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A comparison of resin-modified glass-ionomer and resin composite polymerization shrinkage stress in a wet environment.

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Abstract

OBJECTIVE: The aim of this study was to investigate the polymerization shrinkage stress under water of four resin-modified glass–ionomers and three resin composite materials.

METHODS: Transparent acrylic rods (5 mm diameter x 30 mm) were prepared and secured into drill chucks connected to a universal testing machine. A plastics cup was placed around the lower rod and a distance of 1.00 mm was established between the prepared surfaces which provided a C-factor of 2.5. For composite only, an adhesive layer (Scotchbond Universal Adhesive) was placed on the rod ends and cured to achieve a bond with the rod end. Materials were placed between the rods and a strain gauge extensometer was installed. Materials were light cured for 40 s and the plastics cup was filled with ambient temperature water. To determine polymerisation shrinkage stress (σ_{pol}) three specimens of each material were tested for a 6-hour period to determine mean maximum σ_{pol} (MPa), σ_{pol} rate (MPa/s) and final σ_{pol} (MPa). ANOVA and post hoc Tukey tests were used to determine significant differences between means.

RESULTS: The highest mean maximum σ_{pol} of (5.4 ± 0.5) MPa was recorded for RMGIC and (4.8 ± 1.0) MPa for composite. The lowest mean final σ_{pol} of (0.8 ± 0.4) MPa was recorded for RMGIC. For mean maximum σ_{pol} , σ_{pol} rate and final σ_{pol} there were significant differences between materials within groups, although no significant difference ($p > 0.05$) was observed when comparing the RMGIC group to the composite group.

CONCLUSION: When comparing mean σ_{pol} , maximum σ_{pol} , and σ_{pol} rates between individual RMGIC and composite materials significant differences ($p < 0.05$) were observed. However when comparing the group RMGIC to composite no significant differences ($p > 0.05$) were observed. The null hypothesis that there is no difference in the short term σ_{pol} of RMGIC materials when compared to composite materials is only partly rejected.

RELEVANCE: Limited information is available on the comparison of RMGIC and resin composite σ_{pol} levels. This study provides information on the short term levels in a wet environment and will assist in understanding the initial σ_{pol} rates RMGIC place in cavities..

Keywords:

Resin-modified glass-ionomer

Resin composite

Polymerization shrinkage stress

Polymerization contraction stress

1. Introduction

Photo-polymerisation of adhesively bonded resin composite creates a level of polymerisation shrinkage stress (σ_{pol}) on the adhesive interface which remains after curing is complete (Braga et al., 2005; Giachetti et al., 2006). Resin composite σ_{pol} has been shown to contribute to cuspal deflection (Campodonico et al., 2011; Kim and Park, 2011; Suliman et al., 1993; Tantbirojn et al., 2004; Versluis et al., 2010), enamel cracking (Christensen et al., 1999), marginal gap formation (Huang et al., 2002; Irie et al., 2002) and microleakage (Calheiros et al., 2004; Gerdolle et al., 2008a; Heintze et al., 2008). Secondary caries is the most common reason for replacement in posterior restorations (Kim et al., 2013; Kopperud et al., 2012). The majority of σ_{pol} investigations have been performed on resin composite materials, and investigate σ_{pol} over a short time frame in the absence of water (Braga et al., 2005). Some stress relief of resin composite σ_{pol} can be achieved by the material placement method and by hygroscopic expansion associated with water absorption (Versluis et al., 2010).

The placement of resin-modified glass-ionomer (RMGIC) liners beneath resin composite has been found to significantly reduce volumetric polymerisation contraction (Alomari et al., 2001; Davidson, 1994; Ferracane et al., 2006; Ikemi and Nemoto, 1994; Tolidis et al., 1998b, a). RMGIC restorations have been shown to convert initial inward cuspal contraction to expansion after 1 week (Versluis et al., 2011). Feilzer *et al.* (Feilzer et al., 1995) found two restorative RMGICs reversed initial σ_{pol} in a wet environment and recommended early water exposure to minimize σ_{pol} . In order to establish criteria for successful RMGIC placement procedures, it would be useful to detail their σ_{pol} to provide an understanding of stresses present at the RMGIC bond interface in their initial setting stages. However limited additional information is available on the rates and maximum level of RMGIC σ_{pol} compared to current generation resin composite materials such as ‘bulk fill’ materials that claim up to 5 mm depth of cure.

