Original article

Polymerization shrinkage kinetics and degree of conversion of resin composites

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Abstract: This study compared shrinkage strain, polymerization shrinkage kinetics, and degree of conversion (DC) of a set of resin composites and investigated their influencing factors. Ten commercial resin composites were assessed, and 5 specimens (n = 5) were developed for material and subjected to light curing using light emitting diode light at 650 mW/cm² for 40 s. The laser triangulation method was adopted to assess the shrinkage strain, and Fourier transform infrared spectroscopy was used to measure DC. The shrinkage strain was monitored for 5 min in real time and its data were subjected to differential calculations to get the shrinkage strain rate curve with respect to time, obtaining the maximum shrinkage strain rate (R_max) and gel time. The values of shrinkage strain varied from 1.28% to 2.10%. The R_max values were between 5.17 μm/s and 21.83 μm/s. Gel time values varied from 3.08 s to 4.32 s. The DC yielded values ranging from 53.62% to 87.01%. The values of polymerization shrinkage and DC were dependent on the composition of materials, including the monomer matrix and filler system. Compared to the micro-filler materials, the nano-filler resin composites had higher values of DC. Some resin composites are suitable for clinical applications because of their superior polymerization shrinkage properties and DC.

Keywords: degree of conversion, gel time, resin composite, shrinkage strain, shrinkage strain rate

Introduction

Light-cured resin composite has emerged as the most widely used dental prosthetic material due to its good aesthetics, biocompatibility, and mechanical properties. However, it undergoes polymerization shrinkage during the curing process, causing high shrinkage stress that affects the bond between the tooth and the material. Thus, a slight gap may materialize to form a micro-leakage [1], resulting in secondary caries, marginal discoloration, postoperative sensitivity, and ultimately treatment failure [2]. Such shrinkage stress is impacted by the polymerization shrinkage kinetics, as a higher rate of polymerization generates higher polymerization stress [3]. Therefore, reducing resin composite polymerization shrinkage is an urgent problem that needs to be solved.

Resin composite is primarily composed of an organic matrix, inorganic filler, and an initiation system, with common organic matrices such as bisphenol-A glycol dimethacrylate (Bis-GMA), urethane dimethacrylate (UDMA), and triethylene glycol dimethacrylate (TEGDMA). The matrix undergoes a crosslinking reaction due to the effect of the initiating system, breaking the carbon-carbon double bonds (C=C) of the dimethacrylate monomer molecule. They are then converted to carbon-carbon single bonds (C-C) and form a polymer. Microscopically, intermolecular forces of the monomers are converted from van der Waals to covalent bonds, thereby minimizing the polymerization shrinkage [19]. These nano-fillers are typically composed of mono-dispersed nano-particles and nano-particle clusters; their ratio is increased filler content leads to a direct reduction of the polymerization shrinkage [18]. The hybrid fillers use multiple-sized fillers to enable the incremental filling technique is often used for traditional resin composite because it minimizes polymerization shrinkage and shrinkage stress while ensuring the curing effect. When used for deeper preparation, the operation steps are more complicated, the curing distance is longer, and operation time is longer. Bulk-fill resin composite is a solution to meet these clinical needs. It is capable of filling cavities of up to 4 mm increments, it simplifies the process, reduces the required clinical time, and minimizes the polymerization shrinkage and shrinkage stress [11-14].

The available bulk-fill resin composites are typically classified into 1 of 2 types: low viscosity and high viscosity [14]. The low-viscosity type shows a good flowability due to the low fraction of filler, and the high-viscosity type has a high fraction of filler but exhibits poor flowability [13]. Benetti et al. [15] compared the polymerization shrinkage of both types of bulk-fill resin composites and found that the shrinkage of the high-viscosity type is significantly smaller than that of the low-viscosity type. Therefore, the 3 bulk-fill resin composites studied in this experiment are all highly viscous in nature.

