis(methacryloyloxy)propanol, 2,3-dichloro-4-oxobutenoic acid, 2,3-dibromo-4-oxobutenoic acid, triethyleneglycoldimethacrylate (TEGDMA), Bisphenol A glycidyl methacrylate (BisGMA), camphoroquinone, 2-(dimethylamino)ethyl methacrylate, p-toluenesulfonic acid monohydrate, toluene, sodium bicarbonate, and ethyl acetate were received from Sigma-Aldrich Co. (Milwaukee, WI) without purifications. The Herculite-XRV (particle = 0.7 μm, untreated) glass fillers were received as a gift from Kavo Kerr Dental Specialties (Orange, CA).

2.2. Synthesis

To a mixture containing 2,3-dichloro-4-oxobutenoic acid (0.49 mol), p-toluenesulfonic acid monohydrate (1 mol% of 2,3-dichloro-4-oxobutenoic acid) and toluene, bis(methacryloyloxy)propanol (0.5 mol) was added. After the mixture was refluxed at 110 °C for 4 h during which water was collected by a receiving apparatus, toluene was recovered under reduced pressure. The product was purified by washing with saturated sodium bicarbonate solution, washing with distilled water and extracting with ethyl acetate. The purified 5-[1,3-bis(methacryloyloxy)propanol]-3,4-dichloro-2(5H)-furanone (BCF) was recovered by removing solvent under reduced pressure before drying *in vacuo* (yield = 87%). 5-[1,3-Bis(methacryloyloxy)propanol]-3,4-dibromo-2(5H)-furanone (BBF) was prepared similarly. The synthesis scheme is demonstrated in Fig. 1.

2.3. Characterization

The starting chemicals and synthesized BCF and BBF were identified by FT-IR (Fourier transform-infrared) and NMR (nuclear magnetic resonance) spectroscopy. The proton NMR spectra were acquired on a 500 MHz Bruker NMR spectrometer (Bruker Avance II, Bruker BioSpin Corporation, Billerica, MA) with the sample dissolving in deuterated dimethyl sulfoxide. FT-IR spectra were acquired on a FT-IR spectrometer (Mattson Research Series FT/IR 1000, Madison, WI).

2.4. Sample preparation for evaluations

The experimental composites were prepared with a powder-liquid system, where the liquid contained the synthesized derivative BCF or BBF, BisGMA, TEGDMA, camphoroquinone and 2-(dimethylamino)ethyl methacrylate. BisGMA and TEGDMA were blended in 50/50 (wt/wt) (BT5050), as previously published (Xu et al., 2018). The formed BisGMA and TEGDMA mixture was combined with BCF or BBF in a ratio (wt/wt) of 75/25, 50/50 and 25/75, along with 1% camphoroquinone and 2% 2-(dimethylamino)ethyl methacrylate for photo-initiation (BTBCF7525, BTBCF5050, BTBCF2575, BTBBF7525, BTBBF5050, and BTBBF2575, respectively). The glass Herculite XRV powders were treated with γ-(trimethoxysilyl)propyl methacrylate (Xu et al., 2018). A powder/liquid ratio of 2.5 (wt/wt, equivalent to filler level at 71%) was used. Samples were prepared by blending the treated fillers with the liquid at 24 °C (Xu et al., 2018). In short, the cylindrical samples were mixed in glass tubing with dimensions (mm) of 4 × 8 for compression, 4 × 2 for diametral compression, and 4 × 2 for antibacterial tests. The rectangular samples were made in a plastic mold with dimensions (mm) of 3 × 3 × 25 for bending test and with a glass lid on the top. All the samples were illuminated under a blue light device (EXAKT520, EXAKT Technologies, Inc., OK) for 2 min and then removed

