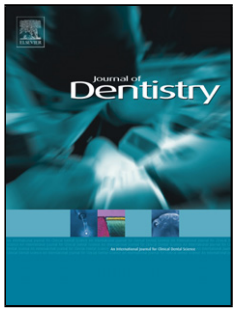

Title: The deformation and strength of a dental ceramic following resin-cement coating

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Title: The deformation and strength of a dental ceramic following resin-cement coating.

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Abstract

Objectives: The hypothesis tested was that processing, pre-cementation and cementation techniques can modify the profilometrically measured deformation of a ceramic.

Methods: Three-point flexural moduli of a resin-cement were characterised following light irradiation at 430 and 180 mWcm-2. Thirty IPS e.max Ceram discs were prepared and a reference surface produced by polishing. Discs were annealed, alumina particle air abraded and resin-coated.
Profilometric evaluation was performed following each pre-cementation or cementation operative technique using a contact diamond stylus profilometer. Bi-axial flexure strength of the resin-coated discs, light irradiated at 430 and 180 mWcm-2 (Groups A and B), and the un-coated discs (Group C) was determined. Data were analysed by a one-way analysis of variance with post-hoc Tukey tests ($P<0.05$), or repeat measure analyses when appropriate.

Results: Annealing (at 510degC for 40 mins) resulted in a significant reduction ($P<0.001$) in the characterised mean deflection, as did alumina particle air-abrasion ($P<0.001$). Resin-cement coating significantly increased the mean deflection for Group A and B ($P<0.001$) specimens against the uncoated state. Furthermore no significant impact of increasing time or irradiation intensity on the mean deflection was identified. The mean bi-axial flexure strength was significantly increased ($P<0.001$) after resin-coating (Groups A and B) when compared with Group C specimens although no difference between Groups A and B specimens ($P=0.291$) was identified.

Conslusion: The results of the profilometric technique in combination with the strength supported a strengthening mechanism sensitive to shrinkage stress generation associated with the polymerisation of resin-cements.

Key Words: transient and residual stresses, profilometric technique, bi-axial flexure strength, ceramic

INTRODUCTION

Porcelain laminate veneer (PLV) or dentine bonded crown (DBC) restorations are more often than not received from the laboratory prepared for cementation with the 'fit' surfaces having been subjected to a pre-cementation conditioning regimen [1]. Ceramic surfaces are frequently alumina particle air-abraded [2,3] or acid-etched [4,5] to create a micro-mechanically retentive surface conducive to bonding to the dental cement. It has been reported for several classes of ceramic material that pre-cementation surface modification impacts on the flexural strength [3,5-9]. The observed strength modification is often accounted for by Griffith's theorem relating the strength of a brittle system to the severity of the critical defect [10]. The authors have demonstrated for a dispersion strengthened dentine porcelain system (Vitadur Alpha dentine: Vita,

Bad Säckingen, Germany) containing less that 10 vol.% dispersed alumina, that the bi-axial flexure strength of the ceramic was significantly reduced following alumina particle air-abrasion [3] and hydrofluoric (HF) acid-etching [5]. However, it has also been demonstrated that the bi-axial flexure strength of the alumina particle air-abraded or HF acid-etched Vitadur Alpha dentine ceramic could be significantly increased following cementation with methacrylate resin-based cements [11-13]. The resin strengthening mechanism was proposed to be through the formation of a resin-ceramic hybrid or transitional layer [12-13] resulting from the interpenetration of the ceramic surface by the resin. By resin-coating ceramic surfaces containing critical defects of differing sizes it has been demonstrated that the magnitude of achievable reinforcement was independent of individual flaw severity [13-14].

In the dental literature one criticism levelled at flexure strength testing methodologies previously employed was that the interpretation of the resultant flexure strength data failed to account for the pre-existing global stress state of the test specimen prior to strength determination [15]. Therefore when assessing the influence of laboratory performed pre-cementation and cementation operative techniques the pattern of observations was assumed to be a function of the severity of the critical defect under stress. The distribution of the fracture strength data for microstructurally and geometrically identical specimens is a function of multiple factors. The use larger sample sizes (n>20) [16] in combination with engineering statistical approaches such as Weibull statistics [17] has enabled some differentiation of the strength data. For bilayered resin-coated discs, the associated strengthening mechanisms currently postulated [11,13-14] neglect to accommodate the contribution of the transient and residual stresses [18] generated within the test specimen.

