©Operative Dentistry, 2011, **36-3,** 281-292

Effect of C-factor on Microtensile Bond Strengths of Low-Shrinkage Composites

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Clinical Relevance

Low-shrinkage composite materials can be a valuable alternative for use in counteracting the deleterious effect of increasing C-factor on bond strength.

SUMMARY

This study evaluated the microtensile bond strength (μ-TBS) of low-shrinkage composites with their corresponding adhesive systems, Filtek Silorane/Silorane adhesive (SIL, 3M ESPE AG, Seefeld, Germany) and Aelite LS/One-Step Plus (AL, BISCO Inc, Schaumburg, IL, USA) in cavities with different C-factors. Filtek Z250/Adper Single Bond Plus (Z, 3M ESPE, St Paul, MN, USA) was used as a control.

Method: Standardized Class I cavities were prepared in extracted human molars after removing occlusal enamel. Cavities were assigned into six different C-factors by applying nail polish to four walls, three walls, two walls adjacent to each other, two walls opposite to each other, one wall, or no walls. Resin composites with their corresponding adhesive systems were applied according to manufacturer instructions. Specimens were sectioned to obtain four rectangular beams from the center of the restorations and μ-TBS was measured. Data were analyzed by Weibull survival analysis. Shrinkage stresses of the resin composites were determined after 30 minutes from the

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DOI: 10.2341/10-105-L

start of light-curing using a tensometer testing machine. Flexure elastic modulus was determined using standard procedures, in accordance with ISO 4049. Data for shrinkage stress and elastic modulus were analyzed by one-way analysis of variance followed by a Tukey multiple-comparisons test ($p<0.05$).

Results: μ-TBS of both SIL and AL were not affected by different C-factors; however, the bond strength of Z decreased significantly when the C-factor increased. Shrinkage stress results were 0.94±0.1, 1.79±0.18, and 2.14±0.23 MPa for SIL, AL, and Z, respectively. The flexural modulus of both the SIL and the AL was significantly lower than that of Z.

Conclusions: Increasing C-factor did not negatively affect the bond strength of low-shrinkage composites.

INTRODUCTION

A significant concern for dental clinician's when placing direct resin-based posterior composite restorations has been polymerization shrinkage. Polymerization of dimethacrylate-based composites is always accompanied by substantial volumetric shrinkage in the range of 2% to 6%.[1] During polymerization, the molecules previously existing at van der Waal's force distances become linked through shorter covalent bonds, and the reduction in free volume within the monomer structure, as it transforms to a more densely packed polymer, contributes to the overall contraction.[2]

In general, a majority of the shrinkage can be resolved in the early plastic state (before the polymerization gel point) by flow, or contraction stresses can be minimized by allowing the composite volume to change shape. Following gel formation, the polymerization process is accompanied by a rapid increase in stiffness or elastic modulus as the lengthening chains become entangled with one another and bridges of covalently bonded molecules link chains together to form a cross-linked network.[3] Contraction stress build-up occurs, since subsequent shrinkage is obstructed, and the material is rigid enough to resist sufficient plastic flow to compensate for the original volume.[4] In addition, the shrinkage manifests itself as stress when the resulting strain in the composite restoration is hindered by the confinement of the material bonded to the tooth walls. Thus, the material is restrained from changing shape, except at the free surface, and further internal stresses will result.[5]

Previous studies have shown that stress is a physical condition, and its magnitude depends on the interactions between the combination of material properties and characteristics of the cavity to be restored. In particular, the influence of the confinement conditions imposed on the composite (C-factor), the restoration's volume, utilized restorative techniques, and the compliance of the bonding substrate have been identified as contributing factors.[6]

The ratio of the bonded surface area to the unbonded or free surface area is called the cavity configuration, or C-factor.[7] When restoring cavities with high C-factor, the resultant stresses put resin-tooth interfaces under severe tension as there is less chance for relaxation of shrinkage stress.[8] It has been reported by several investigators[8-13] that the increase in C-factor is associated with progressive weakening of the bond strength. Therefore, the strength of the adhesive interaction with tooth structure should be able to counteract the generated polymerization stresses. Otherwise, there can be a deleterious effect on marginal integrity and gap formation.[14]

