

# Effective Expansion: Balance between Shrinkage and Hygroscopic Expansion

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## Abstract

The purpose of this study was to investigate the relationship between hygroscopic expansion and polymerization shrinkage for compensation of polymerization shrinkage stresses in a restored tooth. One resin-modified glass-ionomer (RMGI) (Ketac Nano, 3M ESPE), 2 compomers (Dyract, Dentsply; Compoglass, Ivoclar), and a universal resin-based composite (Esthet•X HD, Dentsply) were tested. Volumetric change after polymerization (“total shrinkage”) and during 4 wk of water storage at 37°C was measured using an optical method ( $n = 10$ ). Post-gel shrinkage was measured during polymerization using a strain gauge method ( $n = 10$ ). Extracted human molars with large mesio-occluso-distal slot preparations were restored with the tested restorative materials. Tooth surfaces at baseline (preparation), after restoration, and during 4 wk of 37°C water storage were scanned with an optical scanner to determine cuspal flexure ( $n = 8$ ). Occlusal interface integrity was measured using dye penetration. Data were analyzed using analysis of variance and post hoc tests (significance level 0.05). All tested materials shrunk after polymerization. RMGI had the highest total shrinkage (4.65%) but lowest post-gel shrinkage (0.35%). Shrinkage values dropped significantly during storage in water but had not completely compensated polymerization shrinkage after 4 wk. All restored teeth initially exhibited inward (negative) cuspal flexure due to polymerization shrinkage. Cuspal flexure with the RMGI restoration was significantly less ( $-6.4 \mu\text{m}$ ) than with the other materials ( $-12.1$  to  $-14.1 \mu\text{m}$ ). After 1 d, cuspal flexure reversed to  $+5.0 \mu\text{m}$  cuspal expansion with the RMGI and increased to  $+9.3 \mu\text{m}$  at 4 wk. After 4 wk, hygroscopic expansion compensated cuspal flexure in a compomer (Compoglass) and reduced flexure with Dyract and resin-based composite. Marginal integrity (93.7% intact restoration wall) was best for the Compoglass restorations and lowest (73.1%) for the RMGI restorations. Hygroscopic expansion was more effective in compensating shrinkage stress than would be assumed based on total shrinkage, because only post-gel shrinkage needed compensation. Effective expansion is therefore hygroscopic expansion minus post-gel shrinkage.

**Keywords:** dental materials, dental restoration, polymerization, composite resins, compomers, glass ionomer

## Introduction

Contraction stress from shrinkage during polymerization of resin-based restorative materials has been a clinical concern for more than 50 y (Bowen 1963). Material contraction during setting has been reported not only for resin-based but also for glass-ionomer-based materials (Attin et al. 1995). Shrinkage stress induced by setting contraction has been associated with microleakage, secondary caries, marginal loss, enamel cracks, and postoperative sensitivity (Bausch et al. 1982; Tantbirojn et al. 2004). Fortunately, shrinkage stresses are relieved over time by stress relaxation and water absorption (Segura and Donly 1993; Vaidyanathan et al. 2003; Meriwether et al. 2013).

Absorption of water causes materials to swell, so-called hygroscopic expansion, which counters the contraction originating from the polymerization process (Bowen et al. 1982; Segura and Donly 1993; Kanchanasavita et al. 1995; Meriwether et al. 2013). Not only hydrophilic materials such as resin-modified glass-ionomers (RMGI) show volumetric expansion in water (Attin et al. 1995), but hydrophobic resin-based composites also exhibit hygroscopic expansion (Momoi and McCabe 1994; Martin et al. 2003; Al Sunbul et al. 2015). Compomers,

which are polyacid-modified composite materials that share properties of both traditional resin-based composites and glass-ionomer cements, have also been shown to expand by the reduction in marginal gaps caused by polymerization shrinkage (Huang et al. 2002; Rosales-Leal et al. 2013). Compomers are fundamentally hydrophobic but have hydrophilic acid-functional monomers that absorb water to allow acid-base reactions for clinically desirable properties such as fluoride release (Cattani-Lorente

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et al. 1999; Nicholson 2007). Although compensation of polymerization shrinkage is welcome, if hygroscopic expansion exceeds polymerization shrinkage, it may reverse a shrinkage stress condition into expansion stresses, which could be equally harmful (Momoï and McCabe 1994; Versluis et al. 2011; Park and Ferracane 2014). Hygroscopic expansion of RMGI and compomer core buildup and luting materials has been associated with cracks in all-ceramic crowns (Sindel et al. 1999). Glass-ionomer luting cements have also been reported to cause fracture of moderate-strength indirect ceramic restorations under clinical conditions (Christensen 2007).