The authors recently reported on a profilometric deflection test to characterise the magnitude of the stress induced deformation of a dispersion strengthened ceramic suitable for the manufacture of PLVs and DBCs [19]. The aim of the current investigation was to determine the transient and residual stresses in conventional ceramic test specimens subjected to processing, pre-cementation and cementation operative techniques. The magnitude of the transient and residual stresses were characterised using the profilometric technique and provided insight into the mechanisms operative in the resin-strengthening of dental ceramic restorations.

The hypothesis tested was that processing, pre-cementation and cementation techniques have the potential to significantly modify the profilometrically measured deformation of a ceramic substrate in a thickness representative of a PLV or DBC restoration.

MATERIALS AND METHODS

Specimen condensation and preparation

An optimum powder/liquid slurry consistency was identified for IPS e.max® Ceram (Ivoclar Vivadent AG, Schaan, Liechtenstein) as 0.6 g of IPS e.max® Ceram dentine powder (Shade A2 Lot no. K49034) and 0.16 mL IPS e.max® Ceram build-up liquid (Lot no. K49035), in accordance with the procedure outlined previously [20]. Thirty ceramic discs (13 ± 0.01 mm diameter and 1.05 ± 0.03 mm thickness) were condensed into a perspex mould under ultrasonic vibration (CeramoSonic ^{TA} II Condesedor, Shofu, Kyoto, Japan) and the excess liquid was removed with tissue paper. The disc-shaped specimens were arranged onto a silicon nitride refractory tray and placed into a vacuum furnace (Vita Vacumat 40, Vita Zahnfabrik, Bad Säckingen, Germany). The specimens were fired according to the manufacturers' recommendations, namely air dried at 403°C for 8 mins, heated at 50°C.min^{-1}, vacuum fired from 450°C to 769°C prior to being held for 1 min in air at 770°C. The specimens were allowed to air-cool to room temperature prior to removal from the refractory tray. The surface of the discs that was in contact with the refractory tray during sintering was marked and the specimens were stored in a desiccator.

The marked surface was polished on a Alpha and Beta Grinder-Polisher (Buehler, Lake Bluff, IL, USA) with water lubrication at 100 rpm with increasing grades of silicon carbide abrasive papers (P320, 600, 800, 1200 and 2500) for controlled time intervals under a specimen load of 3.3 N to create a reference surface for profilometric evaluation [19]. The final thickness of the disc-shaped specimens was determined with a digimatic micrometer (Mitutoyo Corp., Tokyo, Japan) to be 0.63 ± 0.06 mm.

Resin modulus determination

The flexural modulus of Rely-X™ Veneer Cement (lot no. 5BP, 3M ESPE, St Paul, MN, USA) was determined from three-point-bend testing monolithic bar-shaped specimens [21] irradiated at the output intensity of the Optilux 501 (Kerr, Orange, CA, USA) halogen light curing unit (LCU) and following irradiation through a representative 0.63 mm veneer thickness of the IPS e.max® Ceram disc. The output intensity was measured (n = 5) at the centre of the exit window using a radiometer incorporated in the LCU at a distance of 0 mm and following irradiation through a 0.63 mm disc of IPS e.max® Ceram. Five bar-shaped specimens (30 × 2 × 2 mm^3) were fabricated in an open-ended, knife-edged, split aluminium mould at 23 ± 1°C [22-23]. As the length of the bar exceeded the LCU tip diameter, the monolithic specimens were irradiated for 20 s at successive overlapping spots. Irradiation was first performed at the centre of the specimen at a distance of 0 mm, before the tip was moved such that, the next irradiated area overlapped a previously exposed area by a quarter of the diameter of the exit window. This was repeated until the entire top surface of the specimen had been irradiated using the 13 mm diameter tip (three irradiations) [23]. The bar-shaped specimens were removed from the mould and the irradiation procedure was repeated on the bottom surface (namely three irradiations for 20 s at successive overlapping spots). A further five monolithic bar-shaped specimens of Rely-X™ Veneer Cement were irradiated through the representative veneer thickness (0.63 mm) of IPS e.max® Ceram disc from the top and bottom surfaces in accordance with the procedure outlined above.