The aim of the study was to test the null hypothesis that there is no difference in the σ_{pol} of RMGIC materials in a wet environment when compared to resin composite materials.

2. Materials and methods

The name, manufacturer and composition of each material are detailed in Table 1. Two of the three tested composites were “bulk fill” materials. Transparent acrylic rods (5 mm diameter x 30 mm long) were prepared by diamond saw (ISOMET[®] 1000 precision sectioning saw; Buhler, Lake Bluff, IL, USA). Rods were polished at one end with 1200-grit silicon carbide paper and air abraded (Microetcher II; Danville Materials Inc, San Ramon, CA) with 50 μ m aluminium oxide (ALOX 50- μ m; BN 2980; Argibond, Cheltenham, Australia) until a uniform surface was achieved, cleaned with oil-free compressed air until the surfaces were clean, and firmly secured into upper and lower drill chucks connected to a single column universal testing machine (Model 5942; Instron, Norwood, MA) fitted with a 500-N static load cell. A small plastics cup was placed around the lower rod and a distance of 1.00 mm was established between the prepared surfaces (Figure 1a) prior to separating the surfaces for material placement.

To ensure resin composite material adhesion to the rods, a single thin layer of a universal adhesive (Scotchbond Universal Adhesive; 3M/ESPE, Seefeld Germany) was placed onto the rod ends and cured as per manufacturer’s instructions. Materials were placed directly onto the lower rod. Manual adjustment of the crosshead was used to move the rods to the pre-determined 1.00 mm position (Figure 1b) and excess material around the rods was removed with a flat plastic instrument. The plastics cup was positioned in order to permit submersion of the material and a 10-mm strain gauge extensometer (Model 2630-101; Instron Norwood, MA) with an accuracy of ± 0.5 % was placed into position (Figure 1c).

The testing machine software (Bluehill 2 Materials Testing Software; Instron, Norwood, MA) maintained the 1-mm distance between the rods via feedback from the linear strain gauge. A 30.00-dB strain gauge proportional gain was set and all measurements on the testing machine were calibrated to zero. Approximately 80 s after the beginning of the test, materials were light-cured from one side using a 1200mW/cm² LED curing light (Radii Plus; SDI Limited, Bayswater) for 40 s at a distance ~5 mm. Intensity of the LED curing light was tested prior to each test with a LED radiometer (LED radiometer; SDI Limited, Bayswater). Immediately after light curing a syringe was used to fill the cup with ambient temperature water to cover the material.

Additional water was supplied with micro-bore plastics tube fitted with a metal outlet inserted into a variable speed peristaltic pump (MasterflexR C/L; Cole-Parmer, Vernon Hills, IL) (Figure 1d). A pump setting was established to maintain the required water level in the plastics cup throughout the test.

Three specimens of each material were tested for a 6-hour period to determine mean maximum σ_{pol} (MPa), σ_{pol} rate (MPa/s) and final σ_{pol} (MPa). The maximum σ_{pol} was determined by the maximum tensile shrinkage force (N) divided by the rod cross sectional area (mm²). The polymerisation rate at each data point was calculated from the difference in σ_{pol} divided by the time period between the previous data point. The final σ_{pol} was determined at 6 h after the start of the test.

Statistical analysis

A statistical analysis package was used to analyse data (PASW Statistics V18, SPSS INC, Chicago, IL) using ANOVA and post hoc Tukey to determine significant differences in mean values.

3. Results

The mean maximum σ_{pol} , σ_{pol} rate and final σ_{pol} results are shown in Table 2 and Figures 2 –

4. Within each column statistically similar values ($p > 0.05$) are marked with the same superscript letter.

3.1 Mean maximum σ_{pol}

For RMGIC, the highest mean maximum σ_{pol} of (5.4 ± 0.5) MPa was recorded for FL, although this was not significantly different from two resin composite materials (FS, BF) and another RMGIC (KN). The lowest mean maximum σ_{pol} (2.4 ± 0.5) MPa was recorded for PF, although this was not significantly different from either of the bulk fill resin composite materials BF and SDR (4.0 ± 0.5 , 3.4 ± 0.8) MPa and another RMGIC (2.5 ± 0.3) MPa. For resin composite materials the mean maximum σ_{pol} value of (3.4 ± 0.8) MPa was recorded for SDR bulk fill resin composite. The highest resin composite mean maximum σ_{pol} result of (4.8 ± 1.0) MPa was recorded for FS. There were significant mean maximum σ_{pol} differences between materials, although no significant difference ($p > 0.05$) was observed when comparing pooled data for specific materials within each group of RMGIC and composite.