Polymerization shrinkage and shrinkage stress as well as water absorption have been extensively studied. However, few have studied volumetric expansion from the water absorption, and expansion is usually determined with respect to the cured material volume instead of the volume of the uncured, prepolymerization material. Rüttermann et al. (2007) measured hygroscopic expansion with respect to total shrinkage and found that it did not compensate for the shrinkage, which seems to contradict previously noted reports of expansion stresses. The relationship between hygroscopic expansion and shrinkage stress has received little scrutiny and appears based on the reasonable presumption that expansion compensates shrinkage. However, since the relationship between shrinkage and stress is not straightforward and depends on transient properties of the restorative and on the material and geometric properties of the restored tooth (Versluis, Tantbirojn, Pintado, et al. 2004), the relationship between hygroscopic expansion and shrinkage stress compensation may also not be forthright. The objective of this study was to examine the balance between polymerization shrinkage and hygroscopic expansion with respect to the residual stress condition in restored teeth. The balance was tested for restorative materials that represented a range of hydrophilicity/hydrophobicity characteristics encountered in glass-ionomer, compomer, and resin-based composite.

## Materials and Methods

One resin-modified glass-ionomer (Ketac Nano; 3M ESPE, St. Paul, MN, USA), 2 compomers (Dyract eXtra [Dentsply DeTrey GmbH, Konstanz, Germany] and Compoglass [Ivoclar Vivadent AG, Schaan, Liech]), and a universal resin-based composite (Esthet•X HD; Dentsply, Milford, DE, USA) were tested. Material information is listed in Table 1. Light curing was performed with a violet-blue LED curing light (VALO; Ultradent Products, South Jordan, UT, USA) in standard mode with a mean irradiation of  $1538 \pm 7 \text{ mW/cm}^2$  ( $n = 3$ ) with the tip placed against the anterior sensor of a Marc Patient Simulator (Bluelight Analytics, Halifax, NS, Canada).

## Volumetric Changes

Dimensional changes (shrinkage or expansion) were determined using a recently published optical method in which the projected surface area of a sample is measured from images captured by a stereomicroscope using image analysis (Tantbirojn et al. 2015). This method measures free shrinkage and is therefore

less affected by specimen shape than shrinkage measurement methods that require specimen fixation. Sample size was 10 for each material. Uncured restorative material, about 6 mm in diameter and 1.5 mm thick, was placed on a silicone platform (Express; 3M ESPE) to ensure free shrinkage. A prepolymerization image was captured from above with a stereomicroscope (SZX16; Olympus, Tokyo, Japan) at 1.25 magnification, immediately followed by a 40-s light cure from approximately 1 mm above the sample surface. A postpolymerization image was captured 10 min after start of the light cure. Samples were stored in the dark at 37°C in deionized water. Images were captured again after 1 and 3 d, as well as 1, 2, and 4 wk. Using public-domain image analysis software (ImageJ; National Institutes of Health, Bethesda, MD, USA), the projected surface areas were determined by tracing the outlines of the captured sample images using the Magic Wand tool, which selects pixels in an image based on tone and color. The area measurement is independent of sample orientation. Image brightness was adjusted to improve contrast between the sample and silicone platform. Dimensional changes in volume percent were obtained using  $[1 - (A_1/A_0)^{3/2}] \times 100\%$ , where  $A_1$  was the projected surface area of the sample after polymerization or water storage and  $A_0$  was the projected surface area before polymerization; shrinkage was defined as a positive value. The results were the changes in total volume after polymerization ("total shrinkage") and during storage in water compared with the original uncured material volume.