The specimens were stored dry at 37 ± 1°C for 24 h and the three-point flexural modulus was calculated within the linear region of the load-deflection curves (equation

1) derived from testing at 1 mm.min^{-1} in accordance with ISO 4049 (2000) for polymer based filling restorative and luting materials [21].

$$E_B = \frac{PL^3}{4bd^3D} \quad \text{Eq 1}$$

where P was the load, L the support span (20 mm), b the width and d the specimen thickness, E_B the flexural modulus and D the deflection.

Profilometric evaluation

Before profilometric measurements could be performed the disc-shaped specimens were placed, aligned and held for the entire duration of the test in a custom-made metallic leveling device. Profilometric measurements were performed on 20 of the 30 specimens using a contact diamond stylus profilometer (Talysurf CLI 2000, Taylor-Hobson Precision, Leicester, UK) across a 10 mm^2 area (10 mm length and 1 mm width) coincident with the centre of the polished reference surface of the specimen. A force of 0.75 mN was delivered through a 90° conisphere stylus tip of 2 µm radius at a velocity of 1 mm.s^{-1}. A 4 µm step-size (y-direction) produced 251 traces with data points recorded every 10 µm (x-direction) at a 40 nm resolution (z-direction) to quantify the mean deflection of the polished reference surface.

The 30 disc-shaped specimens were positioned with the polished reference surface in contact with the silicon nitride refractory tray, and replaced into the vacuum furnace. The specimens were annealed above the glass transition and below the softening temperature [24-25] of IPS e.max® Ceram at 510°C. Specimens were heated from 200 to 510°C in air at 20°C.min^{-1}, held at 510°C for 40 mins prior to cooling to 50°C at 2.4°C.min^{-1}. The mean deflection of the polished reference surface of the previously profiled 20 specimens were re-measured (across the 10 mm^2 area coincident with the

centre of the polished reference surface) to assess the influence of annealing on the mean deflection of the polished reference surface.

Alumina particle air-abrasion was then performed on the unpolished (non-reference) surface, of each of the 30 disc-shaped specimens for 10 s, using 50 μm alumina particles delivered in an air stream (ECO Dry Oxide System, Dentalfarm, Torino, Italy) at a pressure of 2 bar, perpendicular to the specimen surface from a distance of 10 mm [3]. To assess the influence of alumina particle air-abrasion, the mean deflection of the polished reference surface of the 20 specimens was re-profiled according to the procedure outlined above namely across the 10 mm^2 area coincident with the centre of the polished reference surface. The 20 specimens were then randomly sub-dived into two groups of ten (Groups A and B) prior to resin-cementation. The remaining ten specimens (Group C) were stored in a desiccator prior to testing in biaxial flexure.

The alumina particle air-abraded surface of each of the ten Group A and ten Group B specimens was primed with Ceramic Primer S (Lot no. 9YY, 3M ESPE, St. Paul, MN, USA). A consistent mass (0.035 g) of Rely-X™ Veneer Cement (Lot no. 8EB, shade A3, 3M ESPE, St. Paul, MN, USA) was applied to the primed alumina particle air-abraded surface, covered with Mylar and a glass-slide pressed under a controlled load until the resin spread to the edges which produced mean cement thicknesses of 53 ± 11 μm (Group A) and 56 ± 12 μm (Group B). Group A specimens were light irradiated with the Optilux 501 halogen LCU for 20 s at a distance of 0 mm, delivered through a 13 mm light curing tip diameter. Group B specimens were light irradiated through the representative veneer thickness of IPS e.max® Ceram. The polished reference surface of the ten discs in both Groups A and B were re-profiled (across the 10 mm^2 area

coincident with the centre of the polished reference surface) to quantify the mean deflection immediately after cement coating (0 h) and following 24 h dry storage.