3.2 Mean σ_{pol} rate

The highest mean σ_{pol} rates for both RMGIC and resin composite occurred during the first 40 minutes after the beginning of light curing (Figure 3a, 4). The lowest mean σ_{pol} rate of (0.009

± 0.001) MPa.s⁻¹ was recorded for FF. The highest mean σ_{pol} rate of (0.019 ± 0.002) MPa.s⁻¹ was recorded for KN.

For resin composite, there was no significant difference ($p < 0.05$) in the mean σ_{pol} rate between the three materials (Figure 3b). Mean σ_{pol} rate ranged from (0.013 ± 0.002) MPa.s⁻¹ to (0.01 ± 0.00) MPa.s⁻¹. Significant differences in mean σ_{pol} rates were observed when comparing materials, although none were observed ($p = 0.319$) when comparing the pooled data for groups of RMGIC to the resin composite group. The mean σ_{pol} rate correlated to the maximum σ_{pol} with $R^2 = 0.82$ but not with final σ_{pol} with $R^2 = 0.002$.

3.3 Mean final σ_{pol}

The lowest mean final σ_{pol} result of (0.8 ± 0.4) MPa was recorded for the RMGIC PF. Other RMGICs had significantly greater levels ($p < 0.05$), with FL recording the highest mean final σ_{pol} of (4.7 ± 1.2) MPa which was over five times the level reported for PF (Figure 2a).

When comparing RMGIC materials, significant differences ($p < 0.05$) were observed in mean final σ_{pol} , although FF was not significantly different from the means of other RMGICs. For resin composites, FS reported the highest mean final σ_{pol} of (4.4 ± 1.0) MPa. No significant differences ($p > 0.05$) were observed between the three resin composite materials mean final σ_{pol} , although both bulk filled resin composites recorded lower mean final σ_{pol} with SDR reporting (3.1 ± 1.7) MPa. When comparing the RMGIC group and resin composite groups data for specific materials within each group were pooled and no significant differences ($p = 0.228$) were observed.

4. Discussion

Watts pioneered the development of linear diametral measurement of shrinkage strain with a device measuring unrestricted deflection of a glass cover slip (Watts and Cash, 1991).

Feilzer *et al.* (Feilzer et al., 1987) also developed a linear method, however it restricted the height (h) of material during curing and enabled the determination of the σ_{pol} force from a universal testing machine and extensometer. Further development of this concept detailed effects of specimen dimensions and compliance within the system (Boaro et al., 2010; Boaro et al., 2009; Braga et al., 2002). Changing the specimen height and diameter influences the C factor (i.e. ratio of the restorations un-bonded to bonded surfaces) which influences σ_{pol} tests. Increasing C factors and volumes of samples has been shown to increase σ_{pol} results (Witzel et al., 2007) .

Goncalves *et al.* monitored a 10 minute time period to compare σ_{pol} of four different systems including the universal testing machine (glass and acrylic rods), a low compliance system and a single cantilever system, and suggested comparisons of σ_{pol} data from different test methods be avoided (Gonçalves et al.). Figure 2c was included to show detail that is masked on the graphs with the 360-minute x-axes. The results of the current study demonstrate a material's σ_{pol} reported at 10 minutes (Figure 2c) can be significantly different from levels at 360 minutes (Figure 2a, b). For example, the 10 minute σ_{pol} recorded for a RMGIC (PF) was over three times the 360 minute result. Resin composite (FS) 10 minute σ_{pol} was only 80% of the level achieved at 360 minutes. All of the resin composite materials (Figure 2b) appeared to be continuing to increase their σ_{pol} levels compared to only one of the RMGIC (Figure 2a) at 360 minutes, suggesting it would be advisable to quote σ_{pol} levels with a time of measurement, and results without this detail may lead to confusion.