## Post-gel Shrinkage

Post-gel shrinkage was determined using a strain gauge method (Sakaguchi et al. 1997). Sample size was 10 for each material. Uncured restorative material (dome-shaped samples, approximately 4 mm in diameter and 1.5 mm high) was placed on a biaxial strain gauge (CEA-06-032WT-120; Measurements Group, Raleigh, NC, USA) connected to a quarter-bridge strain gauge input module in a USB chassis (NI 9235 and NI cDAQ-9178; National Instruments, Austin, TX, USA). The materials were light-cured for 40 s from approximately 1 mm above the sample surface. The start of the light cure was recorded with a solar cell (AM-1417CA; Panasonic, Osaka, Japan) connected to an analog input module (NI 9215; National Instruments) in the USB chassis. The effect of pre-gel shrinkage occurs during the initial seconds of the polymerization (Versluis, Tantbirojn, and Douglas 2004). Strain and solar cell output was collected at 4 Hz for 10 min using a customized data acquisition program (LabView; National Instruments). Strain values were zeroed at the start of the light cure, identified by the solar cell output. The 2 perpendicular strain components were averaged and the mean strain value was converted to volumetric shrinkage using  $[3L - 3L^2 + L^3] \times 100\%$ , where  $L$  was the strain; shrinkage was defined as a positive value (Tantbirojn et al. 2015).

## Cuspal Flexure

Eight sets of 4 extracted human molars (Institutional Review Board approval 14-03128-XM) with similar size and shape

**Table 1.** Material Information and Bonding Procedures.<sup>a</sup>

Material	Composition and Application Procedures	Batch No.	Manufacturer
<b>Dyract eXtra</b> (compomer) Shade: A2	Resin system: UDMA, TCB resin, TEGDMA, trimethacrylate resin, camphorquinone, ethyl-4-dimethylamino-benzoate, BHT, UV stabilizer Fillers: strontium-alumino-sodium-fluoro-phosphor-silicate glass, highly dispersed silicon dioxide, strontium fluoride, iron oxide, and titanium dioxide pigments	140912 and 141205	Dentsply DeTrey GmbH, Konstanz, Germany
<b>Compoglass F</b> (compomer) Shade: A2	Resin system: 19.3 wt% dimethacrylates Fillers (80.5 wt%): ytterbium trifluoride, Ba-Al-fluorosilicate glass, and spheroid mixed oxide Catalysts, stabilizers, and pigments 0.20 wt%	T08698	Ivoclar Vivadent AG, Schaan, Liechtenstein
<b>Esthet-X HD</b> (resin-based composite) Shade: A2	Resin system: Bis-GMA adduct, Bis-EMA adduct, triethylene glycol dimethacrylate, camphorquinone, photoinitiator, stabilizer, pigments Fillers: barium fluoroborosilicate glass with a mean particle size below 1 $\mu$ m and nanofiller silica (particle size 0.04 $\mu$ m)	1412122 and 140829	Dentsply, Milford, DE, USA
<b>Ketac Nano</b> (RMGI) Shade: A2	Resin system: methacrylate-modified polyalkenoic acid, methacrylate blend including HEMA, water Fillers (69 wt%): fluoroaluminosilicate glass, zirconia/silica nanofillers, and nanoclusters Filler loading: 69 wt% or 56 vol%	N612882	3M ESPE, St. Paul, MN, USA
<b>Xeno III</b> (single-step self-etching adhesive)	Liquid A: HEMA 25% to 50%, ethanol 10% to <25% Liquid B: tetra-methacryloxy-ethyl-pyro-phosphate 50% to 100%, monofluoro phosphazene modified polymethacrylate resin 10% to <25%, diurethane dimethacrylate (mixture of isomers) 3% to <10% Procedures: mix 1 drop each from bottles A and B for 5 s, apply 10 s, air dry >2 s, light cure 10 s	1407001260	Dentsply DeTrey GmbH, Konstanz, Germany
<b>Adhese Universal</b> (single-component adhesive)	VivaPen: HEMA 20% to <25%, Bis-GMA 20% to <25%, ethanol 10% to <25%, 1,10-decandiol dimethacrylate 2.5% to <10%, methacrylated phosphoric acid ester 2.5% to <10%, camphorquinone 1% to <2.5%, 2-dimethylaminoethyl methacrylate 1% to <2.5% Procedures: push 2 to 3 clicks, scrub 20 s, air dry 5 s, light cure 10 s	T24701	Ivoclar Vivadent AG, Schaan, Liechtenstein
<b>Ketac Nano Primer</b> (RMGI primer)	Primer: water 40% to 50%, HEMA 35% to 45%, copolymer of acrylic and itaconic acids 10% to 15% Procedures: apply 15 s, air dry 10 s, light cure 10 s	N586209	3M ESPE, St Paul, MN, USA