Bi-axial flexure strength

The bi-axial flexure strength of the bi-layered resin-coated discs (Groups A and B) and the un-coated discs (Group C) was determined in a ball-on-ring configuration and the stress at failure was calculated using a multilayer analysis using closed form solutions verified by finite element models [26]. The ceramic and resin thickness (t_1) and (t_2) and the elastic modulus of the ceramic (E_1 = 64 GPa) [11] and resin (E_2 – assessed in the resin modulus determination section) determined the position of the neutral plane (t_n) from equation 2.

$$t_n = \frac{E_1^*(t_1)^2 - E_2^*(t_2)^2}{2(E_1^* t_1 + E_2^* t_2)} \quad \text{Eq 2}$$

where: $E^* = \frac{E}{1-\nu^2}$ Eq 3.

A Poisson's ratio (ν) across the bi-layered disc was determined from equation 4

$$\nu = \frac{(\nu_1 t_1 + \nu_2 t_2)}{t_1 + t_2} \quad \text{Eq 4.}$$

where ν_1 (0.23) and ν_2 (0.27) were the Poisson's ratios of the ceramic and resin [11].

At axial positions (z) at the centre of the bilayered specimens, the bi-axial flexure stresses were calculated, where the bonded interface was located at $z=0$, the ceramic surface at $z=t_1$ and the resin surface at $z=-t_2$.

$$\sigma = \frac{-3P(1+\nu)(z-t_n)}{2\pi(t_1+t_2)^3}\left[1+2\ln\left(\frac{a}{b}\right)+\frac{1-\nu}{1+\nu}\left(1-\frac{b^2}{2a^2}\right)\frac{a^2}{R^2}\right]\left[\frac{E_1^*\left(E_1^* t_1 + E_2^* t_2\right)(t_1+t_2)^3}{\left(E_1^* t_1^2\right)^2 + \left(E_2^* t_2^2\right)^2 + 2E_1^* E_2^* t_1 t_2\left(2t_1^2 + 2t_2^2 + 3t_1 t_2\right)}\right] \quad \text{Eq 5}$$

($0 \le z \le t_1$) and

$$\sigma = \frac{-3P(1+\nu)(z-t_n)}{2\pi(t_1+t_2)^3}\left[1+2\ln\left(\frac{a}{b}\right)+\frac{1-\nu}{1+\nu}\left(1-\frac{b^2}{2a^2}\right)\frac{a^2}{R^2}\right]\left[\frac{E_2^*\left(E_1^* t_1+E_2^* t_2\right)(t_1+t_2)^3}{\left(E_1^* t_1^2\right)^2+\left(E_2^* t_2^2\right)^2+2E_1^* E_2^* t_1 t_2\left(2t_1^2+2t_2^2+3t_1 t_2\right)}\right] \quad \text{Eq 6}$$

($-t_2 \le z \le 0$).

P was the load at fracture, ν was the representative Poisson's ratio of the entire bi-layered disc. a and R were the radii of the supporting ring (5 mm) and of the specimen (6.1 mm), respectively while b was the radius of loading contact area at the center of the specimen which was defined by equation 6

$$b = \frac{t_1 + t_2}{3} \quad \text{Eq 7.}$$

Statistical Analysis

A Student's-t-test was employed to compare the mean flexural moduli for the Rely-X^{TM} Veneer Cement monolithic bar-shaped specimens irradiated at the two output intensities at a significance level of $P<0.05$. A Student's-t-test was employed to compare the mean flexural moduli for the Rely-XTM Veneer Cement monolithic bar-shaped specimens irradiated at the two output intensities at a significance level of $P<0.05$. The statistical approach employed was performed using repeat measurements across a polished reference surface (baseline quantification), following annealing and subsequent alumina particle air abrasion. As a result, paired sample t-tests were performed at a 95% significance level on the 20 individual samples in each of the groups (baseline quantification, following annealing and subsequent alumina particle air abrasion) for each comparison. The differences across the polished surface between the magnitude of the mean of the maximum deflection following alumina particle air abrasion to resin-cement coating were determined using paired sample t-tests (95% significance level) on the 10 individual samples in each group. Comparison of the mean deflection for Groups A and B following cement coating was performed using a student t-test at a 95%

