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Thio-urethane oligomers improve the properties of light-cured resin cements

Ataís Bacchi^{1,2}, Rafael L. Consani¹, Gedalias C. Martim³, and Carmem S. Pfeifer^{4,*}

¹Piracicaba Dental School, Campinas State University, Prosthodontics and Periodontics, Av. Limeira, 901 Piracicaba, SP, Brazil. Zip Code 13414-903. Piracicaba, BR 13414-903

²Meridional Faculty - IMED, School of Dentistry, Prosthodontics and Dental Materials, Av. Senador Pinheiro, 304, Passo Fundo, RS, Brazil. Zip Code 99070-220

³Maringa State University, Department of Chemistry, Av. Colombo 5790, Maringa, PR, Brazil. Zip Code 87020-900

⁴Oregon Health and Science University, Biomaterials and Biomechanics, 611 SW Campus Dr, Portland, OR, USA 97239

Abstract

Thio-urethanes were synthesized by combining 1,6-Hexanediol-diisocyanate (aliphatic) with pentaerythritol tetra-3-mercaptopropionate (PETMP) or 1,3-bis(1-isocyanato-1-methylethyl)benzene (aromatic) with trimethylol-tris-3-mercaptopropionate (TMP), at 1:2 isocyanate:thiol, leaving pendant thiols. Oligomers were added at 10–30 phr to BisGMA-UDMA-TEGDMA (5:3:2, BUT). 25wt% silanated inorganic fillers were added. Commercial cement (Relyx Veneer, 3M-ESPE) was also evaluated with 10–20 phr of aromatic oligomer. Near-IR was used to follow methacrylate conversion (DC) and rate of polymerization ($R_{p_{max}}$). Mechanical properties were evaluated in three-point bending (ISO 4049) for flexural strength/modulus (FS/FM, and toughness), and notched specimens (ASTM Standard E399-90) for fracture toughness (K_{IC}). Polymerization stress (PS) was measured on the Bioman. Volumetric shrinkage (VS, %) was measured with the bonded disk technique. Results were analyzed with ANOVA/Tukey's test ($\alpha=5\%$).

In general terms, for BUT cements, conversion and mechanical properties in flexure increased for selected groups with the addition of thio-urethane oligomers. The aromatic versions resulted in greater FS/FM than aliphatic. Fracture toughness increased by twofold in the experimental groups (from 1.17 ± 0.36 to around 3.23 ± 0.22 MPa.m^{1/2}). $R_{p_{max}}$ decreased with the addition of thio-urethanes, though the vitrification point was not statistically different from the control. VS and PS decreased with both oligomers. For the commercial cement, 20 phr of oligomer increased DC, vitrification, reduced $R_{p_{max}}$ and also significantly increased K_{IC} , and reduced PS and FM.

*corresponding author: Carmem S. Pfeifer, DDS, PhD, Assistant Professor, Oregon Health and Science University, Biomaterials and Biomechanics, 611 SW Campus Dr, rm 501, Portland, OR, USA 97239, Tel: 503-494-3288, Fax: 503-494-8260, pfeiferc@ohsu.edu.

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Thio-urethane oligomers were shown to favorably modify conventional dimethacrylate networks. Significant reductions in polymerization stress were achieved at the same time conversion and fracture toughness increased.

Keywords

resin cements; thio-urethane oligomers; polymerization stress; mechanical resistance

1. Introduction

Bonded indirect restorations play a major role in contemporary dentistry [1]. Resin cements have become popular clinically because of their ability to bond both to the tooth structure and to the restoration [2]. Examples of their clinical applications include adhesion of ceramic fragments, crowns, bridges, and intra-canal posts. Due to the necessary (and sometimes excessive) taper on tooth preparations, and to constant incidence of tensile, compressive and oblique loads, resin cements must have high mechanical properties, as well as resistance to dissolution and strong bond to structures [2–4].

Conventional resin cements are based on methacrylate monomers which undergo vitrification at early stages of polymerization [5], increasing the strain/stress at the bonded interface and in the bulk of the material structure [6]. This condition increases the risk of gap formation at the interface of cementation, which may lead to an increase of the material solubility, microleakage and staining, ultimately compromising the longevity of treatment [7]. Based on the confined geometry in which the cement is applied, current operator techniques available are not efficient in avoiding the development of strain/stress during the indirect restoration placement and, therefore, the solution to minimize stress generation needs to be based on improvements made directly to the material [8].

The use of thiol-enes has been proposed in dental composites, with successful results as stress reducing agents. The step growth nature of the thiol-ene and thiol-methacrylate polymerizations, given by chain-transfer reactions of the thiol to the ene/vinyl, leads to more homogeneous network formation and ultimately increased conversion in comparison to the pure methacrylate counterparts [9,10] and for selected compositions, improvements in flexural strength, depth of cure and water solubility have also been reported [9,11]. However, concerns over the somewhat compromised mechanical properties and the stability (shelf-life) of the fully formulated composite materials have delayed the commercial translation of thiol-ene-based materials [9,12]. Another concern that applies to small molecule thiols is the foul odor associated with the material.