The current data were obtained using acrylic rods and results may differ if a higher compliance system with more “stiffness”, such as glass, were used in comparing material σ_{pol} (Boaro et al., 2010). Also the ability of the acrylic rods to absorb water may affect the

compliance of the system over time. σ_{pol} of RMGIC bonded to dentin has been shown to be less than when bonded to a non-compliant material, indicating the dentin can absorb σ_{pol} to some degree. Ferracane *et al.* reported a 75% reduction of σ_{pol} with the application of a RMGIC liner compared to unlined resin composite (Ferracane *et al.*, 2006; Tolidis *et al.*, 1998a). Although not taking into account the greater elasticity of RMGIC, other studies using RMGIC as a resin composite bond have also reported significant decreases in σ_{pol} , indicating that it has an ability to reduce stress caused by resin composite σ_{pol} (Mitra *et al.*, 2007; Tolidis *et al.*, 1998a; Versluis *et al.*, 2007).

In conditions absent of water, resin composites lined with RMGIC have demonstrated higher levels of interfacial stress on model cavities than resin composite alone. Using photoelastic measurements, Luana *et al.* found increased maximum shear stress at the cavity wall in restorations with liners compared to the adhesive-resin composite restoration (Oliveira *et al.*, 2010). RMGIC liners demonstrated double the levels of shear stress in cavity regions compared to composite alone. Stress increased after 2 days, compared to a stable level after 4 hours without a liner. However, the authors noted that their study design made it unlikely for the RMGIC to absorb water, thereby not allowing hygroscopic expansion and consequent stress relaxation.

In general, σ_{pol} tests are performed in the absence of water. Studies have shown that both resin composites and RMGIC absorb water. Although water absorption of resin composite material cannot fully compensate for shrinkage and σ_{pol} , hygroscopic expansion facilitates a reduction in cuspal deformation (Feilzer *et al.*, 1990; Versluis *et al.*, 2011). For the RMGIC (KN), inward cuspal deflection has been demonstrated to reverse in as little as 1 week (Versluis *et al.*, 2011), although the test period in the current study is substantially shorter than 1 week.

Unlike resin composite materials, RMGICs generally have a two-stage reaction which includes an acid-base reaction between the carboxylic acid polymers and the glass powder, and an additional free-radical reaction beginning at the start of visible light curing (Berzins et al., 2010; Nicholson, 1998; Yelamanchili and Darvell, 2008). Water has a crucial role in the clinical success of RMGICs. Firstly, their compositions (Table 1) contain water in the liquid component ranging from 10-20%. Maintaining the water content during the acid-base reaction that occurs after initial light curing is essential in order to achieve properties such as bond strength. Secondly, RMGIC's have an ability to absorb water (Akashi et al., 1999; Feilzer et al., 1995; K. et al., 1993; Kanchanasavita et al., 1997; Nicholson, 1997; Small et al., 1998) which can translate into hygroscopic expansion of the material and in turn reduce σ_{pol} . Dentin and oral fluids can be sources of moisture for the GIC - dentin interface, and variables such as dentin depth affect the initial moisture content of dentin which could affect RMGIC σ_{pol} after placement depending on the level of water presented to the RMGIC (Perdigão, 2010). An interfacial water dependant layer has been observed when RMGIC is bonded to dentin which has been found to act as stress absorbing region (Tay et al., 2004).

Water absorption testing over 6 months has reported the transfer of water into and out of the RMGIC Fuji II LC to be very rapid over the first 7 days compared to resin composite. All RMGIC gained most of their water uptake at 1 day (~7 weight %) and reached an equilibrium state (~10 weight %) at 1 month. In contrast, resin composite material achieved a much lower uptake (~1 weight %) at 6 month (Small et al., 1998).