significance level.. The statistical significance of resin-strengthening of the ceramic discs on the bi-axial flexure strength for Groups A-C was determined using a one-way ANOVA and post-hoc Tukey tests ($P<0.05$). The statistical significance of resin-strengthening of the ceramic discs on the bi-axial flexure strength for Groups A-C was determined using a one-way ANOVA and post-hoc Tukey tests ($P<0.05$).

RESULTS

The output intensities of the halogen LCU determined at a distance of 0 mm and following irradiation through the representative veneer thickness of IPS e.max® Ceram were 430 and 180 $mWcm^{-2}$, respectively. The mean flexural moduli and associated standard deviations of the Rely-X™ Veneer Cement monolithic bar-shaped specimens irradiated at 430 and 180 $mWcm^{-2}$ were 5.5 ± 0.7 and 5.4 ± 0.7 GPa, respectively and a Student's-t-test identified no significant differences between the group means (P=0.781).

The characterised mean deflection of the polished reference surface of the 20 IPS e.max® Ceram discs was determined to be 6.3 ± 2.3 μm, namely a convex (positive) deflection (Table 1). Annealing the 20 discs with the polished reference surface in contact with the refractory tray resulted in a significant reduction (P<0.001) in the mean deflection and a modification of the mean surface form from convex to concave (a negative deflection of -0.6 ± 2.8 μm) (Table 1). Profilometric evaluation of the polished reference surface following alumina particle air-abrasion of the unpolished surface further increased the concave form (namely an increase in the negative deflection of the profiled region) and reduced the characterised mean deflection significantly to -2.9 ± 2.7 μm (P<0.001).

Randomly sub-dividing the profiled, alumina particle air-abraded specimens into two groups of ten (Groups A and B) prior to resin-cementation resulted in mean deflections of -3.5 ± 3.0 μm and -2.4 ± 2.4 μm, respectively with no significant differences between the group means (P=0.456). Resin-cement coating was associated with a significant

increase in the characterised mean deflection (increase in convexity) for Group A and Group B ($P<0.001$) specimens when examined against the mean deflection of the uncoated state. No significant impact of increasing time on the mean deflection was evident following resin-cement coating of Groups A and B ($P=0.168$ and $P=0.061$, respectively). The paired sample t-tests at the 95% significance level on the 10 individual samples in each group revealed a significant impact on the characterised mean deflection measurements of Group A and B specimens following resin-cement coating ($P<0.001$ and $P<0.001$, respectively). However, irradiation at the different output intensities resulted in no significant difference in deflection ($P=0.129$) although the Power of this statistical test was moderate at 49%. The statistical significance of resin-strengthening of the ceramic discs on the bi-axial flexure strength for Groups A-C was identified ($P<0.001$). Post-hoc Tukey tests revealed no significant difference between the mean bi-axial flexure strength of bilayered specimens light irradiated at 430 or 180 $mWcm^{-2}$ ($P=0.291$).

DISCUSSION

PLV restorations have been employed extensively to mask teeth with intrinsic staining, from ageing, tetracycline or fluorosis and give the appearance of straightening to malformed or slightly rotated teeth. Clinically, the thickness of the ceramic restoration results in a barrier to light penetrating to irradiate the methacrylate resin-based composite cement [27-28]. Therefore the durability of the bond formed between the ceramic and resin cement and the cement and tooth structure may be compromised as a result [29].

In the current study, the output of the halogen LCU transmitted through the representative ceramic restoration thickness (0.63 mm) was reduced to 180 $mW.cm^{-2}$ compared with the unattenuated LCU output (450 $mW.cm^{-2}$). For resin-based composites a maximum value for the stiffness may be attained, nominally corresponding to complete conversion of all monomer double bonds to network-contributory single bonds [30]. However, the maximum conversion of double bonds is 45-70% [30-31] since vitrification for practical purposes (through the inhibition of diffusion) stops the reactions [30]. The mean flexural moduli of Rely-X^{TM} Veneer Cement at the two output intensities tested were not significantly different suggesting the cement surfaces were cured to the maximum attainable values (at the given temperature and irradiance time) for the LCU employed.