BHT, butylated hydroxy toluene; Bis-EMA, ethoxylated bisphenol A dimethacrylate; Bis-GMA, bisphenol A diglycidyl ether dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; RMGI, resin-modified glass-ionomer; TCB resin, carboxylated acid-modified dimethacrylate; TEGDMA, triethyleneglycol dimethacrylate; UDMA, urethane dimethacrylate.

<sup>a</sup>Sources: Product's safety data sheet, product profiles, product website, product technical manual.

were selected. The teeth were securely mounted in stainless steel rings, which had 4 reference spheres (Tantbirojn et al. 2004). The coronal surfaces were etched with 37% phosphoric acid for 5 min to achieve a matt surface suitable for optical scanning. Teeth were kept hydrated in deionized water between all subsequent experimental steps. The teeth received mesio-occluso-distal slot preparations (4 mm wide, 4 mm deep). A baseline scan was made 10 min after preparation to allow cuspal relaxation following the preparation (Francis et al. 2014). Surface points on the teeth were scanned every 60  $\mu$ m (resolution), in 3 dimensions, from 8 different directions, and with 5- $\mu$ m accuracy (COMET xS; Steinbichler Optotechnik GmbH, Neubeuern, Germany). After the baseline scan, teeth were restored with the restorative materials using their respective self-etched primer/adhesive, as recommended by their manufacturers. Material information and restorative procedures are listed in Table 1. The restorative materials were placed and light-cured in two 2-mm-thick horizontal increments, following manufacturer recommendation for maximum curing thickness. Light curing was from occlusal direction, 20 s for the mesial half and 20 s for the distal half. Restorations were wiped with alcohol pads to remove the oxygen-inhibited layer, and the restored teeth were rehydrated for 20 min before they were scanned. Restored

teeth were stored in the dark in deionized water at 37°C and scanned again after 1 d and 1, 2, and 4 wk. Scans of the restored teeth were precisely aligned with their baseline scans (prepared teeth). This alignment was performed on the stainless steel reference spheres using Cumulus software (copyright Regents of the University of Minnesota), which minimizes root mean square differences between the reference surfaces. Buccal and lingual cuspal flexure ( $\mu$ m) was calculated over selected buccal and lingual surface areas using a custom software program (CuspFlex). The amount of cuspal flexure reflects the interaction of all mechanical properties and chemical processes during polymerization and storage (Tantbirojn et al. 2004).

### Occlusal Interface Integrity

The integrity of the occlusal interface was evaluated by measuring dye penetration along the buccal and lingual walls of the restorations. After the 4-wk scans were completed, restoration margins were finished to remove excess restorative materials. Root apices were blocked with utility wax and roots were covered with nail polish. The teeth were immersed overnight in 0.5 wt% basic fuchsin solution, embedded in acrylic resin, and sectioned bucco-lingually every 1 mm, yielding 4 to 5 slices per

**Table 2.** Mean (Standard Deviation) Volumetric Change of Materials for Post-gel and Total Shrinkage after Polymerization, and Volume Changes during Water Storage at Various Time Intervals.