As an alternative to conventional thiol-enes or thiol-methacrylates, others have proposed the use of thio-urethane networks in applications where mechanical properties in general, but more specifically toughness and resistance to impact, are desirable [13,14]. Some studies have demonstrated the more homogeneous nature of thiourethane networks compared to the simple urethane counterparts, as well as the increased toughness values [13,14]. In those studies, thiols are combined with isocyanates *in situ*, in a reaction catalyzed by a base. Currently, these are two-part systems (at least until compounds such as photo-base

generators are readily accessible – [15], not suitable for dental composite applications. However, previous studies have demonstrated it to be possible to synthesize high molecular weight pre-polymerized thio-urethane oligomers to be later added to a secondary monomer matrix, polymerizable through a radical mechanism [16]. When the oligomer is designed to have pendant thiols from the backbone, chain-transfer reactions to the surrounding methacrylate matrix result in delayed gelation and vitrification and, as consequence, reduction in polymerization stress [16]. Due to the high molecular weight, reductions in the volumetric shrinkage are also expected, as well as the elimination of the odor concerns. Importantly, thiol-terminated thio-urethanes are capable of forming a more homogeneous network with the methacrylate, and also increase final conversion [17]. Therefore, the objectives of this study were to synthesize thiol-terminated thio-urethane oligomers with different backbone structures and to assess the properties of methacrylate-based resin cements modified with the oligomers. The hypotheses of this study were that the use of thio-urethanes would (I) increase the degree of conversion, (II) improve the material mechanical properties and (III) reduce the volumetric shrinkage/polymerization stress.

2. Materials and Methods

2.1 Experimental materials composition

The experimental resin cement formulated for the study (BUT) was composed of Bis-phenol A diglycidyl dimethacrylate (Bis-GMA; Esstech, Essington, PA, USA), urethane dimethacrylate (UDMA; Esstech) and tri-ethylene glycol dimethacrylate (TEGDMA; Esstech) in a 50:30:20 mass ratio. Photoinitiators were added to the matrix as follows: 0.6 wt % of a tertiary amine (EDMAB - ethyl 4-dimethylaminobenzoate; Avocado, Heysham, England), 0.2 wt% of dl-camphoroquinone (Polysciences Inc., Warrington, PA, USA), and 0.5 wt% inhibitor (BHT - 2,6-di-tert-butyl-4-methylphenol; SigmaAldrich, St. Louis, MO, USA).

Oligomers were synthesized in solution (methylene chloride) by combining 1,6-Hexanediol-diisocyanate (HDDI) (aliphatic) with pentaerythritol tetra-3-mercaptopropionate (PETMP) or 1,3-bis(1-isocyanato-1-methylethyl)benzene (BDI) (aromatic) with trimethylol-tris-3-mercaptopropionate (TMP), at 1:2 isocyanate:thiol molar ratio, leaving pendant thiols. Triethylamine was used as a base in catalytic amounts. Oligomers were purified by precipitation in hexanes and rotaevaporation, and then characterized by ¹H-NMR and mid-IR spectroscopy [18]. The disappearance of the isocyanate peak at 2270 cm⁻¹ and the appearance of resonance signals at 3.70 ppm were used as evidence for completion of isocyanate reaction and thio-urethane bond formation, respectively [19]. Thio-urethane oligomers were added to the methacrylate organic matrix in proportions of 0 (control), 10, 20 and 30 parts per hundred resin, phr (which corresponds to 9.1, 16.7 and 27.7 wt%, respectively).

Filler was introduced at 25 wt% (15% OX-50 - 0.04 µm; 85% Barium glass 0.7 µm, density 3.0 g/ml, refractive index 1.553 - V117 4107, Esstech), with the aid of a mechanical mixer (DAC 150 Speed mixer, Flacktek, Landrum, SC, USA) for 5 min at 2400 rpm. All procedures were carried out under yellow lights.

One commercial light-cured cement (RelyX Veneer, 3M Espe, St. Paul, USA – lot N521803; Ref 7614A1, A1/light yellow shade) composed by BisGMA/TEGDMA and 66wt% zirconia/silica filler was modified by addition of 10 and 20 phr of aromatic oligomer to the organic matrix (or 9.1 and 16.7 wt%, respectively). The unmodified cement served as the commercial control.

2.2 Photopolymerization reaction kinetics and degree of conversion

The degree of conversion (DC) was obtained using near-infrared (NIR) spectroscopy in specimens of 10 mm in diameter and 0.8 mm thick laminated between two glass slides. The methacrylate =CH₂ absorption at 6165 cm⁻¹ [20] was recorded before and after 60s of irradiation at 700 mW/cm² (Bluephase, Ivoclar vivadent, Lichtenstein) with the light source in direct contact with the glass slide mold. Real-time monitoring of the polymerization kinetics was carried out in specimens of the same size at 2 scans per spectrum with 4 cm⁻¹ resolution, which provides a greater than 2 Hz data acquisition rate. Kinetic data was collected continuously for 5 min. Samples (*n*=3) were irradiated for 60s at an incident irradiance of 550 mW/cm². The light attenuation in this case was due to a distance of 2 cm separating the tip of the light guide and the surface of the specimen.

