©Operative Dentistry, 2014, **39-4**, 374-382

Laboratory Research

Polymerization Shrinkage Stress Kinetics and Related Properties of Bulk-fill Resin Composites

HM El-Damanhoury • JA Platt

Clinical Relevance

While achieving adequate curing at 4-mm thicknesses, not all bulk-fill composites are characterized by low-shrinkage stress. Clinicians should be cautious with these material selections for high C-factor applications.

SUMMARY

The present study assessed the polymerization shrinkage stress kinetics of five low-shrinkage light-cured bulk-fill resin composites: Surefil SDR flow (SF, Dentsply), Tetric EvoCeram Bulkfil (TE, Ivoclar Vivadent), Venus Bulk Fill (VB, Heraeus Kulzer), x-tra fil (XF, Voco), and experimental bulk fill (FB, 3M ESPE). Filtek Z250 (FZ, 3M ESPE) was used as a control. Real-time shrinkage stress of investigated composites was measured using a tensometer; maximum shrinkage stress, stress rate (R_{max}), and time to reach maximum stress rate (t_{max}) were recorded. Flexural strength and modulus were measured using a standard procedure, and curing efficiency of 4-mm long specimens was determined using bottom/top percentage Knoop microhardness. Data were analyzed using one-way analysis of variance and Bonferroni multiple range tests at a significance level of α=0.05. Results of shrinkage stress, R_{max}, and t_{max} of all bulk-fill materials were significantly lower ($p<0.05$) than those of the control except for XF. All tested bulk-fill materials were able to achieve acceptable curing efficiency ($\geq$80% bottom/top percentage) at 4-mm depth. In conclusion, this study reports a significant reduction in polymerization shrinkage stress while maintaining comparable curing efficiency at 4 mm for some bulk-fill composites and supports their potential use in posterior clinical situations.

INTRODUCTION

A significant concern for dental clinicians when placing direct resin-based posterior composite restorations is reducing polymerization shrinkage stress. Polymerization of dimethacrylate-based composites is accompanied by substantial volumetric shrinkage ranging from 1%-3% in packable composite and up to 6% in flowable composite.[1] Shrinkage develops during polymerization due to reduction in distance between monomer molecules as a result of short

---

*Hatem M El-Damanhoury, BDS, MS, PhD, assistant professor, Department of General and Specialist Dental Practice, College of Dentistry, University of Sharjah, Sharjah, United Arab Emirates, Department of Operative Dentistry, Faculty of Dentistry, Suez Canal University, Ismalia, Egypt

Jeffrey A Platt, DDS, MS, associate professor, Restorative Dentistry, Indiana University, Indianapolis, IN, USA

*Corresponding author: College of Dentistry, University of Sharjah, Room: M28-126, P.O. Box: 27272, Sharjah, United Arab Emirates; e-mail: hdamanhoury@sharjah.ac.ae, damanhoury414@yahoo.com

DOI: 10.2341/13-017-L

covalent bond formation, reducing the overall free volume within the monomer structure and producing densely packed polymer molecules.[2]

During polymerization, the viscosity of the resin increases as the gel point is approached, accompanied by a rapid increase in stiffness. As the lengthening chains become entangled and a covalently bonded cross-linked network is formed, contraction stress occurs within the material.[3]

Shrinkage stress may be relieved in the early plastic stage (before the polymerization gel point) through flow. Subsequent shrinkage is obstructed, and the material becomes rigid enough to resist significant plastic flow, dramatically decreasing stress relief.[4] In addition, shrinkage manifests itself as stress when the material is confined within a prepared cavity and bonded to preparation walls. Thus, the material is restrained from changing its shape, except at the free surfaces, and further internal stresses will result.[5]

Previous studies have shown that the magnitude of generated stress depends on a combination of material properties and characteristics of the prepared cavity. In particular, confinement conditions imposed on the composite, the restoration's volume, utilized restorative techniques, and the compliance of the bonding substrate have been identified as contributing factors.[6,7] The cavity configuration factor (C-factor) is the ratio of the bonded surface area to the unbonded or free surface area. When restoring cavities with high C-factor, the resultant stresses put resin-tooth interfaces under increased tension as there is less chance for relaxation of shrinkage stress.[8] It has been reported by several investigators[9-13] that the increase in C-factor is associated with a progressive decrease in bond strength and a potential deleterious effect on marginal integrity and gap formation.[14] Alternatively, high bond strengths may cause cusp deflection and enamel cracking.[15,16]

The amount of induced polymerization stress is influenced by many characteristics of the composite formulation, such as matrix type, filler content, polymerization kinetics, degree of conversion, and modulus of elasticity.[17,18] Therefore, several attempts have been made to minimize the amount of generated polymerization stress through changing this formulation. Strategies to reduce polymerization shrinkage have included reduction of reactive sites per unit volume by increasing the filler load with nanometer size fillers,[19,20] increasing the molecular weight per reactive group through the replacement of some of the lower-molecular-weight triethylene glycol dimethacrylate (TEGDMA) with a blend of higher-molecular-weight urethane dimethacrylate (UDMA) and bisphenol A polyetheylene glycol diether dimethacrylate (Bis-EMA),[21,22] or using ring opening polymerizations based on siloranes.[23-26]