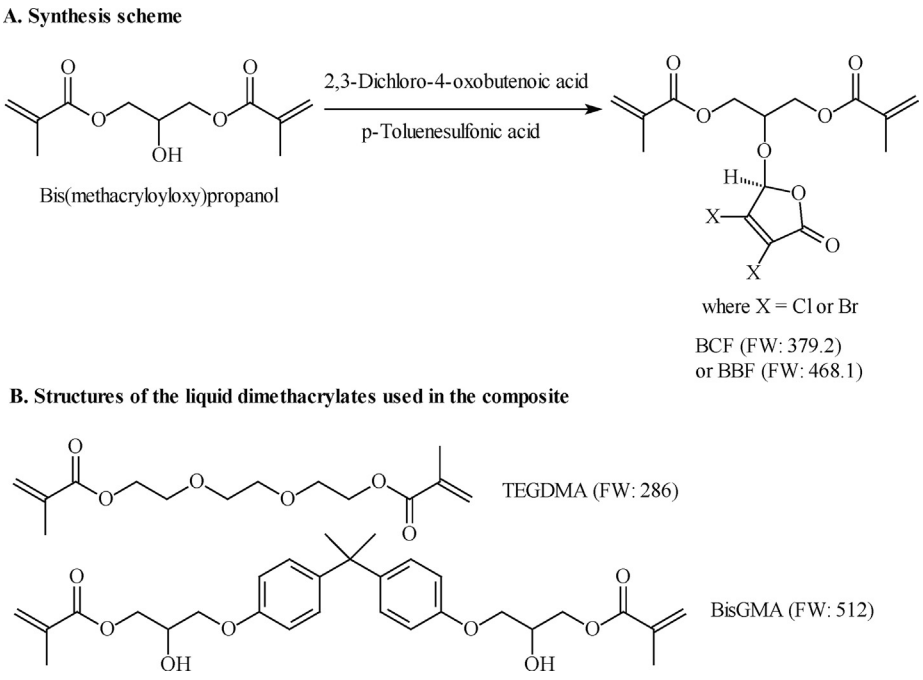

Fig. 1 Synthesis scheme and structures of used chemicals.

from the plastic mold. The samples were immersed in distilled water at 37 °C for 24 h before testing.

2.5. Mechanical strength measurements

Compression, diametral compression and bending tests were carried out on a mechanical tester (QTest QT/10, MTS Systems Corp., Eden Prairie, MN), using 1 mm/min as a crosshead speed (Xu et al., 2018). The bending test was conducted in a three-point bending fixture. Six samples were prepared and tested to gain a mean value for each formulation in every test. Compressive strength was obtained using a formula of $P/\pi r^2$, where P is the load at fracture and r is the radius of the cylinder. Diametral tensile strength was obtained using a formula of $2P/\pi dt$, where P is the load at fracture, d is the diameter of the cylinder, and t is the thickness of the cylinder. Flexural strength was gained using a formula of $3Pl/2bd^2$, where P is the load at fracture, l is the distance between the two supports, b is the breadth of the sample, and d is the depth of the sample.

2.6. Other property determinations

The polymerization shrinkage (%) was measured via an equation of 1- density of uncured composite/density of cured composite) × 100 (Xu and Xie, 2018). The density of the uncured composite was measured by obtaining the weight of the uncured composite paste injected from a calibrated syringe and the density of the cured composite was measured by obtaining the weight of the cured cylindrical specimen in which volume was obtained in water using a calibrated buret. The mean values were obtained by averaging three readings. Water sorption (WS) was measured per ISO 4049. In short, disc sample of the composite with dimensions (mm) of 15 × 1 was made in a circular mold covered with glass slides, followed by illuminating each side with blue light for 1 min. Then the sample was soaked in distilled water for 7 d and dried in a desiccator at 37 °C until its weight became constant (marked as m_o). Then the sample was soaked in water again at 37 °C for 7 d, removed from water, blotted for dry, weighed and recorded as m_t. WS was determined based on an equation of $(m_t - m_o)/V$, where V represents volume of the disc sample. The mean values were obtained by averaging three samples. Degree of conversion (DC) was determined according to the published protocol (Xu and Xie, 2018). Briefly, after a drop of the formulated resin liquid was cast between two KBr crystals, the sample was either directly scanned on FT-IR or illuminated with blue light for 1 min and then scanned on FI-IR. In the acquired FT-IR spectra, the areas under the peaks at 1636 (assigned to C═C on methacrylate) and 1605 cm^{-1} (to aromatic C═C, internal standard for BisGMA-based resin) of uncured and cured specimens were used to calculate DC. DC (%) was calculated via an equation of 1- ($area_{cured}$ at 1636 cm^{-1}/$area_{cured}$ for the internal standard)/($area_{uncured}$ at 1636 cm^{-1}/$area_{uncured}$ for the internal standard) × 100.

2.7. Bacterial viability

The bacterial viability was conducted using the protocol elsewhere (Kim et al., 2007). In short, bacterial colonies were suspended in 5 mL of tryptic soy broth, supplemented with 1% sucrose, to obtain a suspension of 10^8 CFU/mL bacteria. Cultures were incubated for 24 h. Three bacteria species including *Streptococcus mutans (S. mutans), Staphylococcus aureus (S. aureus) and Pseudomonas aeruginosa (P. aeruginosa)* were evaluated. The composite sample was sterilized with ethanol for 10 s, followed by incubating with the above bacterial suspension in 5% CO_2 at 37 °C for 48 h. After that, a 3 μL fluorescent green/red (1:1 v/v) dye mixture (LIVE/DEAD BacLight kit L7007, Molecular Probes, Inc., Eugene, OR,

USA) was added to 1 mL of the above bacterial suspension. The formed mixture was treated by vortexing for 10 s, sonicating for 10 s, vortexing for another 10 s and keeping in dark for about 15 min prior to analysis. Finally, a 20 μL stained bacterial suspension mixture was added to the top of a glass slide. The viable bacteria (green) were imaged with an inverted fluorescence microscope (EVOS FL, AMG, Mill Creek, WA, USA). A bacteria suspension without samples was used as control, where the counts of viable bacteria were designated as 100%. The viability was determined by counting from the recorded images. The mean values were averaged from three measurements for each material.