2.3 Flexural strength, elastic modulus and toughness

Flexural strength of the samples was measured according to the 3-point bending method carried out with a universal test machine (Q-test, MTS, Eden Prairie, WI) at a cross-head speed of 0.5 mm min⁻¹. The bar specimens were prepared in dimensions of 2 mm × 2 mm × 25 mm according to ISO 4049 [21]. The specimens (*n*=10) were fabricated between glass slides and photopolymerized with three overlapping 60 s exposures at 700 mW/cm². Specimens were stored for one week in dark containers at room temperature. The flexural strength (FS) in MPa was then calculated as:

$$FS(\sigma) = \frac{3Fl}{2bh^2}$$

where *F* stands for load at fracture (N), *l* is the span length (20 mm), and *b* and *h* are the width and thickness of the specimens in mm, respectively.

The elastic modulus was determined from the slope of the initial linear part of stress– strain curve.

$$E = \frac{Fl^3}{4bh^3d}$$

F = the load at some point on the linear region of the stress-strain curve

d = the slack compensated deflection at load *F*

l, *b*, and *h* are as defined above

Toughness was calculated in MPa from the integration of the stress×strain curve using software (Origin 9.1, OriginLab Corporation, Northampton, MA, USA).

2.4 Volumetric Shrinkage

The bonded disk method was used to evaluate volumetric shrinkage [22]. Resin cements were placed into a brass ring of approximately 16 mm in diameter and 1.5 mm in height bonded to a glass slide. The cement ($n=5$) was placed so that it did not come in contact with the brass ring, and then the assembly was covered with a microscope cover slip (approximately 0.1 mm thick). A linear variable differential transducer (LVDT) probe was placed in contact with the center of the cover slip. The cement was photoactivated for 60 s at an incidence of 700 mW/cm². As the cement cures and shrinks, it pulls the cover slip down and its deflection is monitored by the LVDT probe. Displacement data was obtained from the signal output of the transducer (in mV). The volumetric shrinkage (%VS) value was calculated as follows:

$$\%VS = \frac{(V_f - V_i) \times f}{h} \times 100$$

Where: V_f is the final displacement value given after polymerization and, V_i is the initial value given by the LVDT probe, in mV, f is the multiplier from the calibration curve and h is the cement specimen thickness after the polymerization, in μm .

Conversion-based predicted shrinkage was calculated according to the equation [23]:

$$VS = [C - C_0] \times DC \times \kappa$$

Where $[C - C_0]$ is the initial carbon-carbon double-bond concentration (in mol/mL); DC is the fractional degree of conversion and κ is the molar shrinkage coefficient for methacrylates (20.4 mL/mol) [24]. Experimental and conversion-based predicted polymerization shrinkage results were compared to highlight the possible effect of phase-separation on dimensional change.

2.5 Polymerization stress

Polymerization stress development was followed in real-time using the Bioman, described previously [25]. This system consists of a cantilever load cell whose extremity is fitted to a rigid integral clamp on its free end. The clamp holds a 10 mm diameter and 22 mm tall steel rod vertically and perpendicular to the load cell axis. A 5-mm diameter, 0.5-mm tall steel rod was fixed at the center of the lower face of the standard rod with a cyanoacrylate adhesive to produce a rod substrate with a reduced surface area to be consistent with a C-factor of 4. The surface of the rod was treated with a thin layer of Metal primer (Z-prime plus, Bisco, Schaumburg, IL). The opposite surface was a rigid fused silica glass plate of 3 mm thickness, treated with a thin layer of silane ceramic primer (3M ESPE, St. Paul, MN, USA). The cement ($n=5$) was then inserted into the 0.5-mm gap between the upper rod and the lower glass slide and shaped into a cylinder. The specimens were photoactivated through the glass during 60 s at an incident irradiance of 700 mW/cm² (Bluephase) and the stress followed for 500 s. The load signal from the cantilever cell was amplified and acquired by a computer.

2.6 Fracture toughness

The fracture toughness of all materials was determined from the stress intensity factor (K) during crack propagation. To determine the fracture toughness (FT), single-edge notch beam (SENB) specimens ($n=5$) were fabricated according to ASTM Standard E399-90 [26] in a 5 mm × 2 mm × 25 mm split steel mold with a razor blade providing a 2.5 mm notch in the center of the specimens. The cement was photoactivated for 60 s at an incidence of 700 mW/cm². The bending fracture test was performed at a crosshead speed of 0.5 mm min⁻¹ using a universal test machine (Q-test) and the fracture toughness (critical stress intensity factor, K_{IC}) was calculated according the following equation:

$$K_{IC} = \frac{3PL}{2BW^{3/2}} \left\{ 1.93 \left(\frac{a}{W} \right)^{1/2} - 3.07 \left(\frac{a}{W} \right)^{3/2} + 14.53 \left(\frac{a}{W} \right)^{5/2} - 25.11 \left(\frac{a}{W} \right)^{7/2} + 25.8 \left(\frac{a}{W} \right)^{9/2} \right\}$$

where P is load at fracture (N), L , W , B , and a are length, width, thickness, and notch length (in mm), respectively. The span length and load cell capacity were 20 mm and 60 N, respectively. The subscript IC denotes mode I crack opening under a normal tensile stress perpendicular to the crack [12,27].