Since the amount of induced polymerization stress is influenced by characteristics of the composite, such as matrix type, filler content, polymerization rate, degree of conversion, and modulus of elasticity,[15-17] several attempts have been made to minimize the amount of generated polymerization stress through changing the formulation of the dental composite. Strategies to reduce polymerization shrinkage involve reduction of reactive sites per unit volume by increasing the filler load, which can be achieved through the incorporation of nanofillers,[18] or by increasing the molecular weight per reactive group[19] through the replacement of some low-molecular-weight triethylene glycol dimethacrylate (TEGDMA) with a blend of high-molecular-weight urethane dimethacrylate (UDMA) and bisphenol-A polyethylene glycol diether dimethacrylate (Bis-EMA).[20]

Another new category of resin matrix for dental composites has been developed based on ring opening monomers. Derived from the combination of siloxane and oxirane, they are named siloranes.[21] It has been claimed[22] that the epoxy ring opening of the silorane produces volume expansion that can partially offset the curing contraction, thus producing superior bonding compared to the methacrylate-based composite matrices.

Many of the studies evaluating siloranes have measured bond strength to flat dentin bonding surfaces without taking into consideration different cavity configurations; thus, these studies do not reflect all clinical situations. The available data regarding bond strength in cavities with different C-factors have either compared the bond strength in box-like cavities (C5) to a flat bonding surface (C1) without showing the effect of other cavity configurations[9-11,23] or were evaluated against an artificial substrate for bonding.[24] The main results from these studies indicate a negative effect of increasing the C-factor on dentin bond strength.

Insufficient data are available regarding the effect of cavity configuration when low-shrinkage composites are used. Consequently, the objective of this *in vitro* study was to investigate how bond strength is affected in cavities with different configurations when low-shrinkage composite materials are used. The null hypotheses tested were 1) there is no difference in bond strength of low-shrinkage vs high-shrinkage composites (referred to as conventional composite in this article) to dentin in cavities with different C-factors; and 2) there is no difference in polymerization shrinkage stresses and elastic modulus between low-shrinkage and conventional resin composites.

MATERIALS AND METHODS

Fifty-four non-carious, non-restored human molars were collected and stored in 0.10% thymol, as approved under the Indiana University-Purdue University Indianapolis (IUPUI)/Clarian Institutional Review Board protocol (No. 0308–74). Superficial dentin was exposed by sectioning the crowns parallel to the occlusal surface with a precision, low-speed diamond saw under distilled water cooling. A second cut was made in the root approximately 3 mm from the cemento-enamel junction, creating two parallel surfaces. The teeth were then mounted on prefabricated acrylic resin blocks. A 4.5 mm×4.5 mm square was drawn with a pencil on the flat occlusal surface of the teeth and examined with a light microscope (Nikon Measurescope UM-2, Nikon Corp, Kanagawa, Japan) with 20× magnification to insure that all the cavity borders were located within the dentin. A #330 carbide bur (Super bur, Caulk, Dentsply, Milford, DE, USA) was mounted in the spindle of a milling machine (Sherline products, Ines, Vista, CA, USA) and used under constant water cooling to prepare standardized Class I cavities with the dimensions of 4.5 ± 0.2 mm in length and 4.5 ± 0.2 mm in width and to a depth of 1.8 ± 0.2 mm below the flat ground dentin. The cavity floor was finished using a low-speed inverted cone bur #5 (Busch & Co, Engelskirchen, Germany) under water cooling to ensure a flat pulpal floor. Burs were replaced after every two preparations. The pulpal floors of the cavities were examined with the light microscope to verify the absence of irregularities or pulp exposures. Teeth were randomly assigned into six groups (groups were designated based on application of nail polish to four walls [C1], three walls [C2], two walls adjacent to each other [C3a], two walls opposite to each other [C3b], one wall [C4], or no walls [C5]) according to the cavity configuration (C-factor), which is defined as the ratio of the bonded surface area to unbonded surface area.[7]

The cavity designs are described in Table 1. Each group was further divided into three subgroups, according to the restorative system used: either Filtek Silorane/Silorane adhesive (SIL, 3M ESPE AG, Seefeld, Germany), Aelite LS/One-Step Plus (AL, BISCO, Schaumburg, IL, USA), or Filtek Z250/Adper Single Bond Plus (Z, 3M ESPE, St Paul, MN, USA), which was used as a control. Materials, manufacturers, lot numbers, and compositions are shown in Table 2.