A different approach to minimizing shrinkage stress is placing composite in small increments toward fewer bonded surfaces to minimize material constraint and allow flow of the shrinking composite from available free surfaces.[22] Although incremental placement techniques may have the advantage of maximizing polymerization of each increment due to less light attenuation through smaller increments of material and increased adaptation of the composite to cavity walls, the value of incremental placement in reducing shrinkage stress has been questioned.[27-29]

Recently, many products have been marketed as low-shrinkage stress materials that have modified initiation systems, potentially allowing placement of these materials in one layer (bulk-fill) of up to 4 mm in thickness with adequate polymerization and short activation times. These materials vary in their rheologic properties and are indicated for use as flowable base materials to be veneered with 2 mm of posterior hybrid composite or as a final filling that does not require veneering.[30-32] Insufficient data are available regarding the shrinkage stress behavior of these bulk-fill low-shrinkage composites. Consequently, the objective of this *in vitro* study was to investigate the shrinkage stress kinetics and some related properties of this new class of materials. The null hypotheses tested were 1) there is no difference in polymerization shrinkage stress, stress kinetics, flexural strength, or flexural modulus between bulk-fill and a microhybrid resin-composite control; and 2) placing this class of material in 4-mm bulk will not compromise its curing efficiency.

METHODS AND MATERIALS

Shrinkage Stress Test

A tensometer (American Dental Association Foundation, Paffenbarger Research Center, Gaithersburg, MD, USA)[33] was used to measure shrinkage stress of five bulk-fill materials: Surefil SDR flow (SF, Dentsply), Tetric EvoCeram Bulkfil (TE, Ivoclar Vivadent), Venus Bulk Fill (VB, Heraeus Kulzer), x-tra fil (XF, Voco), and experimental bulk fill (FB, 3M ESPE). The methacrylate-based microhybrid composite Filtek Z250 (FZ, 3M ESPE) was used as a control material (Table 1).

Table 1: *Materials Used in This Study*

Code	Product	Type	Manufacturer	Lot No.	Composition	Filler Type	Filler Loading
SF	Surefil SDR flow	Bulk-fill base	Dentsply, Konstanz, Germany	11281	UDMA, TEGDMA, EBPDMA	Barium/strontium-aluminofluoro-borosilicate glass	68% by wt and 44% by vol
VB	Venus Bulk Fill	Bulk-fill base	Heraeus Kulzer, GmbH, Hanau, Germany	010031	UDMA, EBPDMA	Barium alumino-fluorosilicate glass, YbF_3, and SiO_2	65% by wt and 38% by vol
FB	Experimental flowable	Bulk-fill restorative	3M ESPE, St Paul, MN, USA	N310870 (EXD-784)	Bis-GMA, Bis-EMA, Procrylat, UDMA	zirconia/silica ytterbium trifluoride	64.5% by wt and 42.5% by vol
TE	Tetric EvoCeram bulk fill	Bulk-fill restorative	Ivoclar Vivadent, Schaan, Liechtenstein	P72398	Dimethacrylate co-monomers	Barium glass, YbF3, oxides, and prepolymers	80% by wt and 60% by vol
XF	x-tra fil	Bulk-fill restorative	Voco, Cuxhaven, Germany	1147096	MMA, Bis-EMA	Inorganic fillers	75% by wt and 58% by vol
FZ	Filtek Z250	Microhybrid restorative	3M ESPE, St Paul, MN, USA	N222162	Bis-GMA, Bis-EMA, UDMA, and TEGDMA	Zirconia/silica	82% by wt and 60% by vol

MMA: Methyl methacrylate, Bis-GMA: Bisphenolglycidyl dimethacrylate, Bis-EMA: Bisphenol A polyetheylene glycol diether dimethacrylate, TEGDMA: Triethyleneglycol dimethacrylate, UEDMA: Urethane dimethacrylate, EBPDMA: Ethoxylated bisphenol A dimethacrylate.

A 4-mm, prefabricated, nylon gauge block was used to adjust the space between two quartz rods attached to the base and cantilever beam of the machine. The C-factor was calculated to be 0.75 for all specimens. The specimens were cured for 20 seconds through the lower rod using a light-emitting diode curing unit (Demetron A.1, Kerr/Sybron, Orange, CA, USA) in standard mode. Output intensity was confirmed to be 1000 ± 50 mW/cm^2 following every five specimens using a hand-held dental curing radiometer (Demetron LED radiometer Model 100, Demetron Research, Orange, CA, USA). As the composite shrinks, it pulls the two ends of the quartz rods closer together; and as the upper rod moves, the frame and beam bend and the amount of movement is measured with a linear variable differential transformer (LVDT). This measurement was used to calculate a corresponding load from a previous calibration curve. The corresponding shrinkage stress was then obtained by dividing the measured tensile force by the cross-sectional area of the sample. The stiffness of the beam was controlled by the location of the upper collet that holds the quartz rods. The location of the beam and the resulting stiffness was determined from the calibration curve provided by the manufacturer.