2.7 Statistical analysis

For the experimental cement, statistical analysis was carried out using two-way ANOVA (thio-urethane concentration and thio-urethane type). One-way ANOVA was performed for the commercial cements, once they used only aromatic oligomers. Multiple comparisons were done using Tukey's test. All tests were carried out at a global level of significance of 95%.

3. Results

3.1 Photopolymerization reaction kinetics and degree of conversion

3.1.1 Experimental cement—The degree of conversion (Table 1) in the groups modified with the aliphatic version of thio-urethanes increased significantly from 64.87±0.44% (control) to up to 73.5±0.3% (30 phr thio-urethane) ($p=0.000$). In the groups modified with aromatic thio-urethanes, a slight reduction was observed in DC for the 20 phr group compared to the control (from 64.87±0.44% to 63.6±0.4%). Aliphatic thio-urethanes were statistically superior to aromatics for all groups within the same concentration ($p=0.000$). The two factors (thiourethane type and concentration) presented statistical interaction ($p=0.000$).

A statistical reduction in the maximum rate of polymerization ($R_{p_{max}}$) values was observed for all experimental groups in comparison to the control ($p=0.000$). For groups modified with the aliphatic thio-urethanes, there was no statistical difference amongst all concentrations. For the aromatic thio-urethanes, $R_{p_{max}}$ was statistically higher for the 10 phr compared to 30 phr. The 20 phr group was statistically similar to 10 and 30 phr. $R_{p_{max}}$ was also influenced by the thio-urethane type, with aromatic thio-urethane groups presenting higher $R_{p_{max}}$ within the same concentration ($p=0.004$). No interaction between the two

factors was observed for $R_{p_{max}}$ ($p=0.188$). All values are presented in Table 1. The conversion at $R_{p_{max}}$ was used as a measure of network vitrification [5], as shown in Table 1. Even though the analysis of variance showed statistical differences between some groups ($p=0.035$), all experimental groups presented results statistically similar to the control.

Figure 1 presents the kinetic profiles of all groups formulated with BisGMA/UDMA/TEGDMA. For some examples (20 and 30 phr aliphatic – 20 AL and 30 AL, respectively, and 30 phr aromatic – 30 AR), not only is the maximum rate of polymerization ($R_{p_{max}}$) lower than the control, but the rate of deceleration is also lower, as evidenced by the $R_{p_{max}} \times DC$ curves shown in Figure 1.

3.1.2 Commercial cement—All results for the commercial cements are presented in Table 2. The use of 20 phr of aromatic thio-urethane oligomer led to an increase in DC ($p=0.030$) in comparison with the control, which in turn was statistically similar to the 10 phr group. Similar to the BUT groups, thio-urethanes caused a statistically significant reduction of the $R_{p_{max}}$ for both concentrations ($p=0.000$), which did not differ from each other. A higher conversion at vitrification for the thio-urethane-modified groups in relation to the control was observed ($p=0.048$).

3.2 Flexural strength, elastic modulus and toughness

3.2.1 Experimental cement—All aromatic groups caused an increase in the flexural strength (FS) (Table 3) in regards to the control, which was only observed for 20 phr aliphatic thio-urethanes ($p=0.000$). The aromatic thio-urethane presented statistically higher values of FS compared to the aliphatic version ($p=0.004$). There was no statistical interaction between the factors (thio-urethane concentration and type) ($p=0.265$).

All groups presented flexural modulus similar to the control, with two exceptions. The use of 10 phr of aromatic thio-urethane caused a statistically significant increase in the flexural modulus, whereas the use of 30 phr aliphatic thio-urethane led to a statistically significant decrease in modulus ($p=0.000$) (Table 3). The thio-urethane type showed to be statistically significant, with aromatic group being superior to aliphatic ($p=0.000$). The interaction between the factors was significant ($p=0.020$). After these evaluations, the analyses with 30 phr of oligomer were discontinued.

As far as toughness (Table 3), aliphatic thio-urethane groups presented a statistically significant increase in the results ($p=0.000$), independent of the concentration. Aromatic oligomers did not affect toughness. The aliphatic oligomer was statistically superior to the aromatic for both concentrations ($p=0.000$). The interaction between the two factors was also significant ($p=0.023$).

3.2.2 Commercial cement—The addition of 20 phr of aromatic thio-urethane led to a statistically significant reduction in the flexural modulus ($p=0.000$) of the commercial cement, whereas the 10 phr group was similar to the unmodified control. For flexural strength ($p=0.062$) and toughness ($p=0.104$), no statistical difference was observed among the groups. All values are presented in Table 2.