Polishing of dental ceramic test specimens prior to mechanical testing has been demonstrated to alter the value of strength determined [32]. Polishing will not only modify the nature and distribution of the surface defects [13-14] but has the capacity to modify the transient and residual stresses within the ceramic body introduced during

fabrication [19]. Heating during grinding and polishing and surface and subsurface plastic deformation may either relieve or exacerbate unfavourable transient and residual stresses that are active across the surface defect integral [13,33]. In the current study the polishing regimen for IPS e.max® Ceram was required to produce a reference surface that enabled the magnitude of the transient and residual stresses to be characterised using high resolution profilometry [19]. The base-line reference of the IPS e.max® Ceram discs following sintering and subsequent polishing demonstrated that the surface was convex with a characterised mean deflection of 6.3 ± 2.3 μm. It is suggested that the transient and residual stresses throughout the ceramic discs were distributed so that the polished reference surface was in relative tension (concave) compared with the unpolished surface.

In accordance with conventional glass theory [24], annealing the IPS e.max® Ceram discs would be expected to markedly reduce the residual thermal stress state across the discs. Glass theory suggests that in the current investigation, on cooling, the top surface of the discs would cool faster than the polished reference surface (which was in contact with the refractory tray), thereby inducing a modification of the transient and residual stress throughout the body of the ceramic discs. The deflection results for annealing the 20 discs confirmed recorded a significant reduction ($P<0.001$) of the characterised mean deflection. This further suggests that the annealing regime used modified the transient and residual stresses for the IPS e.max® Ceram discs, when the polished reference surface was in contact with the refractory tray.

Alumina particle air-abrasion increases the available area for adhesive bonding of the cement [2] through a modification of the ceramic surface topography. Alumina particle

air-abrasion of the unpolished surface of the e.max® Ceram discs significantly decreased the characterised mean deflection of the reference surface. It has been suggested that surface and sub-surface plastic deformation may induce tensile stresses across the surface defect integral [13,33], in a similar way that polishing has been demonstrated to induce a tensile stress state in ceramic materials. Alternatively alumina particle air-abrasion may induce or exacerbate crack extension in the surface facilitating deformation of the ceramic disc (due to the relative compressive stress state of the reference surface).

The significant increase in the reference surface convexity following resin-cement coating suggests that the increased performance of resin-cemented all-ceramic restorations could be at least in part explained by Nathanson's proposal that crack closure stresses secondary to resin polymerisation shrinkage exert a stabilising effect on surface defects [34]. Fleming et al. (2006) demonstrated the creation of crack closure stresses could not be the singular mechanism to contribute to the observed strengthening as crack closure stresses implied a sensitivity to defect size and geometry which is not observed [14]. However, Addison et al. highlighted the magnitude of strengthening was sensitive to the ceramic surface texture and further identified the combination of Poisson constraint and the degree of resin inter-penetration, to from a 'hybrid' layer, were mechanistically important [11-13]. In the current study the alumina particle air-abraded surface is infiltrated by the resin-based cement and the associated shrinkage is constrained within the 'hybrid' layer during polymerisation [11-12]. The resulting compressive stress state manifests as a significantly increased characterised mean deflection of the polished reference surface, demonstrated as increased convexity (Table 1). Therefore the extrapolation of Nathanson's theory by Rosenstiel et al. [9] which related polymerisation shrinkage of resin-based cements to a beneficial compressive

stress state across the entire ceramic defect integral is in alignment with the results of the current study. This is possibly emphasised further in the bi-axial flexure strength results where in excess of a two-fold strength increase was observed following resin-cement coating - independent of the output intensities used in the current investigation. However, given the complexity of the interaction between resin-cements and ceramic surface defects mediated through the resin-ceramic 'hybrid' layer it is unlikely that the induction of a compressive stress state can fully explain the strengthening mechanism.