The shrinkage stress was monitored continuously for 30 minutes from the start of light activation to yield real-time shrinkage stress during polymerization. The mean maximum shrinkage stress was calculated from five samples for each material (n=5). Using the tensometer software, an average stress curve was generated for each material, and stress rate (first derivative of real-time stress), maximum stress rate R_{max} (peak value in first derivative), and time to achieve maximum stress rate (t_{max}) were calculated.

Flexural Strength and Modulus Test

Flexural strength and modulus were determined using standard procedures in accordance with ISO 4049.[34] Five identical bar-shaped specimens (25 mm in length, 2 mm in width, and 2 mm in height) of each tested material were fabricated using a stainless steel mold. Specimens were light-cured using a light-emitting diode curing unit (Demetron A.1, Kerr/Sybron) at the top and bottom surfaces with a 12-mm diameter curing light tip in standard mode. The central portion of each bar-shaped specimen was subjected to an initial irradiation of 20 seconds. Two subsequent overlapping positions (by half the diameter of the curing light tip) were then irradiated for 20 seconds to cure the entire length of the bar-shaped specimen. Output intensity confirmation was done every five specimens. Specimens were stored for 24 hours in double distilled deionized water at 37°C ± 1°C. Flexural strength and modulus of the material were determined using a universal testing machine (Sintech Renew 1123, MTS, Eden Prairie, MN, USA, with TestWorks 4.08 software) with a 2.5-kg load cell at a crosshead speed of 1 mm/min and a support span length of 20 mm. Flexural modulus (E) was determined using the initial slope of the load displacement curve. Flexural strength (σ) and E

Table 2: *Mean Values and SD for Shrinkage Stress, Maximum Stress Rate (R_{max}), Time to Achieve Maximum Stress Rate (t_{max}), Flexural Strength, Flexural Modulus, Top Hardness, Bottom Hardness, and Bottom/Top Hardness % of the Investigated Materials*[a]

Code	Shrinkage Stress, MPa	R_{max}, MPa/s	t_{max}, s	Flexural Strength, MPa	Flexural Modulus, GPa	Top Hardness, KHN	Bottom Hardness, KHN	Bottom/ top, %
VB	1.607 (0.04)^{A}	0.06 (0.01)^{A}	13.30 (1.72)^{A}	107.4 (3.8)^{A}	4.48 (1.08)^{A}	36.60 (0.97)^{A}	35.53 (1.32)^{A}	97.08 (2.31)^{A}
FB	1.649 (0.06)^{B}	0.07 (0.02)^{A}	9.82 (1.87)^{B}	109.8 (9.2)^{A}	5.47 (2.02)^{AB}	39.37 (3.20)^{A}	34.31 (2.60)^{A}	87.21 (3.01)^{BC}
SF	1.710 (0.03)^{BC}	0.08 (0.01)^{A}	8.91 (1.60)^{B}	125.5 (9.4)^{B}	6.76 (1.26)^{B}	48.53 (2.38)^{B}	44.27 (2.78)^{B}	91.31 (5.93)^{AB}
TE	1.883 (0.09)^{C}	0.09 (0.01)^{AB}	9.67 (2.00)^{B}	85.28 (12.8)^{C}	8.98 (3.87)^{C}	55.40 (3.27)^{C}	44.13 (2.26)^{B}	79.73 (2.59)^{CD}
XF	2.135 (0.07)^{D}	0.11 (0.02)^{B}	9.96 (1.35)^{B}	143.7 (8.04)^{D}	16.03 (8.20)^{D}	59.07 (6.37)^{C}	51.20 (7.61)^{C}	86.43 (5.17)^{C}
FZ	2.364 (0.04)^{D}	0.15 (0.02)^{C}	6.54 (1.73)^{C}	143.8 (2.6)^{D}	11.65 (8.32)^{D}	57.40 (1.51)^{C}	43.10 (3.18)^{B}	75.17 (6.57)^{D}

[a] *Within a column, different superscript capital letters indicate significant differences by pair-wise Bonferroni* post-hoc *multiple comparison test ($\alpha=0.05$).*

were calculated according to equations 1 and 2, respectively:

$$\sigma = \frac{3PL}{2bd^2} \tag{1}$$

$$E = \frac{PL^3}{4bdh^3} \times 10^3 \tag{2}$$

where L is the support span length (mm), b the specimen width (mm), h the specimen height (mm), P the load (N) at a convenient point on the straight line portion of the curve, and d the deflection (mm) corresponding to the load P.