2.8. Statistical analysis

Sample statistics were analyzed using ANOVA (one-way analysis of variance) with the post hoc Tukey-Kramer multiple-range test to determine significant differences of the measured properties including compressive strength, yield strength, modulus, diametral tensile strength, flexural strength, water sorption, shrinkage, degree of conversion and bacterial viability among the materials. A level of $\alpha = 0.05$ was used for statistical significance.

3. Results and discussion

3.1. Characterization

Table 1 shows the characteristic peaks from FT-IR and ^{1}HNMR spectra for 2,3-dichloro-4-oxobutenoic acid, bis(methacryloyloxy)propanol and BCF. Several data confirm successful BCF formation. FT-IR showed disappearance of the pseudo hydroxyl peak on 2,3-dichloro-4-oxobutenoic acid at 3361 and the hydroxyl peak on bis(methacryloyloxy)propanol at 3490. At the same time, peaks corresponding to carbonyl groups from 2,3-dichloro-4-oxobutenoic acid and bis(methacryloyloxy)propanol (1795 and 1721), C═C double bonds from 2,3-dichloro-4-oxobutenoic acid and bis(methacryloyloxy)propanol (1637), and chlorine from 3-dichloro-4-oxobutenoic acid (745) appeared on the BCF trace. Additionally, BCF ^{1}HNMR demonstrated the chemical shift disappearance at 3.68 corresponding to the pseudo hydroxyl group on 2,3-dichloro-4-oxobutenoic acid and all the chemical shift appearance from both 3-dichloro-4-oxobutenoic acid and bis(methacryloyloxy)propanol, with a slight shift.

3.2. Evaluation

Fig. 2 shows the effect of BCF and BBF additions on compressive strength (CS) and modulus (M) values of the experimental composites. The mean strength value was in the decreasing rank of: (1) CS (MPa): BTBBF7525 > BT5050 > BTBBF5050 > BTBCF7525 > BTBCF5050 > BTBBF2575 > BTBCF2575 (Fig. 2a), where no significant differences were found among BTBBF7525, BT5050, BTBBF5050 and BTBCF7525, and between BTBCF5050 and BTBBF2575 ($p > 0.05$). (2) M (GPa): BTBBF2575 > BTBBF5050 > BTBBF7525 > BTBCF7525 = BTBCF2575 > BTBCF5050 > BT5050 (Fig. 2b), where there was no significant difference between BTBCF7525 and BTBCF2575. It appears that incorporation of BBF or BCF decreased CS compared to BT5050, especially while BT/BCF or BT/BBF = 25/75. In terms of modulus, a significant increase is observed for both BCF- and BBF-modified composites compared to BT5050, with BBF showing an even higher modulus increase. For comparison, we calculated the contents of carbon-carbon double bonds in each resin formulation and found that both BCF- and BBF-modified composites contain fewer carbon-carbon double bonds than BT5050 does. It was bromine or chlorine-containing 2(5H) furanone that increases modulus, suggesting that bromine or chlorine on furanone as well as furanone ring structures may increase the stiffness to the composites.

Fig. 3 shows the impact of BBF or BCF addition on viability of three bacterial species. For either BCF- or BBF-modified composites, bacterial viability of all three species was in the decreasing rank of BT > BTBCF7525 > BTBCF5050 > BTBCF2575 or BT > BTBBF7525 > BTBBF5050 > BTBBF2575, where all the viability values were significantly different from each other ($p < 0.05$). In other words, increasing BCF or BBF decreased bacterial viability or increased

Table 1 The characteristic peaks from ^{1}HNMR and FT-IR spectra.