For all groups except C5, walls that needed to be isolated were covered, according to the protocol of Mallmann and others,[25] using two layers of a red nail varnish. This technique was used to change the C-factor while approximately maintaining the same volume of resin composite in all of the cavities. Care was taken to prevent the nail varnish from contacting the cavity floor and the other side walls needed for bonding. The nail varnish was allowed to dry completely for 60 minutes and was then examined under a light microscope for any excess nail varnish. Any residual varnish was carefully removed with curettes. The teeth were rehydrated in deionized water at 37°C for 24 hours. For the C5 groups, no varnish was placed, but the teeth were also allowed to dry for 60 minutes and were then rehydrated in deionized water at 37°C for 24 hours to insure that all of the teeth in the study were exposed to similar conditions. The prepared teeth were randomly assigned to one of the three adhesive groups. The adhesive systems were applied to the pulpal floor and non–nail polished walls of the cavity following the manufacturer's recommendations, as shown in Table 2. Corresponding composites were packed into the cavities in one increment in order to maximize the effect of polymerization shrinkage and were then cured for 20 seconds using a light-emitting diode, Demetron A.1 (Kerr/Sybron, Orange, CA, USA), of 1600 ± 18 mW/cm^2 intensity. Monitoring of the

Table 1: *Evaluated Cavity Configurations*

Description	Abbreviation
Class I occlusal cavity design with only the pulpal wall bonded to resin composite. C-factor = 0.38	C1
Class I occlusal cavity design with the pulpal wall and one side wall bonded to resin composite. C-factor = 0.64	C2
Class I occlusal cavity design with the pulpal wall and two adjacent side walls bonded to the adhesive and composite resin. C-factor = 1	C3a
Class I occlusal cavity design with the pulpal wall and two opposing side walls bonded to resin composite. C-factor = 1	C3b
Class I occlusal cavity design with the pulpal wall and three side walls bonded to resin composite. C-factor = 1.8	C4
Class I occlusal cavity design with all walls bonded to the resin composite. C- factor = 2.6	C5

intensity was done prior to fabrication of each specimen using a curing radiometer (Cure Rite, Dentsply Caulk). After light-curing, the restorations were finished with a 600-grit silicon carbide paper, and the restored teeth were stored in deionized water at 37°C for 24 hours.

Microtensile Bond Strength Test

A low-speed diamond saw (Isomet 1000, Buehler Ltd, Lake Bluff, IL, USA) was used for sectioning the teeth under copious water coolant at a fixed cutting speed of 600 RPM and load of 50 g; the restored teeth were sectioned serially, starting from the tooth restoration interface perpendicular to the bonded cavity floor, into four slices. Teeth were rotated 90° and then sectioned again to obtain 16 beams. The saw was adjusted to steps of 1.1 mm, and because the thickness of the blade was 0.3 mm, the resultant sticks had a cross-sectional area of 0.8×0.8 mm^2 $\pm$ 0.1 mm^2. Four beams from the center of the pulpal floor were selected in the study to minimize the variable of the degree of approximation of the beam to either the bonded or the non-bonded walls (n=12). The bonded surface area at the adhesive interface was calculated before testing by measuring the width and thickness of each specimen using a digital caliper (Absolute Digimatic Caliper, Mitutoyo Corp, Kawasaki, Japan). These specimens were then mounted on a modified Bencor Multi-T device (Danville Engineering, Danville, CA, USA) with cyanoacrylate adhesive (Loctite Super Glue, Henkel Consumer Adhesives Inc, Avon, OH, USA) and were then stressed to failure in a universal testing machine (SINTECH 1123, MTS Inc, Eden Prairie, MN, USA) with a 2.5-kg load cell traveling at a crosshead speed of 1 mm/min. The maximum force necessary to break the bonds in tension was divided by the cross-sectional area of the bonded surfaces to obtain the bond strength, which was expressed in MPa.