Knoop Hardness Measurement

A stainless steel cylindrical split-mold, with height of 4 mm and internal diameter of 4 mm, was placed on a glass slide covered by a Mylar strip (Hawe Stopstrip Straight, KerrHawe, Bioggio, Switzerland). The mold was then filled in bulk with one of the six resin composites. The top side of the mold was covered with a second Mylar strip, and the resin material made flush with the mold by use of a second glass slide. A standardized 50-g stainless steel weight was placed over the top glass slide for 30 seconds to ensure proper packing of the composite. The second glass slide was removed, and the resin composite was light-cured for 20 seconds using the same curing unit and protocol that was used for the shrinkage stress test. The curing light tip was kept centered and in contact with the second Mylar strip. After light curing, the specimens were removed from the mold and stored for 24 hours in double distilled deionized water at 37°C ± 1°C.

The top and bottom surfaces of each specimen were polished with a diamond suspension (mean grain size: 5 μm) with an automatic polishing device (Buehler, Lake Bluff, IL, USA) under a 50-g load. Cured composite thickness of each specimen was verified with a digital caliper of 0.01 mm precision (Mitutoyo IP 65, Kawasaki, Japan). Knoop microhardness (KHN) of each top and bottom surface was measured (LECO, M-400 Hardness Tester, St Joseph, MI, USA) at three different points on each surface, with a 10 N load for 15 seconds. The average of three readings was calculated for both top and bottom of each specimen, and the bottom to top percentage was calculated from the average of five specimens (n=5).

Statistical Analysis

Multiple comparisons of group means of shrinkage stress, flexural strength, and modulus and microhardness were made utilizing one-way analysis of variance (ANOVA) and Bonferroni multiple range tests at a significance level of α=0.05. Correlation between the shrinkage stress and flexural modulus results was analyzed using regression statistics.

RESULTS

Descriptive statistics are presented in Table 2. Statistical analysis of the shrinkage stress results revealed that the FZ group recorded the highest ($p<0.05$) mean shrinkage stress value (2.364 ± 0.04 MPa) followed by the XF group, then the TE, SF, and FB groups, respectively, while the VB group recorded the lowest shrinkage stress mean value (1.607 ± 0.04 MPa). The difference between groups was statistically significant ($p<0.05$) as indicated with ANOVA. The Bonferroni *post-hoc* test showed that there was a nonsignificant ($p>0.05$) difference in the shrinkage stress results between the VB and FB, VB and SF, and FB and SF groups. Also, there was nonsignificant ($p>0.05$) difference between the SF and TE groups. Figure 1 compares the shrinkage

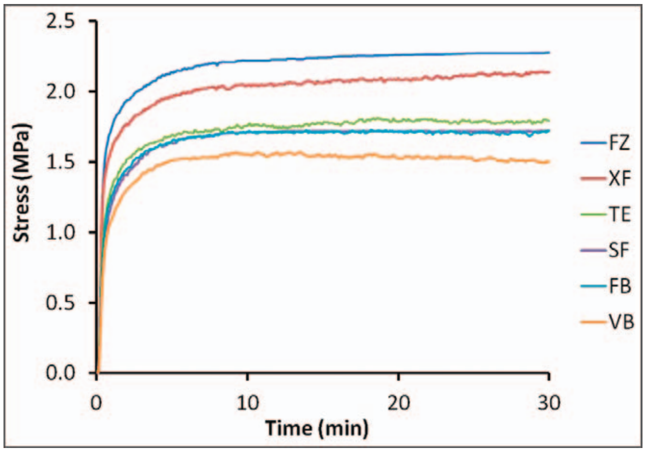

Figure 1. *Comparison of the shrinkage stress development (averaged curves, n=10) as a function of time for the five measured bulk-fill composites and control.*

stress development as a function of time for the five measured bulk-fill composites and control.

Presentation of the rate of shrinkage stress development of the tested materials is shown in Figure 2. As indicated by ANOVA, the control material FZ showed the highest ($p<0.05$) R_{max} (0.15 ± 0.02 MPa/s) and the shortest t_{max} (6.54 ± 1.73 s), VB exhibited the lowest R_{max} (0.06 ± 0.01 MPa/s) and the longest t_{max} (13.30 ± 1.72 s), which was not significantly different ($p>0.05$) than the recorded R_{max} for FB, SF, and TE (0.07±0.02, 0.08±0.01 and 0.09±0.01 MPa/s respectively). No significant difference was found between R_{max} of TE and XF(0.11±0.02 MPa/s). The recorded t_{max} of FB, SF, TE, and XF were not significantly different ($p>0.05$).

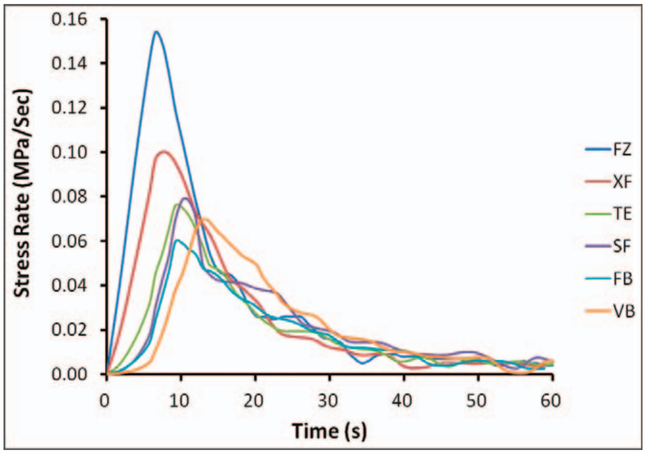

Figure 2. *Shrinkage stress rate development in time within the 60 seconds from composite irradiation, mean curves (n=10) of the investigated materials.*