3.3 Volumetric Shrinkage

For the BisGMA/UDMA/TEGDMA experimental cement, all groups containing thiourethane oligomers provided a statistically significant reduction in the volumetric shrinkage values in relation to the control ($p=0.000$), which was not dependent of the thio-urethane concentration (Figure 2A). The thio-urethane type also influenced the volumetric shrinkage, with the aliphatic one leading to lower values for both concentrations ($p=0.000$). Interaction between the two factors was observed ($p=0.001$). The groups with 10 phr and 20 phr of aromatic thio-urethane led to a reduction of 15.5% and 19.5% of the volumetric shrinkage, respectively. For the aliphatic oligomers, the addition of 10 and 20 phr led to shrinkage reductions of 39.8% and 52.4%, respectively. In the commercial material, the same tendency in reduction was observed for thio-urethane groups, although not statistically significant ($p=0.106$) (Figure 2B). The groups with 10 phr and 20 phr of thio-urethane concentration led to a reduction of, respectively, 5.6% and 21.2% in relation to the control group.

Based on the prediction, the theoretical shrinkage calculated for the control was 5.9%. For the aromatic thiourethane, at a concentration of 10 and 20 phr, the calculated shrinkage values were 5.3 and 4.7 %, respectively (reductions in shrinkage in relation to the control of 10.2 and 20.3 %, respectively) (Figure 3A). For the aliphatic thiourethane, at a concentration of 10 and 20 phr, the calculated shrinkage values were 5.5 and 5.1 %, respectively (reductions in shrinkage in relation to the control of 6.8 and 13.6 %, respectively) (Figure 3B).

3.4 Polymerization stress

For the experimental material, the polymerization stress was statistically reduced in the thio-urethane groups ($p=0.000$), with 20 phr of aliphatic material showing the lowest values (Figure 4A). The thio-urethane type ($p=0.120$) and the interaction between the factors (0.311) were not statistically significant. The concentration of 10 phr and 20 phr led to a reduction of polymerization stress of 47.6% and 61.5%, respectively, in the aromatic material and 55.1% and 86% in the aliphatic material. For the commercial cement, a statistically significant reduction in the polymerization stress was observed with 20 phr of aromatic oligomer ($p=0.033$), 36.7% lower than control, which in turn was similar to the material with 10 phr thio-urethane (Figure 4B).

3.5 Fracture toughness

Fracture toughness results for both thio-urethane-modified groups were statistically higher than the control, with 20 phr aliphatic showing the highest values among them ($p=0.000$). The aliphatic oligomer in 20 phr of concentration was statistically superior to the aromatic in the same concentration ($p=0.011$). The interaction between the two factors was significant ($p=0.034$). The addition of aromatic thio-urethanes led to increases of 88.8% and 108.5% in fracture toughness and the addition of aliphatic versions led to an increase of 105.9% and 176% in fracture toughness, for the 10 and 20 phr concentrations, respectively (Figure 5A). For the commercial material, the addition of 20 phr of aromatic thio-urethane led to a significant increase in fracture toughness ($p=0.020$) 25.5% higher than control, which was

also similar to the 10 phr group (Figure 5B). All fracture toughness specimens failed catastrophically (no plastic deformation was observed prior to failure).

4. Discussion

This study evaluated the potential for mechanical property improvement and stress reduction with the use of light-cured resin cements modified by the addition of thiolterminated thio-urethane oligomers. The stress reduction potential of thiolfunctionalized materials and the toughening potential of thio-urethane networks have been well documented in the literature [13,14]. In this study, the kinetics of polymerization was used as a way to assess network formation and final degree of conversion for methacrylates modified with thio-urethane oligomers. The maximum rate of polymerization marks the end of autoacceleration, or the point in conversion at which network mobility restrictions impair chain propagation, with further contributions to conversion occurring in the vitrified state [5]. For pure methacrylates, deceleration almost immediately follows $R_{p_{max}}$ (Figure 1), which typically occurs at lower conversion, around 15–20 % [6,17]. The addition of molecules with potential for chaintransfer, such as the thiol-terminated oligomers, tends to delay the end of auto acceleration to higher conversions, as well as decrease deceleration rates [16,28]. For the modified groups, even though the conversions at vitrification were similar to the methacrylate control, the rate of deceleration was much lower (Figure 1). The slightly delayed vitrification and the slower deceleration then can be attributed to chain-transfer reactions of the pendant thiols to the methacrylate, which delay network formation and the build-up of diffusional limitations to propagation [17]. In general, the use of thiourethane-modified materials not only increased the degree of conversion in relation to the control, but was also able to reduce the rate of polymerization and delay vitrification for selected compositions. Chain-transfer reactions also likely contributed to the formation of more homogeneous networks, with decreased internal stresses [13], as will be discussed later. Assuming that the thiol concentration and the molecular weight of the oligomer were similar in all groups (which was verified in a pilot study using Ellman's reagent titrations and gel permeation chromatography), it can be inferred that the effect on conversion and network formation was dependent on the thio-urethane structure, as well as on the secondary matrix to which they were added. For the experimental cements, comprised of BisGMA/UDMA/TEGDMA, the addition of the aliphatic version of the thio-urethane was better able to increase conversion while reducing $R_{p_{max}}$, which can be explained by the flexibility of the structure given not only by the thio-urethane bonds but also by the absence of aromatic rings or other rigid substitutions [29]. So, the first hypothesis that the oligomers would increase the degree of conversion was partially accepted. Indeed, a similar effect was only observed for aromatic thio-urethanes at higher concentrations (Figure 1). The increased flexibility may have facilitated the chain-transfer reactions within the methacrylate matrix [29]. even though the effect on the conversion at $R_{p_{max}}$ (vitrification) was not as marked in relation to the control. Statistical differences ($p=0.035$) were still observed amongst thio-urethane-modified groups in regard to vitrification. It is noteworthy that the degree of conversion calculated from the kinetic runs was based on an irradiance of 550 mW/cm², and resulting radiant exposure of 33 J/cm², due to test geometry limitations. The degree of conversion obtained from specimens directly irradiated (700 mW/cm² with radiant exposure of 42 J/