The effects of material and cavity design on microtensile bond strength (μ-TBS) were evaluated using a Weibull survival analysis. Specimens that spontaneously debonded were treated as left-censored at 4 MPa (the smallest measured strength was 4.3 MPa). Specimens that debonded as a result of cyanoacrylate failure were treated as right-censored at the highest measured strength. If the failure of these specimens was at a lower value, then they were treated as censored at the measured MPa. Pairwise comparisons between the treatment combinations were accomplished with and without adjustment for multiple testing using the Sidak method (adjusted p-value = 1–[1–original p-value]), following the protocol recommended by Eckert and Platt in 2007).[26]

Shrinkage Stress Test

A tensometer (American Dental Association Foundation, Paffenbarger Research Center, Gaithers-

Table 2: *Names, Manufacturers, Lot Numbers, Compositions and Application Procedures of the Materials Under Investigation*

Composite	Manufacturer	Composite Lot #	Composite Composition
Filtek Silorane (SIL)	3M ESPE AG, Seefeld, Germany	203908	3,4- epoxycyclo-hexylethyl-cyclopolymethylsiloxane, Bis-3,4-epoxycyclohexylethyl-phenyl-methylsilane, silane, fillers: 53 vol%-73 wt% quartz (0.5 μm)
Aelite LS Posterior (AL)	BISCO Inc, Schaumburg, IL, USA	06000-01146	Bis-EMA, Bis-GMA, TEGDMA fillers: 70 vol%-80 wt% glass frit, amorphous silica (0.05–4.0 μm)
Filtek Z250 (Z)	3M ESPE, St Paul, MN, USA	6CM	Bis-EMA, UDMA, fillers: 60 vol%–-75-85 wt% silane-treated zirconia/silica (0.01–3.5 μm)

Abbreviations: Bis-EMA, ethoxylated bisphenol A dimethacrylate; Bis-GEMA, bisphenol A diglycidyl ether methacrylate; Bis-GMA, bisphenyl glycidylmethacrylate; CQ, camphorquinone; DMAEM, dimethyl-amino-ethyl methacrylate; EMA, ethyl methacrylate; GDM, glycerol dimethacrylate; GPDM, glycerophosphate dimethacrylate; HEMA, hydroxyethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

burg, MD, USA)[27,28] was used to measure shrinkage stress of the three tested materials using the same volume of the materials used to restore the cavities for the microtensile test.

A 1.3-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 to maintain the same composite volume used to restore the cavities in the microtensile study. The C-factor was calculated to be 2.31 for all specimens.

The specimens were cured for 20 seconds through the lower rod using the same curing unit that was used for the μ-TBS test. 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 then 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 shrinkage stress was monitored continuously for 30 minutes from the start of light activation for each sample that yielded real-time shrinkage stress during polymerization. From this data, 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. The mean maximum shrinkage stress was calculated from five samples per each material.

Flexure Modulus Test

Flexure modulus was determined using standard procedures in accordance with ISO 4049. Five identical bar-shaped specimens (25 mm in length, 2 mm in width, and 2 mm in height) of each tested material were fabricated. Specimens were cured in a standard mode with a 12-mm–diameter curing-light tip. The central portion of each bar-shaped specimen was subjected to an initial irradiation for 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. Flexural modulus of the material was determined using a universal testing machine

Table 2: *Names, Manufacturers, Lot Numbers, Compositions and Application Procedures of the Materials Under Investigation (ext.)*