Materials	Post-gel Shrinkage 10 min	Volume Change, %					
		10 min	1 d	3 d	1 wk	2 wk	4 wk
RMGI (Ketac Nano)	0.35 (0.07) A	4.65 (0.47) Bb	0.72 (0.91) Aa	0.26 (1.13) Aa	0.44 (1.14) Aa	0.10 (1.05) Aa	0.24 (0.86) Aa
Compomer (Compoglass)	0.56 (0.03) B	2.90 (0.40) Ad	2.41 (0.74) Bd	1.46 (1.17) Bbc	1.52 (0.76) Bc	0.73 (0.84) ABa	0.79 (0.84) Aab
Compomer (Dyract)	0.63 (0.03) C	2.76 (0.35) Ab	1.92 (1.10) Ba	1.95 (0.91) Ba	1.36 (1.01) Ba	1.47 (1.02) BCa	1.47 (0.62) Ba
Resin-based composite (EsthetX HD)	0.58 (0.03) B	2.73 (0.28) Ab	2.12 (0.83) Bab	2.16 (0.83) Bab	1.83 (0.73) Bab	2.20 (0.57) Ca	1.70 (0.50) Ba

Different capital letters indicate significant differences between materials within a time interval (column); different lowercase letters indicate significant differences in volume changes among time intervals within a material (row) (analysis of variance and Fisher's protected least significant difference post hoc test; significance level 0.05).

RMGI, resin-modified glass-ionomer.

tooth. Images of the restorations were captured under the stereomicroscope (SZX16; Olympus). Two evaluators independently measured dye leakage at the occlusal margins with image analysis software (Stream Basic; Olympus Soft Imaging Solution GmbH, Münster, Germany). Cavity width and wall thickness (buccal and lingual) were also recorded. Cavity width was  $4.06 \pm 0.12$  mm, and wall thickness was  $2.70 \pm 0.28$  mm. Occlusal integrity was defined as the percentage of dye leakage distance for the respective buccal or lingual wall heights. If there was less than 5% difference between the 2 evaluators, the values were averaged; otherwise, a consensus value was reached.

### Statistical Analysis

Volumetric changes, post-gel shrinkage, and cuspal flexure were compared among the restorative materials using 1-way analysis of variance (ANOVA) followed by Fisher's protected least significant difference (LSD) post hoc tests at 0.05 significance levels. Normal distribution conditions of all data were verified using the Anderson-Darling Normality test. Volumetric changes and cuspal flexure during storage were compared among the time intervals within each material using the same statistical methods.

## Results

### Volumetric Changes

There were significant differences in volumetric changes among the 4 materials (1-way ANOVA;  $0.0001 \leq P \leq 0.0128$ ) and within each material during the 4-wk exposure to water (1-way ANOVA;  $0.0001 \leq P \leq 0.0182$ ). The RMGI had significantly higher total shrinkage 10 min after polymerization than the compomers and resin-based composite, which all had similar total shrinkage values (Table 2). Shrinkage decreased during storage in water, with the RMGI dropping sharply by 85% after only 1 d. Shrinkage values of RMGI remained significantly lower than the other materials for 1 wk, after which it was still significantly lower than the Dyract compomer and resin-based composite. The resin-based composite exhibited the least volumetric changes during water storage. Shrinkage of the Compoglass compomer diminished slightly faster than the Dyract compomer and resin-based composite. At 4 wk,

none of the materials had completely compensated the polymerization shrinkage.

### Post-gel Shrinkage

One-way ANOVA indicated significant differences on post-gel shrinkage among the 4 materials ( $P = 0.0001$ ). The lowest post-gel shrinkage value was found for the RMGI and the highest for the Dyract compomer (Table 2). The post-gel shrinkage of the other compomer (Compoglass) was not significantly different from the resin-based composite.

### Cuspal Flexure

Examples of the cuspal flexure caused by polymerization shrinkage and hygroscopic expansion are visualized in Figure 1. There were significant differences in cuspal flexure among the 4 materials (1-way ANOVA;  $P = 0.0001$ ) and within each material during the 4-wk exposure to water (1-way ANOVA;  $0.0001 \leq P \leq 0.0067$ ). All restored teeth exhibited inward flexure of the cusps (shrinkage) after restoration, indicated by negative values in Table 3. The RMGI had significantly less inward cuspal flexure than the other materials and reversed to outward flexure (expansion; positive values) after only 1 d storage in water, which increased gradually during the 4-wk period. Cuspal flexure in the compomer and resin-based composite restored teeth was initially not statistically different from each other and decreased significantly while stored in water. After 2 wk, differences appeared among them, where cuspal flexure with one compomer restoration (Compoglass) was significantly less than with the other compomer (Dyract) and the resin-based composite. At 4 wk, the RMGI restoration had overcompensated the initial cuspal shrinkage by about 250%, causing cuspal expansion, and 1 of the compomers (Compoglass) had compensated the initial cuspal shrinkage flexure. Most remaining cuspal shrinkage flexure was found with the resin-based composite restoration, although flexure had decreased by about 50% from the original value.