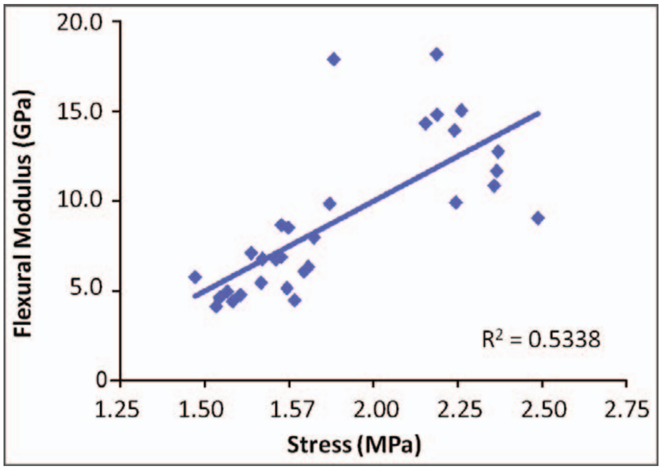

Figure 3. *Linear regression of shrinkage stress vs flexural moduli of the investigated materials.*

XF recorded the highest flexural modulus mean value followed by FZ then TE, SF, and FB, respectively, while VB recorded the lowest mean value. A significant difference ($p<0.05$) was found between all groups except between VB and FB, FB and SF, and XF and FZ. Regression analysis revealed a statistically significant ($p=0.0001$) direct correlation between stress and flexural modulus ($r^2=0.5338$; Figure 3).

The top and bottom hardness results varied widely between the tested materials. The highest mean top hardness value was recorded for XF (59.07 ± 6.37 KHN), which was not statistically different ($p>0.05$) from that for TE (55.40 ± 3.27 KHN) and the control material FZ (57.40 ± 1.51 KHN). The lowest mean top hardness value was recorded for VB (36.60 ± 0.97 KHN), which was not statistically different ($p>0.05$) from that for FB (39.37 ± 3.20 KHN).

The results of the polymerization efficiency test at 4-mm depth revealed that VB exhibited the highest bottom/top hardness percentage value (97.08% ± 2.31%) and was significantly higher ($p<0.05$) than all other tested materials except SF (91.31% ± 5.93%). As indicated by the pair-wise Bonferroni *post-hoc* test, no significant difference ($p>0.05$) was found between the bottom/top hardness percentage of FB and SF (87.21% ± 3.01% and 91.31% ± 5.93%, respectively) and between TE and FZ (79.73% ± 2.59% and 75.17% ± 6.57%, respectively); the latter group exhibited the lowest ($p<0.05$) bottom/top hardness percentage. Regression analysis revealed a significant ($p=0.0001$) positive linear correlation between top hardness and stress ($R^2=0.7135$; Figure 4).

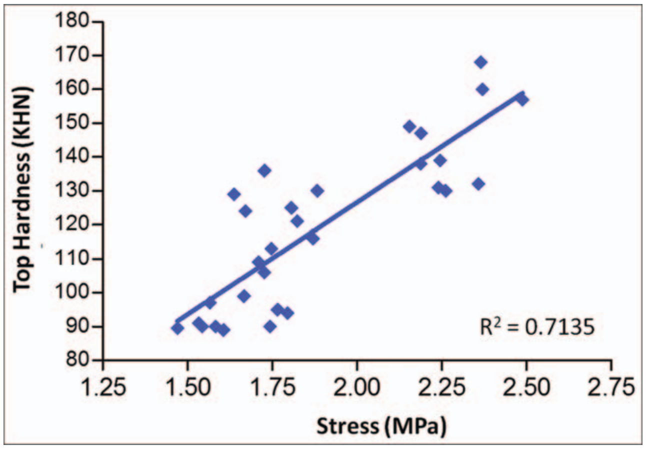

Figure 4. *Linear regression of shrinkage stress vs top hardness of the investigated materials.*

DISCUSSION

This study investigated the shrinkage stress kinetics and related properties of five recently introduced bulk-fill materials and compared them to a hybrid resin composite. The C-factor used in the tensometer was comparatively low, but was standardized for all materials and was the result of placing and curing tested materials in a 4-mm thickness, which might be a significant influencing factor in the shrinkage stress of the bulk-fill material.

Statistically significant differences ($p<0.05$) were found between the shrinkage stress of the studied materials, and accordingly, the first null hypothesis was rejected. On the other hand, there was no statistically significant difference ($p<0.05$) between VB, experimental FB, and SF, which exhibited the lowest shrinkage stress; meanwhile, these materials were significantly different from the bulk-fill materials TE, XF, and control FZ. It is worth mentioning that the setting of this study provided a controlled environment that allows comparing the behavior of materials under such circumstances, but the results may vary under different testing conditions, especially with increasing the C-factor.