Adhesive	Adhesive Lot #	Adhesive Composition	Technique of Application
Filtek Silorane primer	P0273	HEMA, BIS-GMA, water, ethanol, phosphoric acid–methacryloxy-hexylesters, 1.6-hexanediol dimethacrylate, copolymer of acrylic and itaconic acid; DMAEM, phosphine oxide. 8–12 wt% silica	Apply with applicator and rub for 15 s, air-disperse, light-cure for 10 s
Filtek Silorane adhesive	L0163	Dimethacrylate; TEGDMA, phosphoric acid–methacryloxy-hexylesters, hexanediol dimethacrylate 5-10 wt% silica	Apply with applicator, air-disperse, light-cure for 10 s
One-Step Plus	0600000977	Biphenyl dimethacrylate, HEMA, acetone, glass	Etch enamel and dentin with 37.5% phosphoric-acid gel for 15 s. Rinse thoroughly, air- or blot dry for 2–3 s, shake bottle for 3–5 s and vent. Apply two coats with a brush and agitate for 10–15 s. Air-dry for 1–2 s. Light-cure for 10 s
Adper Single Bond Plus	5EX	BisGMA, HEMA, UDMA, ethanol, water, copolymers of acrylic and itaconic acids. Silane-treated silica nanofillers (10%)	Etch enamel and dentin with 7.5% phosphoric-acid gel, rinse with water, and blot dry with a cotton pellet. Apply two to three coats of adhesive to etched enamel and dentin for 15 s with gentle agitation. Air thin for 5 s. Light-cure for 10 s

(MTS Inc) 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 and was calculated using the universal testing machine software, according to the following equation:

$$E = \frac{PL^3}{4bh^3d} \times 10^{-3},$$

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.

Multiple comparisons of group means of shrinkage stress and elastic modulus were made utilizing one-way analysis of variance and Tukey multiple range tests at a significance level of $p<0.05$.

RESULTS

Microtensile Bond Strength Results

The interaction between material and cavity design was significant at p=0.0075, and the comparisons between materials are presented for each cavity design in Table 3.

Microtensile bond strength values for SIL were not affected by different C-factors. For the groups restored with AL, the only statistically significant difference was found between the μ-TBS of C1 and C4 groups (p=0.0164). The C1 group restored with Z yielded the greatest μ-TBS, which was statistically higher than that of all other groups. Furthermore, the results of Z showed a high tendency for decreasing the bond strength when the C-factor was increased.

Shrinkage Stress and Shrinkage Stress Rate Results

The shrinkage stress values of the three tested materials, the maximum shrinkage stress rate (R_{max} [ds/dt]), and time to maximum shrinkage stress rate (t_{max} [minutes]) of the tested materials are shown in Table 4 and Figure 1.

The mean maximum shrinkage stress value for SIL, AL, and Z were 0.94 ± 0.1 MPa, 1.79 ± 0.18 MPa, and 2.146 ± 0.18 MPa, respectively. The Z group yielded the highest shrinkage stress, which was significantly higher than that of SIL ($p<0.001$)

Table 3: *Mean and Standard Deviation of the Microtensile Bond Strength Values[a] for Different C-factors Listed in Table1.*

Material	Mean -TBS (MPa)					
	C1	C2	C3a	C3b	C4	C5
SIL	17.04 (5.7) a	18.52 (8.2) a	16.69 (3.7) a	14.69 (4.9) a	16.57 (9.1) a	17.90 (6.1) a
AL	24.23 (6.0) a	22.79 (5.1) a	21.21 (5.2) a	22.57 (6.7) a	17.38 (4.8) b	19.13 (6.7) ab
Z	33.14 (6.3) a	23.69 (5.0) b	16.01 (3.2) bc	16.36 (4.8) bc	16.29 (5.4) c	14.26 (4.8) c

Abbreviations: AL, Aelite LS Posterior; -TBS, microtensile bond strength; SIL, Filtek Silorane; Z, Filtek Z250.
[a] Standard deviations are given in parentheses. Within a row, values with the same letters are not statistically different.

and AL ($p=0.025$). Furthermore the shrinkage stress for the SIL group was significantly lower than that of the AL group ($p<0.001$).

The maximum shrinkage stress rate of SIL was 0.035 ± 0.009 MPa/s, which was the lowest maximum shrinkage stress rate value that developed at 9.0 ± 0.8 seconds, while the R_{max} for the AL group was 0.057 ± 0.007 MPa/s, which was higher than that of the SIL group. It took AL a longer time (10.2 ± 1.2 seconds) to develop its maximum shrinkage stress rate. Z exhibited the highest maximum shrinkage stress rate, 0.154 ± 0.015 MPa/s, only after 4.2 ± 1.6 seconds.