The method used to reduce polymerization shrinkage in commercial resin composites is mainly focused on the resin matrix and inorganic filler. Organically modified ceramics (Ormocers) and high molecular based monomers have been commercially introduced with regard to the matrix. Unlike traditional resins, Ormocers are made of organic-inorganic hybrid materials compounded at the molecular level that have low polymeriza- tion shrinkage [16]. Monomers with high molecular weights can minimize the number of covalent bonds present in the same volume of space, leading to a reduction in the final shrinkage [17]. Meanwhile, the inorganic filler greatly influences the volumetric shrinkage of the resin, whereby increased filler content leads to a direct reduction of the polymerization shrinkage [18]. The hybrid fillers use multiple-sized fillers to enable the smaller particles to fill the interstices between larger-sized particles, consequently increasing the mass fraction of inorganic filler and reducing the polymerization shrinkage [19]. These nano-fillers are typically composed of mono-dispersed nano-particles and nano-particle clusters; their ratio is optimized to effectively minimize the voids between fillers and increase the density of the inorganic fillers. Thus, this leads to an overall improve- ment of the materials’ mechanical properties and shrinkage reduction [20]. Additionally, the incorporation of prepolymerized fillers significantly reduces the amount of polymerizable resin and increases the content of fillers, thereby minimizing the polymerization shrinkage [19].

In this study, the shrinkage strain, polymerization shrinkage kinetics, usually represents the degree of resin composite polymerization. This is the percentage of polymerizable double bonds that are converted to single bonds.

The DC value of resin composite normally ranges from 52% to 75% [6,7]. The resin composite polymerization shrinkage is proportional to DC, in which an increment of DC leads to an increase in polymerization shrinkage [8]. However, DC greatly influences the mechanical and physical properties of the material. Decreased DC yields a smaller crosslink density of the polymer and creates materials with inferior mechanical properties and more discoloration and degradation, consequently decreasing their wear resistance and color stability [9]. Furthermore, lower DC results in worse biosafety quality of materials because more monomers are released. Therefore, the ideal resin composite should exhibit lower polymerization shrinkage and higher DC. Among several experimental methods of DC, Fourier transform infrared spectroscopy (FTIR) is currently the most commonly used, and it is capable of qualitatively and quantitatively reflecting the DC of materials [10].

The incremental filling technique is often used for traditional resin composite because it minimizes polymerization shrinkage and shrinkage stress while ensuring the curing effect. When used for deeper preparation, the operation steps are more complicated, the curing distance is longer, and operation time is longer. Bulk-fill resin composite is a solution to meet these clinical needs. It is capable of filling cavities of up to 4 mm increments, it simplifies the process, reduces the required clinical time, and minimizes the polymerization shrinkage and shrinkage stress [11-14].

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In this study, the shrinkage strain, polymerization shrinkage kinetics,
Table 1 Technical profiles of resin composites investigated in the study

