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Mimicking nature: Self-strengthening properties in a dental adhesive

Linyong Song [a], Qiang Ye [a,*], Xueping Ge [a], Anil Misra [a,b], Paulette Spencer [a,c,*]

[a] University of Kansas, Bioengineering Research Center, 1530 W. 15th Street, Lawrence, KS 66045-7609, USA
[b] University of Kansas, Department of Civil Engineering, 1530 W. 15th Street, Lawrence, KS 66045-7609, USA
[c] University of Kansas, Department of Mechanical Engineering, 1530 W. 15th Street, Lawrence, KS 66045-7609, USA

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ABSTRACT

Chemical and enzymatic hydrolysis provoke a cascade of events that undermine methacrylate-based adhesives and the bond formed at the tooth/composite interface. Infiltration of noxious agents, e.g. enzymes, bacteria, and so forth, into the spaces created by the defective bond will ultimately lead to failure of the composite restoration. This paper reports a novel, synthetic resin that provides enhanced hydrolytic stability as a result of intrinsic reinforcement of the polymer network. The behavior of this novel resin, which contains γ-methacryloxyproyl trimethoxysilane (MPS) as its Si-based compound, is reminiscent of self-strengthening properties found in nature. The efforts in this paper are focused on two essential aspects: the visible-light irradiation induced (photoacid-induced) sol–gel reaction and the mechanism leading to intrinsic self-strengthening. The FTIR band at 2840 cm^{-1} corresponding to CH_3 symmetric stretch in $-Si-O-CH_3$ was used to evaluate the sol–gel reaction. Results from the real-time FTIR indicated that the newly developed resin showed a limited sol–gel reaction (<5%) during visible-light irradiation, but after 48 h dark storage, the reaction was over 65%. The condensation of methoxysilane mainly occurred under wet conditions. The storage moduli and glass transition temperature of the copolymers increased in wet conditions with the increasing MPS content. The cumulative amounts of leached species decreased significantly when the MPS-containing adhesive was used. The results suggest that the polymethacrylate-based network, which formed first as a result of free radical initiated polymerization, retarded the photoacid-induced sol–gel reaction. The sol–gel reaction provided a persistent, intrinsic reinforcement of the polymer network in both neutral and acidic conditions. This behavior led to enhanced mechanical properties of the dental adhesives under conditions that simulate the wet, oral environment.

Statement of Significance

A self-strengthening dental adhesive system was developed through a dual curing process, which involves the free radical photopolymerization followed by slow hydrolysis and condensation (photoacid-induced sol–gel reaction) of alkoxylsilane groups. The concept of "living" photoacid-induced sol–gel reaction with visible-light irradiation was confirmed in the polymer. The sol–gel reaction was retarded by the polymethacrylate network, which was generated first; the network extended the life and retained the activity of silanol groups. The self-strengthening behavior was evaluated by monitoring the mechanical properties of the hybrid copolymers under wet conditions. The present research demonstrates the sol–gel reaction in highly crosslinked network as a potentially powerful strategy to prolong the functional lifetime of engineered biomaterials in wet environments.

1. Introduction

The structure of methacrylate-based dental adhesives suggests a general mechanism for their chemical and enzymatic degradation. In the oral environment, water can gradually penetrate the resin, which promotes the chemical hydrolysis of ester bonds in polymethacrylate-based materials [1–4]. This reaction may be

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* Corresponding authors at: The University of Kansas, Bioengineering Research Center, School of Engineering, Learned Hall 5109, 1530 W. 15th Street, Lawrence, KS 66045-7609, USA (Q. Ye). The University of Kansas, Dept. Mechanical Engineering, School of Engineering, 1530 W. 15th Street, Lawrence, KS 66045-7609, USA (P. Spencer).

E-mail address: yeq@ku.edu (Q. Ye).

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relatively slow at neutral pH, but changes in pH, caused by diet or cariogenic bacteria, may lead to transient acid or base catalysis [5]. The carboxylate and alcohol degradation products of ester hydrolysis are more hydrophilic than the parent ester, further enhancing the local ingress of water. After years of exposure to salivary fluids, local domains of the polymethacrylate networks become sufficiently degraded and/or hydrophilic to permit access by esterases, which accelerate ester bond hydrolysis [3,6]. In general, the ester bonds within the polymethacrylate-based network are vulnerable to two forms of hydrolytic attack: (1) chemical hydrolysis catalyzed by acids or bases and (2) enzymatic hydrolysis catalyzed by salivary enzymes (particularly esterases) [7].

Deterioration of the adhesive is difficult to detect and even more difficult to repair. Degradation of the dental adhesive and concomitant failure of the bond formed between the adhesive and dentin leads to gaps at the composite/tooth interface. These gaps are penetrated by bacteria, bacterial enzymes, oral fluids, and food. Such activity leads to decay, hypersensitivity, pulpal inflammation and composite restoration failure [6].

Several strategies to enhance the hydrolytic stability of dental adhesives or to improve the integrity of the adhesive/dentin (a/d) interfacial bond have been proposed. One strategy is to change the monomer structure, which especially increases the hydrophobicity of the monomers by introducing either a urethane group [8–10], branched methacrylate linkage [11], or ethoxylated BisGMA (BisEMA) [12]. These strategies temporarily depress water sorption, but the materials will generally reach saturation within 7–60 days [13]. Another strategy involves enhancing the monomer conversion in the hybrid layer by improving the compatibility between the photoinitiator and the hydrophilic-rich phase of adhesive [14,15], or increasing the light-curing time of the adhesive [1,16]. Since the gel effect and vitrification phenomena occur early in the light-irradiation process, the degree of conversion (DC) of C=C double bonds cannot reach 100% [17,18]. A third strategy is to add an effective inhibitor (such as zinc or zinc-chelators) of dentin matrix metalloproteinnases (MMPs) in the adhesive formulation or use a biomimetic remineralization technique [4,19–21]. The MMP-inhibition methods have shown promise [22], but these methods can lead to detrimental changes in the material, e.g. decreased monomer/polymer conversion [23]. Biomimetic remineralization offers protection of the exposed collagen, but this technique does not prevent water sorption and hydrolysis of the adhesive [4].