Flexural Modulus Results

Flexural modulus results are shown in Table 4. The flexural modulus of Z was significantly higher than that of both SIL and AL ($p<0.05$). No significant difference was found between the flexural modulus of the SIL and AL groups.

DISCUSSION

In this study bond strength to the cavity floor was tested using four μ-TBS beams from the center of the cavity floor in order to minimize the variable of the degree of approximation of the beam to either the bonded or the nonbonded walls. However, it is important to clarify that bond strengths along a cavity floor may not be representative of those along walls, particularly as a result of differences in tubule orientation, density, and generated lateral forces during polymerization, which may alter the μ-TBS values.

Results of μ-TBS testing in this study revealed that the increase in cavity configuration factor resulted in a significant reduction in bond strength when the conventional methacrylate-based composite Z was used. Changing the C-factor did not affect the μ-TBS of either SIL or AL. Thus, the first null hypothesis was rejected. Furthermore, the results of shrinkage stress measurement demonstrated that SIL and AL showed significantly lower shrinkage stress and elastic modulus compared to the conventional methacrylate-based composite Z. Thus, the second null hypothesis was also rejected.

Stress developed during the polymerization of a direct resin composite restoration detrimentally affects the maturing bond strength.[9] If the resulting

Table 4: *Mean Maximum Shrinkage Stress, Maximum Shrinkage Stress Rate (R_{max}), Time to Maximum Shrinkage Stress Rate (t_{max}) and Elastic Modulus[a]*

Material	Shrinkage Stress, MPa	R_{max}, MPa/s	t_{max}, s	Elastic Modulus, GPa
SIL	0.94 (0.11) c	0.035 (0.009) a	9.0 (0.8) b	8.85 (0.57) a
AL	1.79 (0.18) b	0.057 (0.007) a	10.2 (1.2) b	8.3 (0.72) a
Z	2.14 (0.23) a	0.154 (0.015) b	4.2 (1.6) a	10.08 (0.45) b

Abbreviations: AL, Aelite LS Posterior; SIL, Filtek Silorane; Z, Filtek Z250.
[a] Standard deviations are given in parentheses. Within each column, values with the same letter mean no statistically significant difference ($p>0.05$).

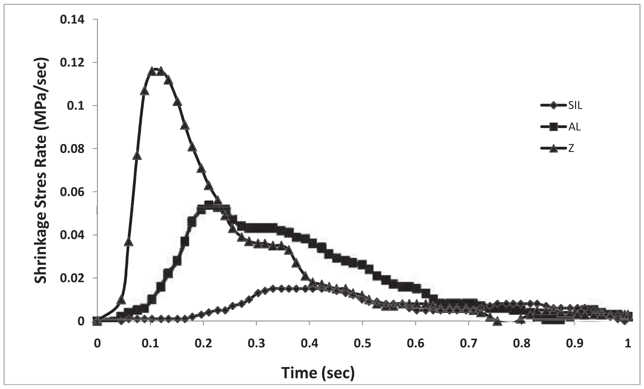

Figure 1. *Shrinkage stress rate of the materials under investigation.*

stresses within the material and at the tooth-restoration interface exceed the adhesive strength of the restorative, gaps will be formed between resin composites and tooth substrate,[14] which in turn can lead to serious clinical problems, such as microleakage, postoperative sensitivity, marginal staining, and secondary caries.[29]

Numerous previous studies concentrated their research on the contributing factors for the stress generated in order to avoid their damaging effect at the tooth-restoration interface. The post-gel shrinkage and the resultant stresses are highly influenced by polymerization kinetics, since the role of composite properties in development of residual shrinkage stress is determined by the time-dependent relationship between volumetric shrinkage on one hand and viscous and elastic modulus on the other hand.[30] However, it is important to recognize that not all shrinkage contributes to shrinkage stress. The developing stiffness of the setting material, known as elastic modulus, is only rapidly increased following gel formation; at this stage the material gains rigidity and is less able to yield.[5] Simultaneously, the contraction stress builds up and is positively correlated with the developing elastic modulus and viscosity.[31]