Code	The characteristic peaks from ^{1}HNMR and FT-IR spectra
	FT-IR
2,3-Dichloro-4-oxobutenoic acid	3361 (O—H stretching), 1765 (C═O stretching), 1643 (C═C stretching), 1332, 1237 and 949 (C—O—C stretching), 1451, 1026 and 778 (O—H deformation), 1279, 1118, 889 and 602 (C—O stretching), 745 (C—Cl stretching)
Bis(methacryloyloxy) propanol	3490 (O—H stretching), 1720 (C═O stretching), 1637 (C═C stretching), 1453, 1015 and 813 (O—H deformation), 2959, 1404, 1378, 1321, 1295, 1161, 945 and 654 (—C—H stretching and deformation)
BCF	1795 and 1721 (C═O stretching), 1637 (C═C stretching), 1453, 1016, 813 and 777 (O—H deformation), 1332, 1231 and 968 (C—O—C stretching), 2959, 1404, 1378, 1322, 1294, 1156, 903 and 653 (—C—H stretching and deformation), 745 (C—Cl stretching)
	^{1}HNMR
2,3-Dichloro-4-oxobutenoic acid	6.25 (—CH), 3.45 (—OH)
Bis(methacryloyloxy) propanol	6.42 (2H, C<u>H</u> on C═C<u>H</u>$_2$), 6.34 (2H, C<u>H</u> on C═C<u>H</u>$_2$), 4.38 (1H, C<u>H</u>), 4.30 (2H, C<u>H</u>$_2$), 4.20 (2H, C<u>H</u>$_2$), 3.68 (1H, O<u>H</u>), 2.01 (6H, C<u>H</u>$_3$)
BCF	6.35 (2H, C<u>H</u> on C═C<u>H</u>$_2$), 6.15 (2H, C<u>H</u> on C═C<u>H</u>$_2$), 5.65 (1H, C<u>H</u>), 4.35 (1H, C<u>H</u>), 4.24 (2H, C<u>H</u>$_2$), 4.12 (2H, C<u>H</u>$_2$), 1.89 (6H, C<u>H</u>$_3$)

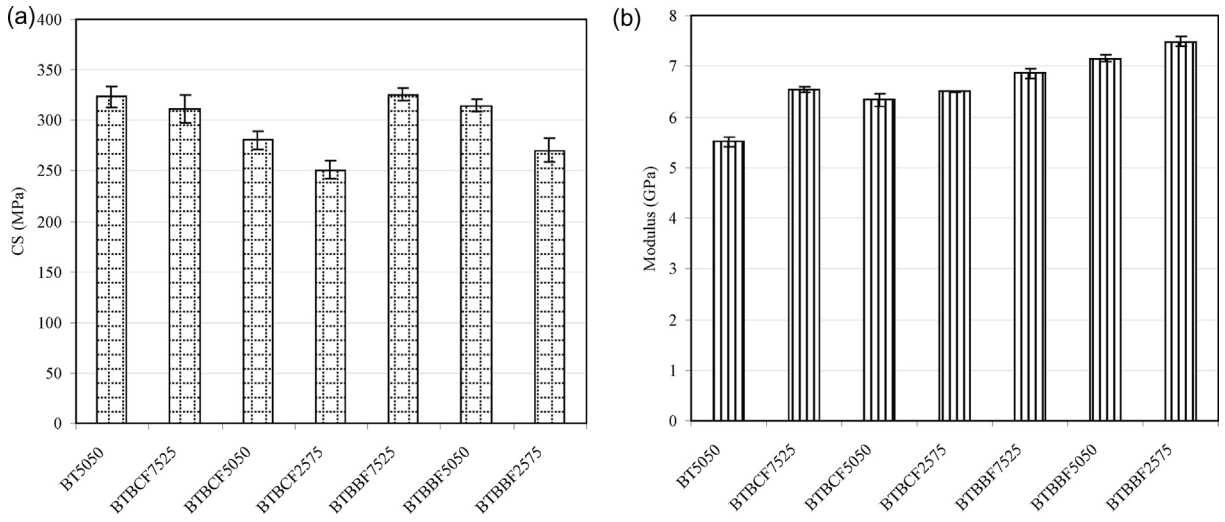

Fig. 2 CS and modulus of the experimental antibacterial composites: (a) CS; (b) Modulus.