cm²) were, as expected, significantly higher. At that higher irradiance, the ranking of conversions presented by cements modified by the aliphatic × aromatic versions of the thio-urethanes is similar as presented from the kinetics run (Table 1). The influence of irradiance on network formation was beyond the scope of this study. For the commercial cement (Table 2), even the aromatic version of the thio-urethane was able to increase conversion by 4.4 % and delay vitrification to a conversion 46.6 % higher. In this case, the exact composition of the methacrylate matrix is not known, but it can be speculated that the flexibility of the thio-urethane bond (in spite of the presence of a more rigid core structure) may have been enough to facilitate the formation of a more homogeneous network, as can be inferred from the reduction of $R_{p_{max}}$ and extended deceleration profile shown in Figure 1 for the experimental materials.

The addition of aromatic thio-urethanes to materials formulated with BisGMA/UDMA/TEGDMA led to an increase of flexural strength of up to 35% (20 phr). For the aliphatic versions, the increase in flexural strength was not as marked, reaching about 19% for the 20 phr concentration. The same trend was observed in terms of flexural modulus, except that for the aliphatic version at 30 phr concentration, in which a reduction was actually observed (Table 3). These results can be explained based on the rigidity of the aromatic rings present in the aromatic versions of the thiourethane, while for the aliphatic version the combination of the flexible thio-urethane bonds with the flexible backbone of both the thiol and the isocyanate precursors were not as efficient at improving flexural strength and modulus of the secondary matrix. This was true in spite of the potentially greater ability to form crosslinks by the aliphatic thio-urethane, once the thiol precursor used in the synthesis is tetra-functional, as opposed to the tri-functional thiol used to make the aromatic thio-urethane. On the other hand, it is evident that the aliphatic version of the thio-urethanes was much more efficient at increasing toughness than the aromatic version, which can also be credited to the greater flexibility of the structure of the former. The toughness value achieved with 20 phr aliphatic thio-urethane (8.21 MPa) represented a 3.5 fold increase in comparison with the control (2.37 MPa). Similar trends have been previously reported in studies where the reaction between isocyanate and thiol took place in situ to form thio-urethane networks in the presence of a base [13]. In the case of those previous studies, thiourethanes were shown to form much more homogeneous networks compared to simple urethanes, though with a slight decrease in glass transition temperature in some cases [13].

For the commercial material, the values of flexural strength and toughness were not affected by the addition of thio-urethane, while the flexural modulus decreased for the 20 phr concentration in relation to the control (Table 2). In this case the correlation between mechanical properties and thio-urethane concentration is complicated by the fact that the oligomers were added to the fully formulated material, and therefore, the filler content for the modified materials was progressively lower than for the unmodified control. Since the commercial material contains 66 wt% filler, according to the manufacturer literature, adding 10 and 20 phr thio-urethane brings the filler content to 63.6% and 60.8 wt%, respectively, which may explain the lack of statistical significance for flexural strength and toughness and the decrease in flexural modulus observed in this study, as these properties are heavily dependent on the inorganic content [30]. In fact, a previous study has shown that the elastic modulus drops from 5.9 to 4.3 GPa when the filler content is reduced by only 5%, from 60

to 55 vol.% [30], which represents roughly a 30 % reduction in modulus. In our case, the reduction in filler content led to a drop in modulus of about 20%, lower than expected based on those previous results. It is also interesting to note that, in spite of the much higher filler content on the commercial materials, the toughness results obtained with the addition of thio-urethanes to BisGMA/UDMA/TEGDMA are not much lower than the ones obtained with the modified commercial materials, which demonstrates the potential for toughening of methacrylate networks with the use of thio-urethanes.