VB, FB, and SF bulk-fill materials have the lowest filler volume fraction (between 38% and 44%), and even though their volumetric polymerization shrinkage remains similar to other flowable resin composites (around 3-6 vol%),[35] they were designed to remarkably reduce shrinkage stress.[36] It was suggested that addition of high filler levels to reduce resin volume is not an efficient approach to reduce post-gel shrinkage and polymerization stress;[37] therefore, another approach was used, which was a modified chemistry that slows the rate of polymerization to reduce shrinkage stress. That was supported in the results of this study, as these composites exhibited longer time to achieve maximum stress rate t_{max} (13.30, 9.82 and 8.91 seconds for VB, FB, and SF respectively) in comparison to 6.54 seconds for the control FZ.

For many years, there was a general understanding among clinicians and researchers that placing resin composite in small increments significantly reduced shrinkage stresses.[21,22] This concept was recently questioned by several researchers,[28-30] who recommended the use of larger increments or even bulk filling of the entire cavity with one increment. One main concern raised with using the bulk filling technique, is that the material may suffer from reduced polymerization at the deeper layer of the increment due to light attenuation. Recently introduced bulk-fill materials were claimed to have more potent initiator systems,[38] and most of the products in this class of material are characterized by low viscosity and high translucency.

It has been reported that resin-based filling materials should exhibit a minimum of 80% bottom/top hardness percentage when cured in a 2-mm increment in order to be considered as adequately polymerized.[39] Accordingly, in the current study, a similar percentage at 4-mm depth was considered acceptable curing , and above 90% was considered high curing efficiency. The results revealed that all investigated bulk-fill materials exhibited acceptable to high curing at the deepest portion of a 4-mm increment (bottom/top% $\geq$ 80%). This is in agreement with comparable studies that showed that bulk-fill materials met the requirements stipulated in the ISO 4049 specification, even with a light-curing time as short as 20 seconds.[40,41] Therefore, the second null hypothesis was accepted, and the reduction in polymerization shrinkage stress of the tested bulk-fill materials cannot be attributed to inadequate curing.[42,43]

A significant difference was found between the flexural modulus of the investigated materials ($p<0.05$), which ranged between 4.0 and 9.0 GPa, with VB exhibiting the lowest value (4.48 ± 1.08 GPa). Meanwhile, the regression analysis revealed a statistically significant correlation between stress and flexural modulus ($r^2=0.5338$) and between stress and filler loading by volume ($R^2=0.7333$). This may confirm that the main contributing factors to the reduced shrinkage of bulk-fill materials are their low flexural modulus and low filler loading. This finding is in agreement with many previous studies.[22] Flexural modulus is a function of many factors such as filler content, monomer chemistry, monomer structure, filler/matrix interactions, and additives. SF, VB, and FB have similar monomer structures based on UDMA, which is characterized by a significant reduction in polymerization shrinkage and higher molecular weight that contributes to reduced shrinkage stress.

It is important to note that the flexural strength and flexural modulus testing in the current study was done with optimum polymerization settings and did not simulate a gradual decrease of polymerization that might be expected if the molds were 4 mm in thickness. Although flexural properties of resin-based materials would vary according to their curing efficiency when placed in large-increment thicknesses, the tested bulk-fill materials in this study maintained acceptable to high curing efficiency at a 4-mm thickness. Further investigation is required to determine if the modulus decreases dramatically in these materials as has been reported for a nano-hybrid composite.[44]

Regression analysis has also revealed a significant ($p=0.0001$) direct relation between top hardness and stress ($R^2=0.7135$; Figure 4); therefore, it can be noted that shrinkage stress, flexural modulus, and hardness correlate positively and that bulk-fill materials which exhibit lower shrinkage stress are characterized by low hardness and flexural moduli. Accordingly, the intended use of bulk-fill materials may vary from one material to another consistent with their mechanical properties. The results of TE and XF were significantly different ($p<0.05$) from those of VB, FB, and SF. These results were expected due to the difference in clinical application, filler loading (60 and 58 % by volume for TE and XF respectively), and rheologic properties of the two groups of materials; TE and XF are designed to be used as final posterior restorative materials in comparison to the recommended use of VB, FB, and SF as base materials, requiring a covering of universal or posterior resin composite.[45] According to the reported differences in top hardness of the bulk-fill materials in this study, further investigation of the wear behavior of these materials should be conducted and would be of high clinical value.

Although its mechanical properties are close to those of control composites, TE exhibited significantly lower stress values than XF and the control material FZ, and stress values that were not statistically different from those of VB, FB, and SF. Moreover, the top hardness results of TE were significantly higher ($p<0.05$) than all of the tested bulk-fill materials except for XF and the control material FZ. These results indicate that among the investigated materials, TE is the only material that can be considered for use as a posterior final restoration while maintaining good mechanical properties and reduced shrinkage stress.