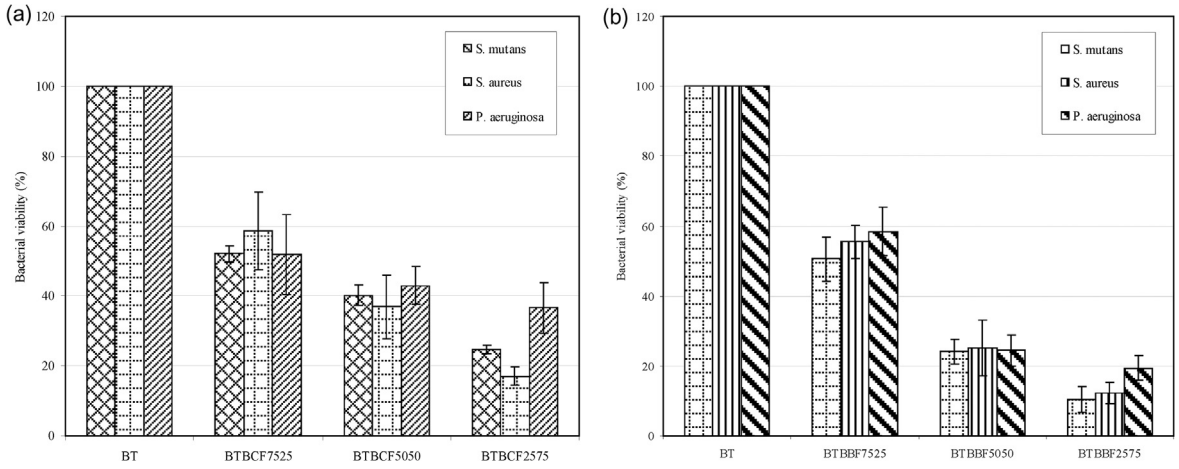

Fig. 3 Bacterial viability of the experimental antibacterial composites with three bacterial species: (a) BCF-based; (b) BBF-based.

antibacterial activity. By using BT resin composite as control, three bacteria species were inhibited from 41 to 48% with 25% BCF addition, 57 to 63% with 50% BCF addition, and 63 to 83% with 75% BCF addition (see Fig. 3a). On the other hand, for BBF addition, three bacteria species were inhibited from 42 to 49% with 25% addition, 75 to 76% with 50% addition, and 81 to 89% with 75% addition (see Fig. 3b). Apparently BBF showed a stronger antibacterial activity than BCF, indicating that the bromine-containing 2(5H)-furanone is a more potent antibacterial agent than its chlorine counterpart. Furthermore, both BCF and BBF seem to be slightly more potent to *S. mutans and S. aureus* than *P. aeruginosa*.

Fig. 4 shows a set of photomicrographs of bacterial viability after incubating bacteria with the experimental composites: (a) untreated *S. mutans*, (b) *S. mutans* with BT, (c) *S. mutans* with BTBCF7525, (d) *S. mutans* with BTBCF5050, (e) *S. mutans* with BTBCF2575, (f) *S. mutans* with BTBBF7525, (g) *S. aureus* with BTBCF2575, and (h) *P. aeruginosa* with BTBCF2575. Apparently, all the images of bacteria incubated with antibacterial composites showed significantly reduced bacterial number as compared to those incubated without treatment (a) and incubated with BT (b). Increasing BCF decreased bacterial viability (c to e). BCF also significantly decreased bacterial viability of *S. aureus* (g) and *P. aeruginosa* (h). BBF showed similar activity as BCF at a lower concentration (f).

Table 2 shows the tested mechanical and physical properties of the BT, BTBCF and BTBBF composites. For comparison, we chose the composites with BT/BCF and BT/BBF at 50/50 and compared them with unmodified composite BT. By comparison, the BBF modified composite (BTBBF) exhibited the highest mechanical strengths other than CS. Its significantly high yield strength (YS), modulus (M), diametral tensile strength (DTS) and flexural strength (FS) as compared to BT suggest that BTBBF is the stiffest composite among them. Both the bromine and the furanone ring may be responsible for its higher mechanical strengths. The chlorine-containing BCF also showed much higher mechanical strengths than BT, except for CS. Furthermore, both BBF- and BCF-modified composites showed significantly reduced