One of the mechanical properties that have been shown to correlate with clinical results is fracture toughness [31]. The groups modified with the aromatic version of the thio-urethanes presented an increase of 88.8% and 108.5% and the groups modified by aliphatic showed an increase of 105.9% and 176% in the K_{IC} for 10 phr and 20 phr concentrations, respectively, for the material formulated with BisGMA/UDMA/TEGDMA. The more than 2-fold increase for the 20 phr concentration can be explained both by a more homogenous network, as already explained, but mainly by the combined contributions of the thio-urethane and the thiolmethacrylate bonds. Moreover, the most flexible structure of PETMP combined with the aliphatic diisocyanate, HDDI, led to significant higher values than the aromatic version. In the same way, the modification of commercial cement also significantly increased the K_{IC} by 25%, with 20 phr of oligomer, in spite of the overall reduction in filler content, as explained above. This is important for resin cements because their clinical application consists in a thin layer of material placed over a tapered preparation constantly subjected to tensile, compressive and oblique loads, with relatively common micro-defects into its structure. In addition, not only is this relatively simple modification important for resin cements, it also provides another avenue for increase in mechanical properties in heavily filled composites, as will be explored in a different study. Generally, the second hypothesis of this study, that thio-urethanes would improve the mechanical properties of resin cements, was accepted.

The volumetric shrinkage (VS) showed significant reductions of 15.5% and 19.5% for aromatic and 39.8% and 52.4% for aliphatic thio-urethane oligomers when added to the non-commercial cement at 10 and 20 phr concentrations, respectively. This was expected based on the decrease in concentration of methacrylate double-bonds per unit volume of the material [23], and indeed the percent reductions in shrinkage, at least for the aromatic versions, are in agreement with the amount of thio-urethane added [32]. The predicted reductions in shrinkage in relation to the control for the aliphatic groups were calculated as 10.2 and 20.3 %, respectively. It is important to note that the reduction in shrinkage was not accompanied by a reduction in conversion, as previously discussed. Much on the contrary, conversion values either stayed constant or increased, as was the case for the aliphatic version. Interestingly, the aliphatic thio-urethane showed shrinkage reductions of 39.7 and 52.3 % with the addition of 10 and 20 phr oligomer in comparison to the control, much higher than predicted based on the molar shrinkage coefficient and the increased conversion [23]. The predicted reductions in shrinkage in relation to the control for the aliphatic groups were calculated as 6.8 and 13.6%, respectively. One hypothesis that may explain this finding is free volume entrapment within the pre-polymerized network, as is the case for more flexible structures such as the aliphatic thio-urethane [33]. For the commercial material, the correlation between the percent reduction in shrinkage (5.6% and 21.2% for the 10 and 20

phr of aromatic concentrations, respectively) is complicated by the dilution of the filler content for the modified materials compared to the un-modified control, as well as the higher filler content on the commercial materials, as already discussed for the mechanical properties. This may help explain why there was no statistically significant difference among the commercial materials groups in terms of shrinkage.

The volumetric shrinkage reduction, in turn, helps explain the significant lower polymerization stress obtained with thio-urethane-based materials. The addition of 10 and 20 phr of thio-urethanes led to reductions in stress values of 44.2% and 61.6%, respectively, for the aromatic version, and 55.1% and 86%, respectively, for the aliphatic version in relation to the control for the non-commercial materials tested. It is important to note that the elastic modulus and the conversion were similar or greater for all modified formulations in relation to the control, as already discussed. It is important to note that even though there was a reduction in shrinkage, it was not large enough to completely justify the level of reduction in stress observed in this study. Hence, it can be inferred that chain-transfer reactions from the pendant thiols on the thio-urethane backbone to the surrounding methacrylate matrix indeed delayed gelation/vitrification, as demonstrated by the kinetic profiles for these materials, shown in Figure 1. Even though the conversion at vitrification did not seem to be significantly affected by the addition of thio-urethane, the rate of deceleration was significantly lower, which was possible by avoiding early-stage diffusion limitations to polymerization [28], reducing the stress development, which typically increases as soon as diffusion limitation occurs [9]. For the commercial cement, only the aromatic thio-urethane was tested for stress. The addition of 10 and 20 phr oligomer led to stress reductions of 11.1% and 36.7%, respectively, although only the 20 phr group was statistically lower than the control. Again, for the 20 phr group, the stress reduction was greater than expected based on the shrinkage reduction alone, especially when the increase in conversion is considered. On the other hand, in the case of the commercial material, the stress reduction for the group containing 20 phr oligomer is partially explained by the reduction in modulus, which in turn stemmed from the dilution of filler, as already discussed. Therefore, because the composition was not completely controllable for the commercial material, and given the complex nature of the factors leading to polymerization stress, the effect of thiourethanes in stress reduction in commercial materials was not conclusive. Taking in consideration the experimental material formulated front controlled proportions, it can be established that the third hypothesis of this study, that oligomers would cause a reduction in the volumetric shrinkage and polymerization stress, can be accepted.