| Type            | Materials                          | Code | Shade | Resin matrix                                      | Inorganic filler                                | Filler Content (vol% / wt%) | Manufacturer                      | Lot number   |
|-----------------|------------------------------------|------|-------|--------------------------------------------------|--------------------------------------------------|----------------------------|----------------------------------|--------------|
| Micro-hybrid    | Filtek Z250                        | Z2   | A2    | Bis-GMA, Bis-EMA, UDMA                            | Zirconia, silica                                 | 60/82                      | 3M Oral Care, St. Paul, MN, America | N657490      |
|                 | Filtek P60                         | P6   | A3    | Bis-GMA, Bis-EMA, UDMA                            | Zirconia, silica                                 | 61/84                      | 3M Oral Care                      | N799224      |
|                 | Surefil                            | SF   | A2    | Bis-GMA, UDMA                                     | Barium aluminum fluoride borosilicate glass, silica | 58-66/82                   | Dentply Caulk, Milford, Delaware, America | 170329       |
| Nano-hybrid     | Kalore                             | KA   | A2    | DX-511, UDMA, Dimethacrylate comonomer            | Fluorooaluminosilicate glass, silica, strontium / barium glass, prepolymerized filler (lanthanide fluoride) | 69/82                      | GC Corporation, Tokyo, Japan       | 1604261      |
|                 | Admira Fusion                       | AF   | A2    | Organic modified ceramics, Aliphatic and aromatic dimethacrylates | Silica, glass ceramics                           | /84                        | Voco GmbH, Lower Saxony, Cuxhaven, Germany | 1642447      |
|                 | Clearfil Majesty Posterior          | CMP  | A2    | Bis-GMA, TEGDMA, Hydrophobic amine dimethacrylate | Surface treated alumina micro-filler, silanated glass ceramics, silica | 82-92                      | Kuraray Nosticate Dental Inc, Tokyo, Japan | 630034       |
|                 | Premisa                            | PR   | A2    | Bis-EMA, TEGDMA                                   | Barium glass, prepolymerized filler, silica      | 69/84                      | Kerr Corporation, Orange, CA, USA | 6147069      |
| Bulk-fill       | Tetric N-Ceram Bulk Fill (Micro-hybrid) | TNC  | IVA   | Bis-GMA, Bis-EMA, UDMA                            | Barium glass, prepolymerized filler, ytterbium trifluoride, mixed oxides | 53-55/75-77                | Ivoclar Vivadent, Schaan, Liechtenstein | V35948       |
|                 | Filtek One Bulk Fill (Nano-filled)  | OBF  | A2    | UDMA, AUDMA, DDDMA, AFM, Dimethacrylate           | Zirconia, silica, ytterbium trifluoride           | 58.5/76.5                  | 3M Oral Care                     | N868903      |
|                 | X-tra Fill (Multi-hybrid)           | XF   | U     | Bis-GMA, UDMA, TEGDMA                             | Barium boron aluminum silicate glass              | 70.1/86                    | Voco GmbH,                        | 1543160      |

Bis-GMA, Bisphenol A glycol dimethacrylate; Bis-EMA, ethoxylated bisphenol-A dimethacrylate; UDMA, urethane dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; AUDMA, aromatic urethane dimethacrylate; DDDMA, 1,12-dodecanediol dimethacrylate; AFM, addition-fragmentation monomers

Fig. 1 The shrinkage strain measurement setup (laser triangulation method).

and DC of 10 commercially available resin composites were investigated. The null hypothesis was that there are no significant differences between the results of the materials.

Materials and Methods

Composite Materials
The current study assessed 10 commercially available resin composites from various manufacturers. The types and composition of these materials are summarized in Table 1. Filtek Z250, Filtek P60, Surefil, and Tetric N-Ceram Bulk Fill were micro-hybrid resin composites. Kalore, Admira Fusion, Clearfil Majesty Posterior, and Premisa were nano-hybrid resin composites. Tetric N-Ceram Bulk Fill, Filtek One Bulk Fill, and X-tra fill were bulk-fill resin composites.

Measurement of Shrinkage Strain

Measuring device
The laser triangulation method described by Gao and Zheng was used to determine shrinkage strain (patent right belongs to Peking University School of Stomatology) [21]. The device is shown in Fig. 1 and it is cited from ref. 21. The measurement device was a noncontact measuring system based on laser-ranging technology, which consists of a self-assembled measuring setup and a related professional software LK-Navigator (Keyence Corp., Osaka, Japan). The measuring setup was comprised of a slot for curing, a light emitting diode (LED) curing light (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein), 2 mounting bases, 2 laser displacement sensors (LK-G10 and LK-G30, Keyence Corp.), and an associated signal amplifier and PC card data acquisition system (NR2110, Keyence Corp.). The slot for curing was made of polytetrafluoroethylene (PTFE) and was rectangular-shaped, having a cavity through the transverse diameter. Its upper surface was not closed to facilitate direct illumination of the curing light. The curing mode of the LED curing light was low power and it was placed 2 mm above the slot with a light intensity of 650 mW/cm² for 40 s. Meanwhile, the laser sensors were mounted on the bases separately and placed at each end of the slot in order to measure the amount of shrinkage strain at both ends: its sum was recorded as total linear shrinkage strain. The resin composite specimen showed an outer dimension that was 6.00 mm long and a cross-sectional dimension of 2.00 mm × 2.00 mm.