C-factor is considered to represent another important factor that can affect the developing stress when cavities are restored with resin composite. This effect was markedly demonstrated in the results of Z, which showed a significantly decreased bond strength when the material became more restricted by increasing the bonded surfaces. The reduction of the free surface area limits the flow of the shrinking material, depriving the material of the ability to change its shape and restricting relaxation of the developed stress. In addition, the shrinking material will pull the opposing walls of the cavity closer together, thereby increasing the stresses generated at the bonded walls.[5,7,17]

Several studies[9,11,12,23,32,33] have revealed lower bond strength when the bulk technique is used to restore Class I cavities, as this highly stressful configuration maximizes the competition between the polymerization shrinkage and the adhesion between resin and dentin. Furthermore, Z revealed the highest maximum shrinkage stress rate and the shortest time to reach it (Table 4); this finding can additionally explain the inverse relationship between the tested bond strength and the cavity configuration of this material. The fast development of maximum shrinkage stress, which may result in early development of the material's stiffness, would allow minimal time for stress relaxation and the highest mean shrinkage stress value. It has been reported in many studies[28,34,35] that any stress relaxation prior to the vitrification stage does not provide as much benefit to overall volumetric shrinkage reduction as expected, even though the decreased stress rate exerts great influence on stress development.

On the same basis, we can explain why the bond strength of low-shrinkage composites was not affected by increasing cavity configuration. Low-shrinkage composite revealed lower shrinkage stress, and this can mainly be attributed to the difference in monomer composition of their resin matrix and kinetics of its polymerization reaction. Weinmann and others[19] compared the product profile of SIL with the product profiles of different methacrylate-based restoratives, including AL. The volumetric shrinkage of the SIL was determined to be 0.94 vol% (bonded disk method) and 0.99 vol% shrinkage (Archimedes method) followed by AL 1.7 vol% (bonded disk method) and 2.1 vol% shrinkage (Archimedes method) and these were the lowest values observed for the investigated materials. The volumetric shrinkage of other methacrylate-based restoratives increased to the levels of 2.5-3 vol%.[19]

The epoxy ring opening of the silorane produces volume expansion, which can partially offset the curing contraction resulting from the simultaneous formation of covalent bonds and the reduction in space between adjacent molecules.[19,22,36,37] Additionally, in contrast to the radical polymerization reaction that forms parallel chains and significant reduction in volume with increased chain length, the cationic ring opening polymerization of a multifunctional monomer such as silorane results in a network formation that is accompanied by minimal reduction in volume.[19,37]

Alternatively, the chemical composition of the resin matrix of AL is based on a combination of Bis-EMA, bisphenyl glycidylmethacrylate (Bis-GMA), and TEDGMA. The replacement of some low-molecular-weight TEGDMA with higher-molecular-weight Bis-EMA that has fewer double bonds per unit of weight increases the distance between polymer chains, which in turn decreases the polymerization contraction of the material.[38,39]

Results also revealed significantly lower elastic modulus exhibited by both SIL and AL, which is consistent with the results obtained by Eick and others for SIL.[37] According to Hooke's law, stress is equal to the elastic modulus multiplied by the strain.[40] Thus, lower shrinkage, combined with the lower elastic modulus of both SIL and AL, can explain the decreased stress within the composite structure**.** A low modulus of elasticity of a material was not necessarily associated with high bond strength. However, it causes a more uniform stress distribution at the restorative composite-tooth interface, thus increasing the possibility that the bond with the cavity walls will be formed and will survive during setting.[41]

Additionally, the lower polymerization stress of AL, compared with that of Z, could be affected by the higher filler loading associated with low-resin matrix fraction, while maintaining a low viscosity.[42] A material's filler content is thought[43] to affect both volumetric shrinkage and elastic modulus in opposite ways.

According to Watts and others,[44] composites with relatively high filler content have significant reductions in volumetric shrinkage, accompanied by lower contraction stress values. On the contrary, other studies[45,46] have revealed that materials that are heavily filled exhibit high levels of stiffness and a reduction in the material's flow capacity, which is also associated with high stress levels. However, the elastic modulus of AL in this study was significantly lower than that of Z, despite the higher filler loading of the former. The low-shrinkage characteristics of AL monomer as well as the decrease in its matrix fraction might result in the reduction of its volumetric shrinkage without obvious parallel increases in material stiffness, thus decreasing the overall material stress.