The use of the high resolution profilometry technique in the current investigation enabled characterisation of the mean deflection in the ceramic test specimens following processing, pre-cementation and cementation operative techniques. The measured strength of dental ceramic materials determined using conventional laboratory testing methods can obscure the complexity of factorial interactions between surface defects, transient and residual stresses and microstructure which contribute to the modification of the strength of a ceramic body.

REFERENCES

[1] Fleming GJP, Addison O. Adhesive cementation and the strengthening of all-ceramic dental restorations. *Journal of Adhesive Science and Technology* 2009; **23**:945-59.

[2] Wolf DM, Powers JM, O'Keefe KL. Bond strength of composite to etched and sandblasted porcelain. *American Journal of Dentistry* 1993; **6**:155-8.

[3] Addison O, Fleming GJP. The impact of modifying alumina air abrasion parameters on the fracture strength of a porcelain laminate restorative material. *Dental Materials* 2007; **23**:1332-41.

[4] Horn HR. Porcelain laminate veneers bonded to etched enamel. In: Phillips RW, editor. Symposium on dental materials. *Dental Clinics of North America* 1983; **27**:671-84.

[5] Addison O, Marquis PM, Fleming GJP. The impact of hydrofluoric acid surface treatments on the performance of a porcelain laminate restorative material. *Dental Materials* 2007; **23**:461-8.

[6] De Jager N, Feilzer AJ, Davidson CL. The influence of surface roughness on porcelain strengths. *Dental Materials* 2000; **16**:381-8.

[7] Yen TW, Blackman RB, Baez RJ. Effect of acid etching on the flexural strength of a feldspathic porcelain and a castable glass ceramic. *Journal of Prosthetic Dentistry* 1993; **70**:224-33.

[8] Pagniano RP, Seghi RR, Rosenstiel SF, Wang R, Katsube N. The effect of a layer of resin luting agent on the biaxial flexure strength of two all-ceramic systems. *Journal of Prosthetic Dentistry* 2005; **93**:459-66.

[9] Rosenstiel SF, Gupta PK, Van der Sluys RA, Zimmerman MH. Strength of a dental glass-ceramic after surface coating. *Dental Materials* 1993; **9**:274-9.

[10] Griffith AA. Phenomena of rupture and flow in solids. *Philosophical Transactions of the Royal Society* 1921; **221**:163-98.

[11] Addison O, Marquis PM, Fleming GJP. Resin elasticity and the strengthening of all-ceramic restorations. *Journal of Dental Research* 2007; **86**:519-23.

[12] Addison O, Marquis PM, Fleming GJP. Resin strengthening of dental ceramic – The impact of surface texture and silane. *Journal of Dentistry* 2007; **35**:416-24.

[13] Addison O, Marquis PM, Fleming GJP. Quantifying the strength of a resin-coated dental ceramic. *Journal of Dental Research* 2008; **87**:542-7.

[14] Fleming GJP, Maguire RF, Bhamra G, Burke FM, Marquis PM. The strengthening mechanism of resin cements on porcelain surfaces. *Journal of Dental Research* 2006; **85**:272-6.

[15] Fok SL, Mitchell BC, Smart J, Marsden BJ. A numerical study on the application of Weibull theory to brittle materials. *Engineering Fracture Mechanics* 2001; **68**:1171-9.

[16] McCabe JF, Carrick TE. A statistical approach to the mechanical testing of dental materials. *Dental Materials* 1986; **2**:139-42.

[17] Weibull W. A statistical distribution function of wide applicability. *Journal of Applied Mechanics* 1951; **18**:293-7.

[18] Coffey JP, Anusavice KJ, Dehoff PH, Lee RB, Hojjatie B. Influence of contraction mismatch and cooling rate on flexural failure of PFM systems. *Journal of Dental Research* 1988; **67**:61-5.

[19] Isgró G, Addison O, Fleming GJP. Stress induced deformation of a dental ceramic following adhesive cementation. *Journal of Dental Research* 2010; **89**:87-90.