Measurement process
The laser displacement sensor was preheated for 1 h, and the experiment was formally initiated after the voltage stabilized. The beam size was 20 μm and wavelength was 650 nm. The 2 PTFE molds were mounted and secured at both sides to form an intact cavity, while the inner surface of the slot was smeared with a small amount of silicone oil to increase lubrication. Then, 2 sandblasted and silanized aluminum sheets were placed on the side walls of the slot to ensure that the resin composite specimen did not adhere to the cavity. Following this, the resin composite was inserted into the slot, and the 2 PTFE molds were carefully removed after the resin was completely filled. At this point, the rectangular composite specimen adhered to the 2 aluminum sheets because of the resin viscosity and the pressure of the filling process. Next, the laser beam was aligned with the center of the aluminum sheets and the composite specimen subjected to light curing using the LED curing light for 40 s after the data acquisition...
The data acquisition process for linear shrinkage strain during the entire curing process was carried out for 5 min, as the polymerization shrinkage of the resin composite almost stopped after each duration. Each material was measured in an environment of 22 ± 1°C and 60 ± 10% relative humidity, and the medians were subsequently calculated accordingly (n = 5 per composite material). The linear shrinkage strain (lin%) could be converted into volumetric shrinkage strain (vol%) according to the following equation (Eq. 1) [22]:

$$\text{vol}\% = 3 \times \text{lin}\% - 0.03(\text{lin}\%)^2 + 0.0001(\text{lin}\%)^3$$ (1)

The shrinkage strain data were tested using the differential calculation to generate the shrinkage strain rate curve with respect to time. Subsequently, the maximum shrinkage strain rate ($R_{\text{max}}$) and the time at which $R_{\text{max}}$ occurred were obtained. Fano et al. [23] proposed that $R_{\text{max}}$ of resin composites occurs at gel point, because the auto-acceleration of the polymerization rate is a result of the “gel effect”. Therefore, the time at which $R_{\text{max}}$ occurred was recorded as the “gel time”.

Measurement of DC
The DC of the investigated resin composites was detected using FTIR (Nicolet iS10, Thermo Scientific, Waltham, MA, USA), which operated at a resolution of 4 cm⁻¹ with 32 scans, and the spectra ranged from 300 to 4,000 cm⁻¹. Five specimens were measured for each selected material, and the uncured specimens were smeared on potassium bromide sheets and their absorption peaks consequently recorded. Rueggeberg’s research showed that a light intensity of 400 mW/cm² was enough for the polymerization of a 2-mm thick resin composite specimen [24]. Therefore, a 650 mW/cm² LED curing light was used. The specimens of the 10 resin composites, each with a diameter of 6.00 mm and thickness of 2.00 mm, were irradiated for 40 s with an LED curing light at 650 mW/cm², then protected from light for 24 h. The cured specimens were ground into fine powder using a mortar and pestle. Ten milligrams of the ground powder were mixed with 100 mg of potassium bromide powder, after which the circular potassium bromide sheets were made using a pressure of 10 tons. Then, the FTIR spectra were recorded.