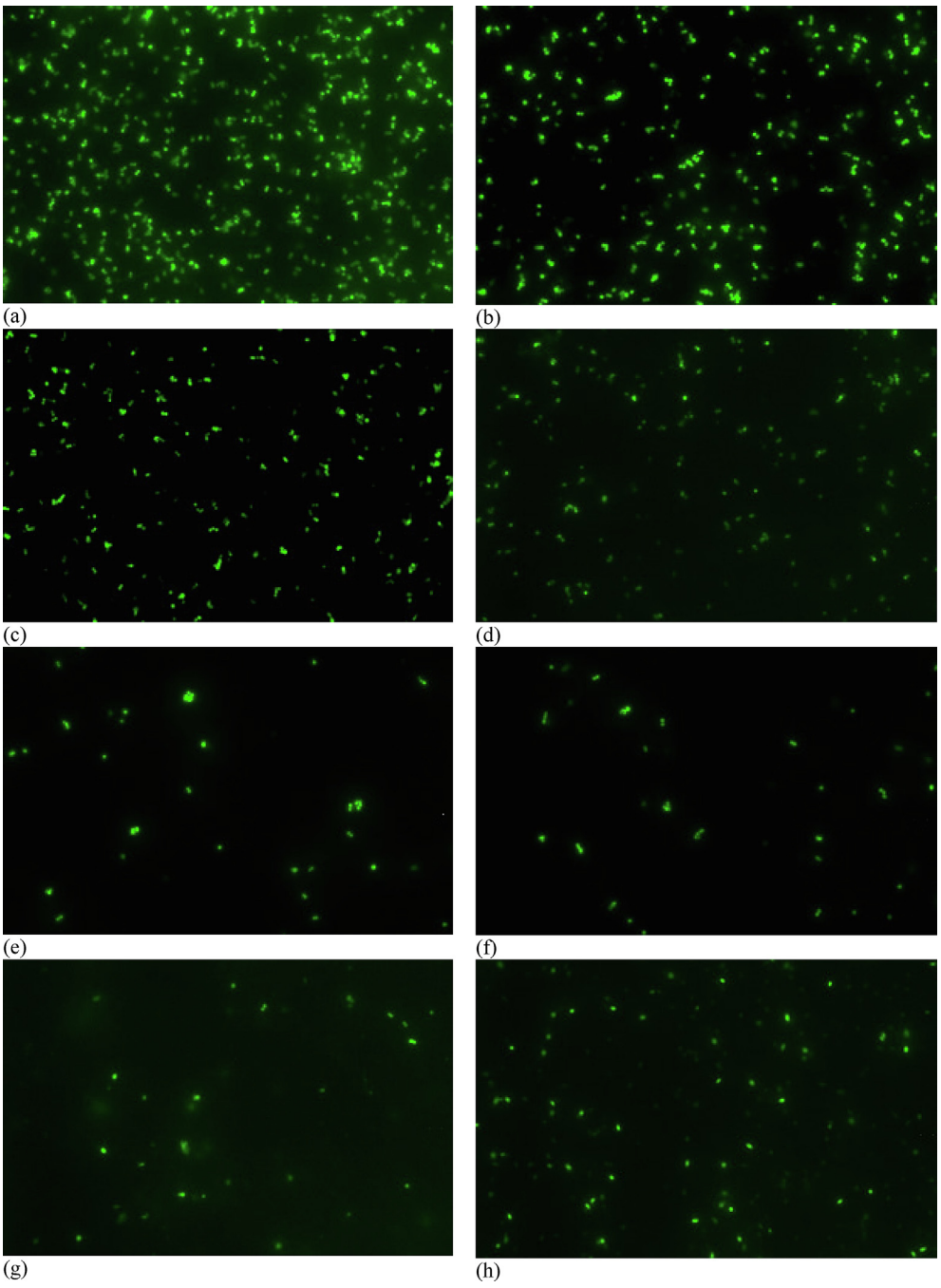

Fig. 4 Bacterial images after incubating with antibacterial composites vs. control for 48 h: (a) untreated *S. mutans*, (b) *S. mutans* with BT, (c) *S. mutans* with BTBCF7525, (d) *S. mutans* with BTBCF5050, (e) *S. mutans* with BTBCF2575, (f) *S. mutans* with BTBBF7525, (g) *S. aureus* with BTBCF2575, and (h) *P. aeruginosa* with BTBCF2575.

water sorption (58–68% reduction) and slightly reduced shrinkage. It is known that water sorption is detrimental to dental composites (Craig and Power, 2002). Reduction in water sorption favors stability of dental composites (Yoshida et al., 2013). Reduced water sorption in BBF or BCF-modified composites can be attributed to increased hydrophobicity of the modified composite due to bromine or chlorine incorporation, because bromine or chlorine is known for its significant hydrophobicity (Solomons and Fryhle, 2000). Regarding polymerization shrinkage, both BBF- and BCF-modified composites showed slightly lower shrinkage values than the BT composite, which can be related to the reduced contents of its carbon-carbon double bonds. Based on the molecular weights of BCF (379.2), BBF (468.1), TEGDMA (286) and BisGMA (512), one gram of BTBCF resin contains 5.36 mmole of carbon-carbon double bonds and BTBBF contains 4.86 mmole. On the other hand, one gram of BT resin contains 5.45 mmol of carbon-carbon double bonds. All the

Table 2 Properties of the studied composites.[1]

Material	YS [MPa]	M [GPa]	CS [MPa]	DTS [MPa]	FS [MPa]	WS [μg/mm^3]	Shrinkage [%]	DC [%]
BT	116.9 (3.0)	5.51 (0.10)	323.7 (10)[a,2]	42.8 (5.4)[b]	84.6 (5.9)[c]	26.4 (1.8)	3.9 (0.29)	72.1 (1.7)[d]
BTBCF	153.1 (2.4)	6.34 (0.12)	280.5 (8.9)	49.2 (5.8)[b]	89.5 (4.2)[c]	20.2 (1.3)	3.6 (0.23)	69.4 (1.1)[d]
BTBBF	177.9 (1.1)	7.16 (0.06)	314.9 (5.9)[a]	56.9 (4.9)	101.7 (8.8)	16.5 (0.9)	3.3 (0.11)	67.9 (1.5)[d]

[1] BT = BisGMA/TEGDMA = 50/50 (wt/wt); BTBCF = BT/BCF = 50/50; BTBBF = BT/BBF = 50/50.