Si-based materials are used in many aspects of daily life and show a beneficial role in *in vivo* applications. Silicate gels can be synthesized by hydrolyzing tetrafunctional alkoxide precursors which employ an acid or base as a catalyst [24–26]. The *hydrolysis reaction* replaces the alkoxide group (OR) with a hydroxyl group (OH). The subsequent *condensation reaction*, involving silanol groups, produces a silicon oxygen bond (Si–O–Si) plus the by-products alcohol (ROH) or water. At the functional group level, three reactions are generally used to describe the sol–gel process [25]:

$$\equiv \mathrm{Si{-}OR} + \mathrm{H_2O} \xrightarrow{\text{hydrolysis}} \equiv \mathrm{Si{-}OH} + \mathrm{ROH} \tag{1}$$

$$\equiv \mathrm{Si{-}OR} + \mathrm{OH{-}Si} \equiv \xrightarrow{\text{alcohol condensation}} \mathrm{Si{-}O{-}Si} \equiv + \mathrm{ROH} \tag{2}$$

$$\equiv \mathrm{Si{-}OH} + \mathrm{OH{-}Si} \equiv \xrightarrow{\text{water condensation}} \equiv \mathrm{Si{-}O{-}Si} \equiv + \mathrm{H_2O} \tag{3}$$

Currently, organosilanes are mainly used as a coupling agent to connect the organic and inorganic components in dental composites [27–30]. A common method to apply silane agents into the restorative materials is to use them pre-hydrolyzed in a solvent mixture consisting of water or ethanol. The shelf life of the pre-hydrolyzed silane solutions is relatively short, which limits its application [30].

In 1978, Fox et al. first reported that the onium salt photolysis was efficient at promoting the hydrolysis–condensation of alkoxylsilyl precursors [31]. Since the pioneering work of Crivello, onium salts have been widely used as photoinitiators to generate photoacids and initiate the cationic photopolymerization [32]. The photoacid-induced sol–gel reaction has been used in a few studies to prepare nanocomposite films [32–37]. Under acidic conditions, it is likely that an alkoxide group is protonated in a rapid first step, and then the hydrolysis occurs. Photoacids generated by photolysis of onium salts have been shown to catalyze the sol–gel reaction of alkoxides. Moreover, the addition of water was not necessary since diffusion of moisture from the air into the film was sufficient for the hydrolysis reaction [36]. The photoacid-induced sol–gel reaction opens new opportunities for the application of organosilane agents in dentistry.

We propose the development of a dental adhesive system that utilizes the sol–gel reaction in conjunction with free radical polymerization to provide a polymer with enhanced hydrolytic stability and intrinsic self-strengthening properties. The sol–gel reaction of organosilane agents and the free radical photopolymerization of methacrylate are carried out simultaneously, and both reactions are induced by visible light irradiation. To our knowledge, this “one-pot” *in situ* bulk polymerization approach has not been previously employed in dental adhesives. It is postulated that the visible-light induced free radical photopolymerization will be followed by a sol–gel process; these processes will lead to polysiloxane chains strictly interconnected within the polymethacrylate matrix. The first objective is to evaluate the validity of the photoacid-induced sol–gel reaction in the dental adhesive system with visible-light irradiation. The second objective is to assess the proposed intrinsic self-strengthening mechanism by monitoring the mechanical properties of the hybrid copolymers under wet conditions. The overall research hypotheses of this study were: (1) the photoacid-induced sol–gel reaction cannot occur without the addition of iodonium salt, (2) water is necessary for the hydrolysis of photoacid-induced sol–gel reaction, (3) the mechanical properties of silane-containing dental adhesive will show self-strengthening behavior under wet conditions.

2. Materials & methods

2.1. Materials

2,2-Bis[4-(2-hydroxy-3-methacryloxypropoxy)phenyl] propane (BisGMA) and 2-hydroxyethyl methacrylate (HEMA) were obtained from Sigma-Aldrich (St. Louis, MO) and used as received without further purification as monomers in dental adhesives. γ-methacryloxypropyltrimethoxysilane (MPS) was used as received from MP Biomedicals, Santa Ana, CA. Camphoroquinone (CQ), ethyl-4-(dimethylamino) benzoate (EDMAB), and lactic acid (LA) were obtained from Sigma-Aldrich (St. Louis, MO). *p*-octyloxy-phenylphenyl iodonium hexafluoroantimonate (OPPIH) was purchased from Gelest Inc., (Morrisville, PA). All other chemicals were reagent grade and used without further purification.

2.2. Preparation of adhesive formulations

Neat methacrylate monomer mixtures were made by mixing 45 wt% HEMA and 55 wt% BisGMA [14,38]. CQ (1.0 wt%), EDMAB (1.0 wt%), and OPPIH (2.0 wt%) were used as photoinitiator (PI) systems with respect to the total amount of monomers [39]. The chemical structures of monomers and PI are shown in Scheme 1.