CONCLUSIONS

The current study showed that in comparison with a conventional posterior resin composite, the distinctive shrinkage stress kinetics, flexural properties, and enhanced initiation systems of only some of the investigated bulk-fill materials resulted in significant reduction in shrinkage stress while maintaining adequate curing at a 4-mm thickness. This may support the intended use of these materials for bulk filling high C-factor and deep cavities.

Acknowledgement

The dental companies listed in Table 1 are gratefully acknowledged for the generous donation of materials used for this study.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article. JA Platt was redacted from all review and publication decisions concerning this manuscript.

(Accepted 10 April 2013)

REFERENCES

1. Kleverlaan CJ & Feilzer AJ (2005) Polymerization shrinkage and contraction stress of dental resin composites *Dental Materials* **21(12)** 1150-1157.
2. Ferracane JL (2008) Placing dental composites—A stressful experience. *Operative Dentistry* **33(3)** 247-257.
3. Venhoven BA, de Gee AJ & Davidson CL (1993) Polymerization contraction and conversion of light-curing BisGMA-based methacrylate resins *Biomaterials* **14(11)** 871-875.
4. Dauvillier BS, Feilzer AJ, De Gee AJ & Davidson CL (2000) Visco-elastic parameters of dental restorative materials during setting *Journal of Dental Research* **79(3)** 818-823.
5. Davidson CL & de Gee AJ (1984) Relaxation of polymerization contraction stresses by flow in dental composites *Journal of Dental Research* **63(2)** 146-148.
6. Davidson CL & Feilzer AJ (1997) Polymerization shrinkage and polymerization shrinkage stress in polymer-based restoratives *Journal of Dentistry* **25(6)** 435-440.
7. Alster D, Venhoven BA, Feilzer AJ & Davidson CL (1997) Influence of compliance of the substrate materials on polymerization contraction stress in thin resin composite layers *Biomaterials* **18(4)** 337-341.

8. Feilzer AJ, de Gee AJ & Davidson CL (1987) Setting stress in composite resin in relation to configuration of the restoration *Journal of Dental Research* **66(11)** 1636-1639.

9. El-Sahn NA, EL-Damanhoury HM, EL-Kassas D, Fahmy OM, Gomma H & Platt JA. (2011) Effect of C-factor on micro-tensile bond strengths of low-shrinkage composites. *Operative Dentistry* **36(3)** 281-292.

10. Shirai K, De Munck J, Yoshida Y, Inoue S, Lambrechts P, Suzuki K, Shintani H & Van Meerbeek B (2005) Effect of cavity configuration and aging on the bonding effectiveness of six adhesives to dentin *Dental Materials* **21(2)** 110-124.

11. Yoshikawa T, Sano H, Burrow MF, Tagami J & Pashly DH (1999) Effects of dentin depth and cavity configuration on bond strength *Journal of Dental Research* **78(4)** 898-905.

12. Armstrong SR, Keller JC & Boyer DB (2001) The influence of water storage and C-factor on the dentin-resin composite microtensile bond strength and debond pathway utilizing a filled and unfilled adhesive resin *Dental Materials* **17(3)** 268-276.

13. Nikaido T, Kunzelmann KH, Chen H, Ogata M, Harada N, Yamaguchi S, Cox CF, Hickel R & Tagami J (2002) Evaluation of thermal cycling and mechanical loading on bond strength of a self-etching primer system to dentin *Dental Materials* **18(3)** 269-275.

14. Price RB, Dérand T, Andreou P & Murphy D (2003) The effect of two configuration factors, time, and thermal cycling on resin to dentin bond strengths *Biomaterials* **24(6)** 1013-1021.

15. Moorthy A, Hogg CH, Dowling AH, Grufferty BF, Benetti AR & Fleming GJP (2012) Cuspal deflection and microleakage in premolar teeth restored with bulk-fill flowable resin-based composite base materials *Journal of Dentistry* **40(6)** 500-505.

16. Choi KK, Ferracane JL, Ryu GJ, Choi SM, Lee MJ & Park SJ (2004) Effects of cavity configuration on composite restoration *Operative Dentistry* **29(4)** 462-469.

17. Chen HY, Manhart J, Hickel R & Kunzelmann KH (2001) Polymerization contraction stress in light-cured packable composite resins *Dental Materials* **17(3)** 253-259.

18. Bouschlicher MR, Vargas MA & Boyer DB (1997) Effect of composite type, light intensity, configuration factor and laser polymerization on polymerization contraction forces *American Journal of Dentistry* **10(2)** 88-96.

19. Lu H, Lee YK, Oguri M & Powers JM (2006) Properties of a dental resin composite with a spherical inorganic filler *Operative Dentistry* **31(6)** 734-740.

20. Mitra SB, Wu D & Holmes BN (2003) An application of nanotechnology in advanced dental materials *Journal of the American Dental Association* **134(10)** 1382-1392.

21. Braga RR & Ferracane JL (2002) Contraction stress related to degree of conversion and reaction kinetics *Journal of Dental Research* **81(2)** 114-118.