The DC was usually decided by a comparison of the peak height absorbance intensity of aliphatic C=C with that of aromatic C=C, before and after irradiation. The aliphatic C=C owned an absorption peak around 1,639 cm⁻¹, while the aromatic C=C was derived from the benzene rings in the monomer. A peak height around 1,609 cm⁻¹ became the internal standard because the intensity was unchanged during the polymerization process. DC was calculated using the following equation (Eq. 2):

$$\text{DC}\% = \frac{[1 - \text{cured (1,639 cm}^{-1}/1,609 \text{ cm}^{-1})/\text{uncured (1,639 cm}^{-1}/1,609 \text{ cm}^{-1})]}{100}\%$$ (2)

However, for some resin composites that do not contain Bis-GMA (KA, OBF, and AF), the carbonyl group (C=O) was used as the internal standard with peak at 1,720 cm⁻¹ because of the lack of benzene ring structure. DC was calculated using the following equation (Eq. 3):

$$\text{DC}\% = \frac{[1 - \text{cured (1,639 cm}^{-1}/1,720 \text{ cm}^{-1})/\text{uncured (1,639 cm}^{-1}/1,720 \text{ cm}^{-1})]}{100}\%$$ (3)

Statistical Analysis
Statistical software, SPSS ver. 19.0 (SPSS Inc., Chicago, IL, USA), was utilized for data analysis purposes, and the shrinkage strain, $R_{\text{max}}$, gel time, and DC results were evaluated using a nonparametric rank test. Kruskal-Wallis and Mann-Whitney U-test with Bonferroni correction were conducted for multiple comparisons in which the significance level for all tests was set at $\alpha = 0.05$. 

![Fig. 2](image1)

Shrinkage strain mean rank and distribution of the investigated materials.

![Fig. 3](image2)

$R_{\text{max}}$ mean rank and distribution of the investigated materials.

![Fig. 4](image3)

Gel time mean rank and distribution of the investigated materials.

![Fig. 5](image4)

Shrinkage strain rate curve for investigated materials.
Results

The results of the polymerization shrinkage kinetics of 10 resin composites are given in Figs. 2-5, while Fig. 6 reveals the results of DC. There were significant differences in the results obtained for all 10 resin composites ($P < 0.01$).

Shrinkage Strain

The shrinkage strain values varied from 1.28% (CMP) to 2.10% (TNC). The measured values were in the order of TNC > SF = Z2 = P6 = OBFB = XF > PR > KA ≥ AF = CMP (Fig. 2). The shrinkage strain value of TNC was the highest and was statistically different from that of other resin composites. The materials SF, Z2, P6, OBFB, and XF showed intermediate values and there were no statistical differences among them, but they did exhibit significant differences compared with other resin composites. CMP presented the lowest shrinkage strain value, which showed no significant difference compared to AF and KA.

R$_{max}$ and Gel Time

The shrinkage strain rate curves, with respect to time, of 10 resin composites are shown in Fig. 5. There was a rapid increase in the shrinkage strain rate that occurred at the beginning of photopolymerization until the peak was reached, and thereafter, a slower decrease was observed before the polymerization reaction was stopped. The shrinkage strain rate curve indicates R$_{max}$ and gel time. As is shown in Fig. 5, TNC gave the highest R$_{max}$ (>20 μm/s), XF and P6 presented higher R$_{max}$ (>10 μm/s), and OBFB, PR, and XF showed longer gel time (>4 s).

The R$_{max}$ values were between 5.17 μm/s (CMP) and 21.83 μm/s (TNC). The measured values were in the order of TNC > XF = P6 ≥ KA = Z2 = OBFB = SF = AF = PR ≥ CMP (Fig. 3). The highest R$_{max}$ was observed for TNC; however, that value did not differ significantly from that of XF or P6. No statistical differences were found among the materials KA, Z2, OBFB, SF, AF, and PR. They demonstrated intermediate values and only showed significant differences when compared with CMP. CMP had the lowest R$_{max}$ value, which was significantly lower than that of TNC, XF, and P6.

The gel time values ranged from 3.08 s (AF) to 4.32 s (OBFB). The measured values were in the order of OBFB = PR = XF > Z2 = P6 = TNC = CMP = SF = KA = AF (Fig. 4). OBFB gave the longest gel time and the value was not significantly longer than that of PR or XF. No significant differences were found among the rest of the materials. Z2, P6, TNC, CMP, SF, KA, and AF showed significant differences compared with OBFB, PR, and XF.