Different immersion fluids modify the water sorption and volumetric expansion properties of RMGIC. Studies have reported more than a doubling of the water absorption of RMGIC

stored in artificial saliva compared to deionised water. At 6 months, up to 16% volumetric change was reported for Fuji II LC (Kanchanasita et al., 1997). RMGICs have demonstrated "perm-selectivity" properties that alter their water sorption characteristics in terms of diffusion coefficient, which can be affected by cure time, temperature and ionic content in the immersion media. Differences in the water sorption profile of RMGIC can be attributed to structural changes in hydrophilic segments of the polymer components in which more "compact molecular coils" are formed which act differently from those formed in water absent of certain ions (Nicholson, 1997).

Watts *et al.*, also investigated storage media and temperature effects on the expansion of RMGIC to determine levels of "intrinsic" shrinkage and "hygroscopic expansion" and reported RMGIC stored in water expanded more (> 8 volume %) at higher temperatures, although results were similar at 1 month when compared to lower temperature stored specimens (Watts et al., 2000). The σ_{pol} of RMGIC in saliva has not been investigated and the effect of temperature and saliva on this test method is unknown.

The hydrophilic components of the RMGIC structure have also been investigated. Akashi *et al.*, discussed the concept of water moving through "micro-voids" not present in resin composite, suggesting a different mechanism for water diffusion in RMGIC compared to resin composite materials. Equilibrium water uptake of Fuji II LC was reported to be ~6 weight %. Compared to Fuji II LC, a third RMGIC (Vitrebond; 3M/ESPE, Seefeld, Germany) demonstrated significantly higher water uptake (~12.7 weight %) and a three times higher diffusion coefficient than Fuji II LC (Akashi et al., 1999), indicating that compositional differences in RMGIC have a large effect on their water uptake.

Fluorescent microscopy techniques have further demonstrated that PF possesses a highly porous structure with an ability for water to diffuse uniformly through restorations (Pautke et al., 2007). In contrast FL restorations demonstrated a 25- μm layer across the restorative material-dentin interface involved in water uptake, indicating the “bulk” material is a more close packed system with respect to fluid transport in comparison to the interfacial regions. This could contribute to the results of FL achieving the highest maximum and final mean σ_{pol} compared to PF, as it may have less ability to achieve a certain level of hygroscopic expansion over a 6-hour period. Less information is available for FF and KN, although KN has been demonstrated to expand over a 1-week period (Versluis et al., 2011).

RMGIC has also been shown to shrink in a similar manner to resin composite materials. Irie et al. reported diametral linear shrinkage-strain of RMGIC compared to resin composite material in an effort to determine marginal gap formation (Irie et al., 2002). All materials exhibited some degree of marginal gap formation, with the gap formation adjacent to the RMGICs, Fuji II LC and Photac Fil, in a tooth cavity not significantly different from six other resin composite materials tested. However, longer term values were not reported. Marginal gap reduction in resin composite materials has been attributed to water sorption (Huang et al., 2002). Other studies have shown RMGIC to have higher shrinkage strain and microleakage values to resin composite materials and concluded a higher shrinkage resulted in higher levels of microleakage (Gerdolle et al., 2008b). Similarly, tests have reported that there is a direct correlation between σ_{pol} and microleakage for resin composite materials (Calheiros et al., 2004).

Studies on Fuji II LC have reported 1-hour linear shrinkage of up to ~1.3 % for samples stored at 100% relative humidity (Kanchanavasita et al., 1995). Other studies have shown Photac-Fil and Fuji II LC shrink ~3% in the absence of water after 5 minutes of cure, which

further shows the critical role of water in maintaining an appropriate environment for σ_{pol} tests (Attin et al., 1995). Shrinkage of RMGIC shrinkage measured with a dilatometer in the absence of water has also been reported, however when reviewing data on shrinkage properties it should be noted that a relationship between volumetric shrinkage measurements and σ_{pol} has not been established (Gonçalves et al.).

Although dehydration of RMGIC was not possible in this study, it is detrimental and can cause failure by marginal gap formation. Mean gap formation has been reported after 15 minutes of dehydration, which can be visible in both adhesive and cohesive failure of the RMGIC bonded to dentin and demonstrates their sensitivity to an environment that changes in moisture levels (Sidhu et al., 1997).