[20] Fleming GJP, Shaini FJ, Marquis PM. An assessment of the influence of mixing induced variability on the bi-axial flexure strength of dentine porcelain discs and the implications for laboratory testing of porcelain specimens. *Dental Materials* 2000; **16**:114-9.

[21] ISO 4049 (2000). (E) Dentistry, polymer based filling restorative and luting materials. International Organisation for Standardisation.

[22] Musanje L, Darvell BW. Curing-light attenuation in filled-resin restorative materials. *Dental Materials* 2006; **22**:804-17

[23] Bhamra GS, Fleming GJP. Effects of halogen irradiation variables (tip diameter, irradiance, irradiation protocol) on flexural strength properties of resin-based composite materials. *Journal of Dentistry* 2008; **36**:643-50.

[24] Denry IL, Tarr LA. Effect of heat treatment on microcrack healing behaviour of a machinable dental ceramic. *Applied Biomaterials* 1999; **48**:791-6.

[25] Isgró G, Wang H, Kleverlaan CJ, Feilzer AJ. The effects of thermal mismatch and fabrication procedures on the deflection of layered all-ceramic discs. *Dental Materials* 2005; **21**:649-55.

[26] Hsueh CH, Lance MJ, Ferber MK. Stress distributions in thin bilayer discs subjected to ball-on-ring tests. *Journal of the American Ceramic Society* 2005; **8**:1687-90.

[27] Lee I, An W, Chang J, Um C. Influence of ceramic thickness and curing mode on the polymerization shrinkage kinetics of dual-cured resin cements. *Dental Materials* 2008; **24**:1141-7.

[28] Ilie N, Hickel R. Correlation between ceramics translucency and polymerization efficiency through ceramics. *Dental Materials* 2008; **24**:908-14.

[29] McLean JW. Ceramics in clinical dentistry. *British Dental Journal* 1988; **164**:187-94.

[30] Bhamra GS, Fleming GJP, Darvell BW. Influence of LED irradiance on flexural properties and Vickers hardness of resin-based composite materials. *Dental Materials* 2010; **26**:148-55.

[31] Silikas N, Kavvadia K, Eliades G, Watts D. Surface characterisation of modern resin composites: A multitechnique approach. *American Journal of Dentistry* 2005; **18**:95-100.

[32] Yang H, Gao L, Yuan R, Kim K, Jung J. Effect of residual stress on the bending strength of ground Al2O3/TiCN ceramics. *Materials Chemistry and Physics* 2003; **80**:305-8.

[33] Konig W, Popp M. Precision machining of advanced ceramics. *Ceramics Bulletin* 1989; **68**:550-3.

[34] Nathanson D. Principles of porcelain use as an inlay/onlay material. In: Gaber GA, Goldstein RE, editors. Porcelain & Composite Inlays & Onlays. Illinois: Quintessence; 1993. p.23-32.

Table 1: The characterised mean of the maximum deflection values (μm) and associated standard deviations (in parenthesis) for IPS e.max® Ceram dentine discs measured at baseline (after polishing), after annealing, after alumina particle air-abrasion and resin-cement coating at 0 and 24 h. (Different small letters denote statistical significance by a paired sample t-tests were performed at a 95% significance level on the 20 individual samples in each of the groups (baseline quantification, following annealing and subsequent alumina particle air abrasion) for each comparison and different CAPITAL letters denote statistical significance determined using paired sample t-tests (95% significance level) on the 10 individual samples in each group for the effect of the factors cement coating and time).

Treatment	**Mean of the maximum deflection (μm)**		
	(n=20)	Group A (n=10)	Group B (n=10)
After Polishing	6.3 (2.2)[a]		
After Annealing	-0.6 (2.8)[b]		
After Alumina particle air abrasion	-2.9 (2.7)[c]	-3.5 (3.0)[A]	-2.4 (2.4)[A]
After Resin-cement coating (0 h)		2.4 (2.8)[B]	5.0 (3.4)[B]
After Resin-cement coating (24 h)		2.7 (2.8)[B]	5.5 (3.5)[B]

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