DC

The DC values ranged from 53.62% (TNC) to 87.01% (AF). The measured values were in the order of AF > CMP = OBFB = PR > KA = XF > P6 = Z2 = SF = TNC (Fig. 6). AF showed the highest DC and the value was significantly higher than that of other resin composites. CMP, OBFB, and PR exhibited higher DC values and showed significant differences compared with other materials, which were not significantly different from each other. No significant differences in DC were observed between the materials KA and XF, which demonstrated intermediate values and exhibited significant differences compared with other resin composites. There were no significant differences among the rest of the materials. P6, Z2, SF, and TNC had significantly lower DC values than those of the other resin composites.

Discussion

In this study, the shrinkage strain, polymerization shrinkage kinetics, and DC of 10 resin composites were examined, in which several newly introduced bulk-fill materials were also included. Significant differences in results were successfully displayed among different materials, thereby rendering the null hypothesis rejected. At present, there is a lack of a gold standard for accurately measuring the polymerization shrinkage of resin composites. The laser triangulation method used in this experiment is a noncontact measurement method for detecting tiny deformations in the object surface, and it is capable of preventing experimental errors generated by the contact between the instrument and specimen prior to curing. Furthermore, the adoption of a data acquisition system allows the monitoring of curing shrinkage for the resin composite in real time and accurate detection of subtle changes during the polymerization process, with an accuracy of up to 0.01 μm. Moreover, the 2 dynamic indexes of R$_{max}$ and the corresponding gel time can be obtained to evaluate the polymerization shrinkage and polymerization shrinkage kinetics of the light-curing resin composite [21].

The results showed that nano-hybrid resin composites had lower shrinkage strain values compared with nano-hybrid materials. This was related to the size of the filler particles. The smaller particles in nano-hybrid materials could result in a large interface and strong interfacial interactions between fillers and organic matrix, thereby influencing the polymerization kinetics and leading to low shrinkage values [10,25]. The experimental results also showed that shrinkage strain results for bulk-fill resin composites were not reduced compared with traditional resin composites, and TNC had a higher shrinkage strain, similar to the previous reports provided by Benetti and Sunbul [15,26]. The volume of inorganic fillers remains unchanged before and after curing, thereby rendering increased content of such fillers and resulting in reduced shrinkage [27].

TNC possessed the lowest filler loading amount among the investigated materials, with merely 75%–77% filled by weight. TNC also showed the highest shrinkage strain value. In contrast, CMP, in particular, displayed the highest filler loading by revealing that 92% was filled by weight. CMP also had the lowest shrinkage strain value. In addition, Satterthwaite et al. [28] found that resin composites with spherical filler particles exhibited lower shrinkage strain values compared with those with irregular filler particles. However, due to the lack of data regarding filler shape of materials, it is difficult to discuss this further.

As bulk-fill materials, the filler loading of OBFB was similar to that of TNC, but its shrinkage values were not significantly different than those of traditional resin composites. OBFB is characterized by the incorporation of new types of high molecular weight based monomers into the matrix, which includes aromatic urethane dimethacrylate (AUDMA) and 1,12-dodecanedioil dimethacrylate (DDDMA). AUDMA can adjust the polymerization shrinkage and shrinkage stress by reducing the number of reactive groups. Meanwhile, DDDMA has a hydrophobic backbone that increases the mobility of its molecules. It also exhibits low volatility, a low exothermic rate, and reduced volume shrinkage [29,30].

As the nano-hybrid materials, AF and KA also contain new types of organ matrix. AF is a new kind of resin composite from Ormocers that is described as an inorganic-organic hybrid copolymer. Ormocers are comprised of organic networks formed through the polyaddition reaction of polymerizable organic units and inorganic network polymers formed via polycondensation of its inorganic backbone. The long Ormocers molecular chains typically have a high molecular weight and exhibit little polymerization shrinkage [31]. The matrix of KA is a mixture of dimethyl acrylate containing a high molecular based monomer, DX-511, based on the chemical structure of UDMA. DX-511 exhibits a higher molecular weight (895) than Bis-GMA (513), and it has an initially lower double bond concentration that serves to reduce the volumetric shrinkage [32]. This further explains the low shrinkage values of AF and KA.