[2] Entries are mean values with standard deviations in parentheses, where the mean values with the same superscript letter were not significantly different from each other ($p > 0.05$). Samples for strength tests were conditioned in distilled water at 37 °C for 24 h before testing.

BCF- or BBF- modified composites contain slightly fewer carbon-carbon double bonds than the BT composite. The carbon-carbon double bond is partially responsible for polymerization shrinkage (Painter and Coleman, 1997). That may be why a slightly reduced shrinkage is observed. Degree of conversion (DC) values of all the three resins were pretty much the same with one another, with BT resin showing the highest, followed by BTBCF and BTBBF resins, where there was no statistically significant difference among them.

4. Conclusions

A new furanone-containing antibacterial dental composite has been developed. The modified composite exhibited a significantly increased antibacterial function along with enhanced mechanical and physical properties. It was found that the bromine-containing composite showed a higher antibacterial activity than its chlorine-containing counterpart. The modified composites showed increases in YS (30–53%), modulus (15–30%), DTS (15–33%) and FS (6–20%), compared to unmodified composites. They also showed decreases in bacterial viability (57–76%), water sorption (23–37%), shrinkage (8–15%) and CS (8–13%), compared to unmodified composites. It seems that this experimental composite may possibly be introduced to dental clinics in the future as an attractive dental restorative due to its improved properties as well as enhanced antibacterial function. Future studies will include evaluation of other mechanical and physical properties such as hardness and long-term stability and *in vitro*/*in vivo* biocompatibility of this new dental composite.

Conflict of interest

The authors declared that there is no conflict of interest.

Ethical statement

All the ethical concerns are taken into consideration before submitting the manuscript.

Acknowledgements

This study was partially sponsored by IUPUI BBRC Research Support Funds Grant, Indiana University, USA. This work was also partially supported by 1R03AR068724-01 from the National Institutes of Health to GGA, USA.

References

Beyth, N., Yudovin-Farber, I., Bahir, R., Domb, A.J., Weiss, E.I., 2006. Antibacterial activity of dental composites containing quaternary ammonium polyethylenimine nanoparticles against *Streptococcus mutans*. Biomaterials 27, 3995–4002.

Cherchali, F.Z., Mouzali, M., Tommasino, J.B., Decoret, D., Attik, N., Aboulleil, H., Seux, D., Grosgogeat, B., 2017. Effectiveness of the DHMAI monomer in the development of an antibacterial dental composite. Dent. Mater. 33, 1381–1391.

Craig, R.G., Power, J.M., 2002. Restorative Dental Materials. Mosby-Year Book, Inc., St Louis, pp. 614–618.

Deligeorgi, V., Mjor, I.A., Wilson, N.H., 2001. An overview of reasons for the placement and replacement of restorations. Prim. Dent. Care 8, 5–11.

Demarco, F.F., Collares, K., Coelho-de-Souza, F.H., Correa, M.B., Cenci, M.S., Moraes, R.R., Opdam, N.J., 2015. Anterior composite restorations: a systematic review on long-term survival and reasons for failure. Dent. Mater. 31, 1214–1224.

Forss, H., Widstrom, E., 2004. Reasons for restorative therapy and longevity of restorations in adults. Acta. Odontol. Scand. 62, 82–86.

Gottenbos, B., van der Mei, H.C., Klatter, F., Nieuwenhuis, P., Busscher, H.J., 2002. In vitro and in vivo antimicrobial activity of covalently coupled quaternary ammonium silane coatings on silicone rubber. Biomaterials 23, 1417–1423.

Huang, Q., Huang, S., Liang, X., Qin, W., Liu, F., Lin, Z., He, J., 2018. The antibacterial, cytotoxic, and flexural properties of a composite resin containing a quaternary ammonium monomer. J. Prost. Dent. 120, 609–616.

Imazato, S., Russell, R.R., McCabe, J.F., 1995. Antibacterial activity of MDPB polymer incorporated in dental resin. J. Dent. 23, 177–181.

Jones, J.B., Young, J.M., 1968. Carcinogenicity of lactones III: The reactions of unsaturated 4-lactones with l-cysteine. J. Med. Chem. 11, 1176.

Jung, J.H., Pummangura, S., Chaichantipyuth, C., Patarapanich, C., Fanwick, P.E., Chang, C.J., Mclaughlin, J.L., 1990. New bioactive heptenes from melodorum fruticosum (annonaceae). Tetrahedron 46, 5043–5054.