### Occlusal Interface Integrity

One-way ANOVA indicated significant differences in occlusal interface integrity among the 4 restoration materials ( $P = 0.0183$ ).

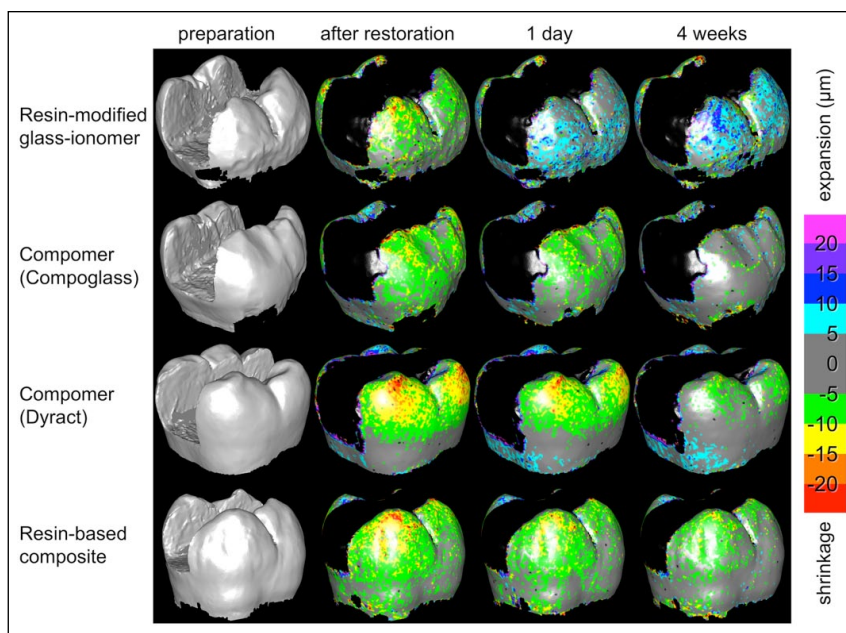


The occlusal integrity, defined as the percentage of intact restoration wall and averaged for buccal and lingual walls, ranged from 73% (RMGI) to 94% (Compoglass compomer) (Table 3).

## Discussion

This study investigated volume change of restoratives during and after polymerization and how it affected the stress conditions in a restored tooth. It was found that the volumetric shrinkage caused by polymerization was not compensated by hygroscopic expansion after 4 wk, with 38% to 95% of the polymerization shrinkage still present. Yet, the RMGI restoration caused substantial expansion of the cusps despite the 5% shrinkage remaining according to the measured volumetric changes for the RMGI material. Moreover, cuspal flexure was compensated in the Compoglass compomer-restored tooth even though the material volume change measurements showed 27% total shrinkage remaining. And the cuspal flexure of the Dyract compomer and resin-based composite was reduced by 50% to 67% despite the total shrinkage reducing only 38% to 47%. The cuspal flexure of restored teeth therefore appears to contradict the volumetric changes in the restorative materials.

Volumetric change due to hygroscopic expansion has been well documented in glass-ionomer-based, compomer, and resin-based materials (Attin et al. 1995; Cattani-Lorente 1999; Jedynakiewicz and Martin 2001). In addition, hygroscopic expansion has been shown to compensate for marginal gaps, cuspal flexure, and polymerization shrinkage stress (Huang et al. 2002; Rosales-Leal et al. 2013; Meriwether et al. 2013; Park and Ferracane 2014). How hygroscopic expansion and stresses correspond has received little scrutiny. Tacitly, it may be assumed that compensation of shrinkage will correspond with stress compensation. However, total shrinkage is not directly related to stress development and cuspal deformation because during the polymerization reaction, not all shrinkage causes stress (Bowen 1963). Early in the polymerization process, usually called “pre-gel,” some shrinkage stress is compensated by flow in the restorative material (Versluis, Tantbirojn, and Douglas 2004). Post-gel shrinkage can be defined as the shrinkage component for which flow does not compensate stress development. Since cuspal flexure stresses the restored tooth, the cuspal flexure observed after polymerization of the restorations was caused by the post-gel shrinkage. Consequently, compensating shrinkage stress requires only the compensation of stresses caused by post-gel shrinkage; expansion beyond post-gel shrinkage will result in expansion stresses. The effectiveness of hygroscopic expansion for stress compensation should thus be expressed by the effective expansion, which can be defined as the difference between expansion and post-gel