When the polymerization reaction reaches a certain extent, the elastic gel network structure will form, indicating that it has reached the gel point. Prior to the gel point, volume shrinkage can be partly compensated for by the free flow of materials, generating negligible stress. After gelation, the monomers will crosslink into networks, the movement of monomers and radicals is limited, and resin viscosity increases rapidly while fluidity...
decreases, rendering the volume shrinkage noncompensable [21,33]. The rate of polymerization shrinkage impacts the amount of shrinkage stress, whereby a higher rate leads to higher stress [34]. Meanwhile, a shorter gel time indicates that materials are more sensitive to light curing, resulting in shorter time duration to allow resin flow and less ability to relieve the shrinkage stress. Therefore, an ideal resin composite should have a lower \( R_{\text{max}} \) and a longer gel time.

Figure 5 reflects the shrinkage strain rate behavior and shows the rising and falling portions of the shrinkage strain rate during the initial stage of light curing. Such a pattern is explainable using the theory of “auto-acceleration, auto-deceleration” observed in the polymerization stage of dimethacrylate monomers [35]. Such a polymerization reaction is in accordance with the diffusion-control theory [36]. At an early stage of the polymerization process, the matrix reveals a gelation effect due to an increase in crosslinking density, which results in a continuous acceleration of the polymerization reaction. When the gel point is reached, the matrix system becomes more viscous and the movement of free radicals and monomers is restricted. The polymerization rate reaches its peak and begins to drop. Therefore, \( R_{\text{max}} \) is both the end point of the auto-acceleration stage and the starting point of the auto-deceleration stage, and it is influenced by the viscosity of the reaction matrix. The less viscous matrix may facilitate the movement of free radicals, thereby increasing their DC [43]. Bis-GMA, among all 10 materials, the DC values of the nano-filler resin composites were significantly different than that of traditional resin composites. This may indicate that the ratio of TEGDMA may also lead to differences in the DC value.

In this study there were some limitations of using this FTIR method to measure DC. The thickness of the potassium bromide sheets made by mixing the potassium bromide powders with the cured resin powders was difficult to control. Also, the potassium bromide powders might influence the signal of cured resins, resulting in the deviation from the uncured resins. To reduce errors in the experimental results as much as possible, the same quality of potassium bromide powders and cured resin powders were used to make the mixture sheets and the same amount of pressure was applied. In addition, when using the FTIR method, the internal standard is selected according to the chemical structure of the material. In this study, the carbonyl group served as an internal standard for the resin composites without the Bis-GMA system, while the aromatic C=C was used as an internal standard for materials containing a benzene ring. This might have affected the DC results. Although the chemical structure of the initiator camphorquinone (CQ) also contained a carbonyl group made up of ketones, and the carbonyl group contained in monomers without a benzene ring structure was a carboxylic ester in this study, their infrared absorption peaks were different. Moreover, there was no change in the structure and absorption peak of the carbonyl group contained in CQ during the curing process of the resin matrix. Some published studies have also used C=O as an internal standard to measure DC of a monomer while CQ served as an initiator, which supports the idea that the presence of the carbonyl group contained in CQ did not affect the results of DC [47-50].

In accordance with the limitations of the study, several conclusions can be made as follows. For one, 10 commercial resin composites showed significant differences in shrinkage strain, polymerization shrinkage kinetics, and DC. These differences were closely related to their monomer matrix and filler system. Second, the nano-filler resin composites presented higher DC than the micro-filler resin composites. Third, CMP, AF, and PR have lower polymerization shrinkage and higher DC, making them beneficial for various clinical applications. And finally, because they are bulk-fill materials, the polymerization shrinkage of XF and OB was not significantly different than that of traditional resin composites.

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Conflict of interest
None declared.

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