Differences in RMGIC setting behaviour can be attributed to compositional variations and would be expected to affect σ_{pol} as shown in this study. Various RMGIC phases have been observed in transmission electron microscopy studies and layers of silica-rich hydrogels have been observed covering glass filler particles after RMGIC storage in water (Tay et al., 2001). Phase separation of 2-hydroxyethyl methacrylate and polyalkenoic acid components could also contribute to their susceptibility to dehydration, although this can be reversed to some extent with rehydration and subsequent hygroscopic expansion (Sidhu et al., 1997).

Light-cured RMGIC materials also demonstrate viscoelastic behaviour (Yamazaki et al., 2006) when subjected to deformation, which may allow them to dissipate energy (stress relieve) as they move to a higher stress state. Figure 2a demonstrates that both KN and PF 6-hour σ_{pol} is decreasing and it is not known if the ultimate “residual” σ_{pol} will reach zero. It is not possible to determine if this result is from water sorption/expansion or viscoelastic properties of the RMGIC materials themselves as a response to the applied stress. The same

trend is not seen for resin composite materials (Figure 2b) which appear to have increasing σ_{pol} with time which could be attributed to a slower continued rate of polymerization of residual monomer retained after initial light curing. However, a relationship with visco-elastic behaviour of RMGIC and σ_{pol} resulting from a restricted specimen height test has not yet been reported. Additionally the σ_{pol} rates reported for both resin composite (Figure 3b) and RMGIC (Figure 3a) are not steady, and this may be influenced by the viscoelastic response of the developing polymer networks to the applied stress of the constant distance between the rods or other factors such as degree of conversion or reaction kinetics (Braga and Ferracane, 2002). Cured composite and RMGIC have demonstrated both elastic deformation (reversible deformation) and viscoelastic properties during application of a stress after they are cured (El Hejazi and Watts, 1999).

The initial rapid set caused by light curing implies stresses have been retained within the material where as slow setting implies a certain amount of stress relief has occurred before the glass transition point of the material has been reached. The lack of correlation with final σ_{pol} $R^2 = 0.002$ implies other stress relief mechanism are taking place after the material has set via the initial polymerization process.

Although the bond strengths achieved by RMGIC to tooth structure are inherently lower than those of resin composite, the RMGIC bond has been shown to be one of the most durable (Carvalho et al., 2012; Peumans et al., 2005). Lower long-term σ_{pol} stresses (Versluis et al., 2011) presented to the tooth by RMGIC compared to resin composite restorations could contribute to their longevity, although limited information is available to compare the bulk fill resin composites used in this study.

It must be highlighted that this study utilized a specimen dimension (Calheiros et al., 2004) with a C-factor of 2.5. The σ_{pol} results may be affected by modifying the test duration, cavity configuration (C-factor) and the temperature or type of immersion media used.

5. Conclusions

When comparing mean σ_{pol} , maximum σ_{pol} , and σ_{pol} rates of RMGIC to resin composite material significant differences were found comparing different materials within each group. However when comparing the group RMGIC to resin composite no significant differences were observed. The null hypothesis that there is no difference in the σ_{pol} of RMGIC materials when compared to resin composite materials in a wet environment is only partly rejected.

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Table 1 - Material composition.