**Figure 1.** Visualized cuspal flexure of teeth after restoration and after 1 d and 4 wk of storage in water.

shrinkage. Figure 2 illustrates the differences among total volume change, effective expansion, and cuspal flexure.

The rate of water absorption and hygroscopic expansion depends on the surface area exposed to water, diffusion rate, and the thickness of the sample or restoration. It can be expected that the hygroscopic expansion rate was much faster in the total shrinkage samples because they were exposed to the water from all sides and were thinner than the restorations, which had only one exposed surface and were much deeper. Therefore, the hygroscopic expansion and cuspal flexure cannot be directly compared at the same time periods. Moreover, even if the tooth shapes and properties would be comparable, the elastic modulus values and how they evolve during water absorption (unpublished data over a period of 4 wk showed that the elastic modulus values leveled out and stabilized after 24 h) can also affect the response of the cuspal flexure. Such complex relationships can be studied by finite element analysis, which, unlike cuspal flexure, can provide insight into the corresponding internal stress distributions.

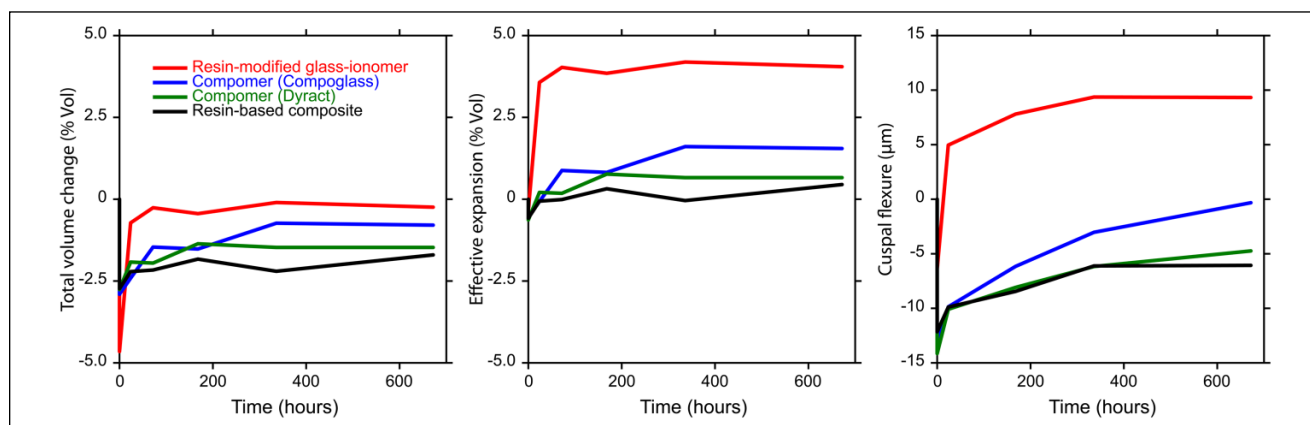
Nevertheless, this study showed that hygroscopic expansion is more effective in shrinkage stress compensation than may have been assumed based on water absorption studies. Hygroscopic expansion is generally viewed favorably because it closes gaps and is thought to be less deleterious or at least benign compared with shrinkage (Huang et al. 2002; Rosales-Leal et al. 2013). This may originate from the “wall-to-wall” concept for shrinkage stress, which implies that shrinkage pulls on the interfaces between 2 cavity walls. Hygroscopic expansion would reverse those pulling forces into compressive forces, which may give the impression of securing a restoration in the cavity. However, shrinkage stresses are not only “wall to wall” but also act laterally in the interfacial plane. Those lateral stresses challenge the interfacial bonding as well and are likely

**Table 3.** Mean (Standard Deviation) of Cuspal Flexure ( $\mu\text{m}$ ) and Percentage of Intact Interface at the Restoration Walls.