5. Conclusion

For the cements where the composition was completely known (BisGMA/UDMA/TEGDMA experimental cements, 25 wt% filler), it was demonstrated that thio-urethane oligomers, specially the aliphatic versions, are able to improve conversion and mechanical properties, with more than 2 fold increases in toughness and fracture toughness. At the same time conversion and properties improved, polymerization shrinkage and stress are significantly reduced for selected compositions. This was accomplished using photoinitiators commonly present in commercial materials, facilitating the bench top to chair-side implementation of such additives without changing common operator procedures.

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Highlights The formulation of resin cement with thio-urethane oligomers provided

1. Increase in Degree of conversion and reduction in $R_{p_{max}}$
2. Reduction in volumetric shrinkage and polymerization stress
3. Significant increase in toughness and fracture toughness
4. Increased flexural strength

Figure 1. Degree of conversion as a function of the rate of polymerization for the control and experimental groups. The organic matrix is composed of BisGMA/UDMA/TEGDMA and aromatic (AR) or aliphatic (AL) thio-urethanes at increasing concentrations (10–30 phr).

Figure 2.
Volumetric shrinkage for the (A) BisGMA/UDMA/TEGDMA cement and (B) for the commercial cement (RelyX Veneer).

Figure 3. Theoretical and experimental volumetric shrinkage for the (A) aromatic and (B) aliphatic oligomer.

Figure 4. Polymerization stress values for the (A) BisGMA/UDMA/TEGDMA cement and (B) for the commercial cement (RelyX Veneer).

Figure 5. Fracture toughness values for the (A) BisGMA/UDMA/TEGDMA cement and (B) for the commercial cement (RelyX Veneer).

Degree of conversion, maximum rate of polymerization ($R_{p_{max}}$) and conversion at vitrification for experimental cements. Values followed by the same superscript within the same test are statistically similar ($\alpha=5\%$).

Table 1

	Degree of conversion (%) [*]		$R_{p_{max}}$ (%·s ⁻¹) ^{**}		Vitrification (%) ^{**}	
	aromatic	aliphatic	aromatic	aliphatic	aromatic	aliphatic
control	64.87(0.44) ^d		4.5(0.6) ^a		15.7(1.1) ^{ab}	
10 phr	64.8(0.3) ^d	66.2(0.3) ^c	2.2(0.3) ^b	1.7(0.1) ^{b,c}	13(1.8) ^{ab}	11.6(1.6) ^b
20 phr	63.6(0.4) ^e	69.4(0.3) ^b	2.1(0.1) ^{b,c}	1.2(0.0) ^c	11.8(1.5) ^b	17.7(3.8) ^a
30 phr	64.9(0.4) ^d	73.5(0.3) ^a	1.6(0.1) ^c	1.2(0.2) ^c	18.2(2.2) ^a	15.2(4.1) ^{ab}

^{*} obtained from photoactivation accomplished with the light guide in direct contact with the specimen

^{**} obtained from specimens photoactivated in the IR chamber

Table 2

Mean and standard deviation for degree of conversion, maximum rate of polymerization (R_{pmax}), conversion at vitrification, flexural strength, flexural modulus and toughness for RelyX Veneer cement modified with aromatic thio-urethane oligomers. Values followed by the same superscript within the same test are statistically similar ($\alpha=5\%$).

	Degree of conversion (%)	R_{pmax} (% $\cdot s^{-1}$)	Vitrification (%)	Flexural strength (MPa)	Flexural modulus (GPa)	Toughness (MPa)
Control	65.35(0.16) ^b	4.69(0.13) ^a	10.93(0.50) ^a	234(24.86) ^a	8.06(0.79) ^a	4.76(0.55) ^a
10 phr	66.77(1.23) ^{ab}	1.35(0.34) ^b	15.36(1.17) ^b	226.42(27.89) ^a	7.09(0.94) ^{ab}	5.48(0.49) ^a
20 phr	68.25(1.15) ^a	0.75(0.03) ^b	16.03(3.39) ^b	205.03(28.03) ^a	6.42(0.74) ^b	5.5(0.8) ^a

Table 3

Mean and standard deviation for flexural strength, flexural modulus and toughness for the BisGMA/UDMA/TEGDMA cements modified with aromatic or aliphatic thio-urethane oligomers. Values followed by the same superscript within the same test are statistically similar ($\alpha=5\%$).

	Flexural strength (MPa)		Flexural modulus (GPa)		Toughness (MPa)	
	aromatic	aliphatic	aromatic	aliphatic	aromatic	aliphatic
control		90.61(18.91) ^c		2.02(0.17) ^b		2.37(0.62) ^b
10 phr	108.56(20.68) ^{ab}	100.96(15.84) ^{bc}	2.23(0.26) ^a	2.04(0.13) ^{ab}	3.83(0.78) ^b	7.32(1.96) ^a
20 phr	122.52(12.78) ^a	108.13(9.84) ^{ab}	2.15(0.11) ^{ab}	2.08(0.19) ^{ab}	3.48(1.36) ^b	8.21(3.69) ^a
30 phr	112.5(8.62) ^{ab}	95.28(6.28) ^{bc}	2.03(0.08) ^b	1.72(0.13) ^c	-	-