Microtensile results for SIL and AL can also be attributed to the lower shrinkage stress rate and the longer time to reach the maximum shrinkage stress rate for both materials, in comparison to those associated with Z. This is consistent with the results of Palin and others,[47] who explained that the longer time exhibited to reach gel point and the slower development of a cross-linked network in SIL provide for sufficient flow of the molecules, allowing them to arrange themselves in less stressed configurations. These results were also supported by the significantly lower elastic modulus exhibited by both SIL and AL.

The cationic polymerization reaction of SIL is known to be slower than the radical polymerization of the methacrylate-based composite.[19,36] Moreover, this type of polymerization was proved to affect the degree of conversion. Previous studies[48,49] carried out to compare the degree of conversion of SIL compared to that of methacrylate-based composites, particularly Z, revealed a lower initial degree of conversion exhibited by SIL. This may allow for longer time for viscous flow of the molecules to relieve some of the developing shrinkage stress. The relatively slow shrinkage of SIL possibly represents an advantage in relation to faster shrinking materials, as it may decrease the overall stresses within the material and at the tooth restoration interface as a result of this "intrinsic soft-start."[19,36,50]

Although the results demonstrated that low-shrinkage composites, when placed in bulk, are more immune to changes in C-factor with respect to bond strength, it seems that they do not necessarily solve all adhesion problems, and this was also supported by a recent study.[51] The bond strengths for these composites in low–C-factor cavities are inherently lower than that of the control, particularly for SIL. On the other hand, the μ-TBS of AL was similar to or higher than that of both SIL and Z for each C-factor except for C-factor 1, in which Z exhibited a higher mean μ-TBS value. These results can be attributed to the acetone co-solvent used in AL, as it might induce phase separation and precipitation of adhesive components, impairing its bond strength.[52]

SIL adhesive system can be considered a "mild" self-etch adhesive, which is known to have lower bond strength in comparison to the etch-and-rinse adhesives of AL and Z.[53-55] Moreover, the stiffness of the uncured composite during bulk placement is thought to interfere with the close adaptation of SIL to the cavity walls, resulting in air bubbles observed at the composite-dentin interface, and might have led to failure at lower bond strength, as was reported in a recent study,[51] in which the μ-TBS of SIL was found to be influenced by factors other than polymerization shrinkage. On the other hand, it was suggested by another study[56] that better bond durability may be expected with aging when using silorane-based resin systems, and this improved bond durability was attributed to the complete absence of water trees with silorane; these water trees had been seen immensely infiltrating into the hybrid and adhesive layers of methacrylate-based composite.

Therefore, although lower values of μ-TBS of low-shrinkage composites were recorded in this study with low–C-factor cavities, these values might be considered sufficient to counteract its polymerization shrinkage stress, which has been reported to be less than that of methacrylate-based composites, and, accordingly, the need for a very strong adhesive might be reduced.[56] On the contrary, the bond strength of conventional methacrylate-based composites in high–C-factor cavities might be comparable to that of low-shrinkage composites, but the generated stresses at the bonding interface might raise a question about their ability to distribute and withstand further thermo-mechanical stresses in the oral cavity.

CONCLUSIONS

In contrast to conventional composite, increasing C-factor did not negatively affect the bond strength of low-shrinkage composites. Variation in the effect of cavity configuration on the μ-TBS of the tested materials in this study can be attributed to the difference in the developed shrinkage stress. Dissimilarity in chemical structure and mode of polymerization of each material are reflected by the rate of polymerization and elastic modulus, which in turn affect the shrinkage stresses induced by the tested material.

Note

This research work was presented at the 87th General Session of the International Association for Dental Research (IADR), Miami, FL, USA, April 2009.

Acknowledgments

The authors thank George Eckert, MS for his help in the statistical analysis of this study. Also, special thanks go to 3M ESPE and BISCO for their generous donation of the materials used in this study.

(Accepted 28 March 2011)

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