Materials	Cuspal Flexure, $\mu\text{m}$					% Wall Intact
	After Restoration	1 d	1 wk	2 wk	4 wk	
RMGI (Ketac Nano)	-6.4 (5.5) Ba	+5.0 (1.9) Bb	+7.8 (3.2) Bbc	+9.4 (3.1) Cc	+9.3 (3.4) Cc	73.1 (8.1) B
Compomer (Compoglass)	-12.8 (2.6) Aa	-9.9 (3.2) Aa	-6.2 (3.5) Ab	-3.0 (2.5) Bc	-0.3 (2.4) Bc	93.7 (2.5) A
Compomer (Dyract)	-14.1 (2.0) Aa	-10.1 (2.7) Ab	-8.1 (2.7) Abc	-6.2 (2.5) Acd	-4.7 (2.1) Ad	76.0 (15.6) B
Resin-based composite (EsthetX HD)	-12.1 (3.3) Aa	-9.9 (4.0) Aab	-8.4 (3.7) Abc	-6.1 (3.6) Ac	-6.1 (3.3) Ac	80.5 (18.9) AB

Negative cuspal flexure values indicate shrinkage (cusps moving inward), and positive values indicate expansion (cusps moving outward). Different capital letters indicate significant differences among the materials at each time interval (column); different lowercase letters indicate significant differences within a material (row) during the 4-wk experiment (analysis of variance and Fisher's protected least significant difference post hoc test; significance level 0.05).

RMGI, resin-modified glass-ionomer.

**Figure 2.** Mean volumetric changes, effective expansion for compensating shrinkage stress based on compensation of post-gel shrinkage, and cuspal flexure for the restorative materials during 4-wk storage in water.

to be equally deleterious in tension as compression. In this study, the interfacial integrity was examined at the end of the 4-wk period. All restored teeth showed cuspal contraction after polymerization of the restorations, indicating considerable bond strength able to stand up against the shrinkage stresses. After 4 wk of storage, the lowest interfacial integrity was found for the RMGI, which had the lowest post-gel shrinkage, exhibited the least cuspal flexure (as expected considering the lowest post-gel shrinkage and also indicating significant intact bonding), and had high effective expansion (which does not require intact bonding), whereas the best interfacial integrity was found for the restorative that successfully compensated its cuspal flexure (Compoglass compomer). Although we could not determine at which stage some of the interfacial integrity was lost or what the bond strength was for the different adhesive system-restorative combinations, it is not inconceivable that this observation supports the hypothesis that excessive expansion may be as harmful for the survival of restorations in the long term as polymerization shrinkage can be in the short term.

This study was originally conceived to evaluate polymerization and water absorption effects of compomers and compare them with a hydrophilic RMGI and a hydrophobic resin-based composite. We found that the measured volumetric expansion for the materials was not enough to explain the observed cuspal flexure. In the literature, few have noticed that hygroscopic expansion does not compensate polymerization shrinkage

because the expansion is usually determined for materials that were already cured. Rüttermann et al. (2007), however, measured hygroscopic expansion with respect to the uncured volume and also found that polymerization shrinkage was not compensated. To explain why hygroscopic expansion still has the potential to generate expansion stresses, we were reminded that Bowen (1963) noted that not all shrinkage causes stress during polymerization. Consequently, hygroscopic expansion only needs to counter the post-gel component of the total shrinkage to achieve compensation of shrinkage stress. This explains why hygroscopic expansion appears more effective in counteracting and even overcompensating shrinkage stress.

### Author Contributions

E.A. Suiter, D. Tantbirojn, A. Versluis, contributed to conception, design, data acquisition, analysis, and interpretation, drafted and critically revised the manuscript; L.E. Watson, J.S.B. Lou, contributed to data acquisition and analysis, critically revised the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

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