Kim, Y., Farrah, S., Baney, R.H., 2007. Membrane damage of bacteria by silanols treatment. Electron. J. Biotechnol. 10, 252–259.

Lattmann, E., Dunn, S., Niamsanit, S., Sattayasai, N., 2005. Synthesis and antibacterial activities of 5-hydroxy-4-amino-2(5H)-furanones. Bioorg. Med. Chem. Lett. 15, 919–921.

Lee, S.B., Koepsel, R.R., Morley, S.W., Matyjaszewski, K., Sun, Y., Russell, A.J., 2004. Permanent, nonleaching antibacterial surfaces. 1. Synthesis by atom transfer radical polymerization. Biomacromolecules 5, 877–882.

Li, F., Chen, J., Chai, Z., Zhang, L., Xiao, Y., Fang, M., Ma, S., 2009b. Effects of a dental adhesive incorporating antibacterial monomer on the growth, adherence and membrane integrity of *Streptococcus mutans*. J. Dent. 37, 289–296.

Li, F., Chai, Z.G., Sun, M.N., Wang, F., Ma, S., Zhang, L., Fang, M., Chen, J.H., 2009a. Anti-biofilm effect of dental adhesive with cationic monomer. J. Dent. Res. 88, 372–376.

Lu, G., Wu, D., Fu, R., 2007. Studies on the synthesis and antibacterial activities of polymeric quaternary ammonium salts from dimethylaminoethyl methacrylate. React. Funct. Polym. 67, 355–366.

Manhart, J., Garcia-Godoy, F., Hickel, R., 2002. Direct posterior restorations: clinical results and new developments. Dent. Clin. North. Am. 46, 303–339.

Murata, H., 2007. Permanent, non-leaching antibacterial surfaces—2: how high density cationic surfaces kill bacterial cells. Biomaterials 28, 4870–4879.

Nedeljkovic, I., Teughels, W., De Munck, J., Van Meerbeek, B., Van Landuyt, K.L., 2015. Is secondary caries with composites a material-based problem? Dent. Mater. 31, 247–277.

Osinaga, P.W., Grande, R.H., Ballester, R.Y., Simionato, M.R., Delgado Rodrigues, C.R., Muench, A., 2003. Zinc sulfate addition to glass-ionomer-based cements: influence on physical and antibacterial properties, zinc and fluoride release. Dent. Mater. 19, 212–217.

Painter, P.C., Coleman, M.M., 1997. Fundamentals of Polymer Science. CRC Press, Boca Raton.

Solomons, G., Fryhle, C., 2000. Organic Chemistry. John Wiley & Sons Inc, New York.

Takahashi, Y., Imazato, S., Kaneshiro, A.V., Ebisu, S., Frencken, J. E., Tay, F.R., 2006. Antibacterial effects and physical properties of glass-ionomer cements containing chlorhexidine for the ART approach. Dent. Mater. 22, 647–652.

Thebault, P., Taffin de Givenchy, E., Levy, R., Vandenberghe, Y., Guittard, F., Geribaldi, S., 2009. Preparation and antimicrobial behaviour of quaternary ammonium thiol derivatives able to be grafted on metal surfaces. Eur. J. Med. Chem. 44, 717–724.

Weng, Y., Howard, L., Chong, V.J., Guo, X., Gregory, R.L., Xie, D., 2012. A novel furanone-modified antibacterial dental glass-ionomer cement. Acta. Biomater. 8, 3153–3160.

Wiegand, A., Buchalla, W., Attin, T., 2007. Review on fluoride-releasing restorative materials – fluoride release and uptake characteristics, antibacterial activity and influence on caries formation. Dent. Mater. 23, 343–362.

Xie, D., Weng, Y., Guo, X., Zhao, J., Gregory, R.L., Zheng, C., 2011. Preparation and evaluation of a novel glass-ionomer cement with antibacterial functions. Dent. Mater. 27, 487–496.

Xu, Y., Xie, D., 2018. A triethylene glycol dimethacrylate free dental composite for reduced water-sorption and shrinkage. J. Comp. Mater. 52, 1579–1588.

Xu, Y., Zhang, J., Wang, H., Xie, D., 2018. Preparation of a low viscosity urethane-based composite for improved dental restoratives. Dent. Mater. J. 37, 400–407.

Yamamoto, K., Ohashi, S., Aono, M., Kokubo, T., Yamada, I., Yamauchi, J., 1996. Antibacterial activity of silver ions implanted in SiO_2 filler on oral streptococci. Dent. Mater. 12, 227–229.

Yoshida, K., Kurogi, T., Torisu, T., Watanabe, I., Murata, H., 2013. Effect of 2,2,2-trifluoroethyl methacrylate on properties of autopolymerized hard direct denture reline resins. Dent. Mater. J. 32, 744–752.