22. Braga RR, Ballester RY & Ferracane JL (2005) Factors involved in the development of polymerization shrinkage stress in resin-composites: A systematic review *Dental Materials* **21(10)** 962-970.

23. Weinmann W, Thalacker C & Guggenberger R (2005) Siloranes in dental composites *Dental Materials* **21(1)** 68-74.

24. Guggenberger R & Weinmann W (2002) Exploring beyond methacrylates *American Journal of Dentistry* **13 (Special Issue 5)** 82D-84D.

25. El-Damanhoury HM, Moore BK, El-Sahn NA, Abi El-Hassan MH, Aboul-Enein NM & Habib AN (2009) Effect of hydrolytic stability on flexural properties of silorane-based composite *Egyptian Dental Journal* **55(4.2)** 2581-2596.

26. El-Damanhoury HM, Moore BK, El-Sahn NA, Abi El-Hassan MH, Aboul-Enein NM & Habib AN (2009) Bonding effectiveness of silorane-based composite to dentine *Egyptian Dental Journal* **55(4.2)** 2597-2606.

27. Versluis A, Douglas WH, Cross M & Sakaguchi RL (1996) Does an incremental filling technique reduce polymerization shrinkage stresses? *Journal of Dental Research* **75(3)** 871-878.

28. El-Badrawy W, Jafarbour S, Jazi HS & McComb D (2012) Effect of composite insertion technique on cuspal deflection using *in vitro* simulation model *Operative Dentistry* **37(3)** 299-305.

29. Rees JS, Jagger DC, Williams DR, Brown G & Duguid W (2011) A reappraisal of the incremental packing technique for light cured composite resins *Journal of Oral Rehabilitation* **31(1)** 81-84.

30. Ilie N & Hickel R (2011) Investigations on a methacrylate-based flowable composite based on the SDR technology *Dental Materials* **27(4)** 348-355.

31. El-Safty S, Silikas N & Watts DC (2012) Creep deformation of restorative resin-composites intended for bulk-fill placement. *Dental Materials* **28(8)** 928-935.

32. Ellakwa A, Cho N & Lee IB (2007) The effect of resin matrix composition on the polymerization shrinkage and rheological properties of experimental dental composites *Dental Materials* **23(10)** 1229-1235.

33. Lu H, Stansbury JW, Dickens SH, Eichmiller FC & Bowman CN (2004) Probing the origins and control of shrinkage stress in dental resin-composites: I. Shrinkage stress characterization technique *Journal of Materials Science: Materials in Medicine* **15(10)** 1097-1103.

34. ISO-Standards (2009) ISO 4049 Dentistry—resin-based filling materials *International Organization for Standardization*.

35. Labella R, Lambrechts P, Van Meerbeek B & Vanherle G (1999) Polymerization shrinkage and elasticity of flowable composites and filled adhesives *Dental Materials* **15(2)** 128-137.

36. Boaro LC, Gonçalves F, Guimarães TC, Ferracane JL, Versluis A & Braga RR (2010) Polymerization stress, shrinkage and elastic modulus of current low-shrinkage restorative composites *Dental Materials* **26(12)** 1144-1150.

37. Ferracane JL (2005) Developing a more complete understanding of stresses produced in dental composites during polymerization *Dental Materials* **21(1)** 36-42.

38. Fleming GJ, Awan M, Cooper PR & Sloan AJ (2008) The potential of a resin-composite to be cured to a 4 mm depth *Dental Materials* **24(4)** 522-529.

39. Bouschlicher MR, Rueggeberg FA & Wilson BM (2004) Correlation of bottom-to-top surface microhardness and conversion ratios for a variety of resin composite compositions *Operative Dentistry* **29(6)** 698-704.

40. Flury S, Hayoz S, Peutzfeldt A, Hüsler J & Lussi A (2012) Depth of cure of resin composites: Is the ISO 4049 method suitable for bulk fill materials? *Dental Materials* **28(5)** 521-528.

41. El-Safty S, Akhtar R, Silikas N & Watts DC (2012) Nanomechanical properties of dental resin-composites *Dental Materials* **28(12)** 1292-1300.

42. Stansbury JW, Trujillo-Lemon M, Lu H, Ding X, Lin Y & Ge J (2005) Conversion-dependent shrinkage stress and strain in dental resins and composites *Dental Materials* **21(1)** 56-67.

43. Lu H, Stansbury JW, Dickens SH, Eichmiller FC & Bowman CN (2004) Probing the origins and control of shrinkage stress in dental resin composites. II. Novel method of simultaneous measurement of polymerization shrinkage stress and conversion *Journal of Biomedical Materials Research. Part B, Applied Biomaterials* **71(1)** 206-213.

44. Leprince JG, Leveque P, Nysten B, Gallez B, Devaux J, & Leloup G (2012) New insight into the "depth of cure" of dimethacrylate-based dental composites *Dental Materials* **28(5)** 512-520.

45. Burgess J & Cakir D (2010) Comparative properties of low-shrinkage composite resins *Compendium of Continuing Education in Dentistry* **31(Special Issue 2)** 10-15.