Type	Product Name	Manufacturer	Code	Lot (shade)	Composition
RMGIC ¹	Fuji II LC (Improved) capsules	GC Corporation, Tokyo, Japan	FL	1008091 (A2)	Powder: Alumino-fluoro-silicate glass (amorphous) (95-100%) Liquid: Polyacrylic acid (20-25%), 2-Hydroxymethyl methacrylate (30-35%), 2,2,4, Trimethyl hexamethylene dicarbonate (1-5%), Proprietary Ingredient (5-15%)
RMGIC	Fuji Filling LC	GC Corporation, Tokyo, Japan	FF	1107111 (A2)	Paste A: Alumino-fluoro-silicate glass (amorphous) (78-85%), HEMA (10-12%), UDMA (2-5%) Paset B: Distilled water (20-30%), polyacrylic acid (20-30%), urethane dimethacrylate (12-15%), silicon dioxide (fumed/amorphous) (10-15%)
RMGIC	Photac Fil Quick	3M/ESPE, Seefeld, Germany	PF	411820 (A2)	Powder: Silane treated glass powder (>99%), N,N-Dimethylbenzocaine (<0.5%) Liquid : Copolymer of acrylic acid-maleic acid (30-50%), HEMA (25-50%), Water (20-30%), mono and di-HEMA phosphate, magnesium salt (5-15%), diurethane dimethacrylate (3-10%)
RMGIC	Ketac Nano	3M/ESPE, Seefeld, Germany	KN	N156309 (A2)	Paste A: Silane treated glass (40-55%), silane treated zirconia (20-30%), PEGDMA (5-15%), silane treated silica (5-15%), HEMA (1-15%), glass powder <5, BisGMA<5%, TEGMA<1% Paste B: Silane treated ceramic (40-60%), copolymer of acrylic and itaconic acid (20-30%), waer (10-20%), HEMA (1-10%)
Resin composite	Filtek Supreme Ultra	3M/ESPE St. Paul, USA	FS	N410612 (A2)	Silane treated ceramic (60 – 80%), silane treated silica (1 – 10%), BisGMA (1–10%), Bisphenol A diglycidyl ether dimethacrylate (1-10%), silane treated zirconia (1-10%), PEGDMA (<5%), TEGDMA (<5%), 2,6-di-tert-butyl-cresol (<0.5%)
Resin composite	Filtek Bulk Fill Flowable Restorative	3M/ESPE, Seefeld, Germany	BF	N356855 (A2)	Silane treated ceramic (50-60%), UDMA (10-20%), substituted DMA (10-20%), BISEMA-6 (1-10%), YbF ₃ (1-10%), BISGMA (1-10%), Benzotriazol (<1%), TEGDMA (<1%), ethyl 4-dimethyl aminobenzoate (<1%)
Resin composite	SureFil®SDR® Flow	Dentsply DeTrey, Konstanz, Germany	SDR	120207 (A2)	Dimethacrylate resins (< 10%), Urethane dimethacrylate (<25%), Barium boron fluorosilicate glass (< 50%), Strontium Aluminosilicate glass (< 50%), Titanium dioxide (< 1%)

¹RMGIC = resin-modified glass-ionomer cement.Table 2 – Mean and standard deviations of maximum σ_{pol} (MPa), σ_{pol} rate (MPa.s⁻¹), final σ_{pol} (MPa)

Group	$\sigma_{pol} \pm SD$	σ_{pol} rate $\pm SD$	final $\sigma_{pol} \pm SD$
FL	5.4 $\pm$ 0.5 ^c	0.017 $\pm$ 0.003 ^{bc}	4.7 $\pm$ 1.2 ^c
FF	2.5 $\pm$ 0.2 ^a	0.009 $\pm$ 0.001 ^a	1.4 $\pm$ 0.8 ^{ab}
PF	2.4 $\pm$ 0.4 ^a	0.010 $\pm$ 0.002 ^a	0.8 $\pm$ 0.4 ^a
KN	5.2 $\pm$ 1.0 ^{bc}	0.019 $\pm$ 0.002 ^c	3.9 $\pm$ 1.5 ^{bc}
FS	4.8 $\pm$ 1.0 ^{bc}	0.013 $\pm$ 0.003 ^{ab}	4.4 $\pm$ 1.0 ^b ^c
BF	4.0 $\pm$ 0.4 ^{abc}	0.013 $\pm$ 0.002 ^{ab}	3.5 $\pm$ 1.1 ^{abc}
SDR	3.4 $\pm$ 0.8 ^{ab}	0.01 $\pm$ 0.000 ^a	3.1 $\pm$ 1.6 ^{abc}

Within each column, means with the same superscript are not significantly different ($p > 0.05$)

Figure 1 – a) Establishing a 1.00-mm distance between rod surfaces. b) Position re-established after material has been placed between rods c) Plastics cup placed in position and extensometer installed onto rods. d) After photo-polymerization has been completed a metal tube connected to a pump, is placed in position for supply of water to the sample.

Figure 2a – RMGIC σ_{pol} (MPa) as a function of time (min)

Figure 2b – Composite σ_{pol} (MPa) as a function of time (min)

Figure 2c – σ_{pol} (MPa) as a function of time (min): 15-min

Figure 3a – RMGIC σ_{pol} rate (MPa.s^{-1}) as a function of time (min)

Figure 3b – Resin composite σ_{pol} rate (MPa.s^{-1}) as a function of time (min)

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