Reduction of load-bearing capacity of all-ceramic crowns due to cement aging

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1. Introduction

All-ceramic crowns are recognized in the field of restorative dentistry not only for their biocompatibility and esthetic characteristics, but also for the superior mechanical properties in sustaining multidirectional chewing forces. The monolithic ceramic crown and the bilayered ceramic crown, which is composed of a tough and opaque ceramic core and a...
veneering porcelain, are used for dental restorations. Many studies have been conducted to understand fracture of all-ceramic crowns in laboratory and clinical manners. In vitro studies have primarily focused on flat layered structures by means of Hertzian contact testing, which ignore the complex geometry of the tooth crown. Based on their findings there are three primary fracture modes including surface cone cracks, subsurface quasi-plastic damage and radial cracks at the bottom surfaces of the framework ceramic (Jung et al., 2008; Zhang and Lawn, 2004; Dong and Darnell, 2003; Wang and Darvell, 2007). However, due to the complex geometry and loading condition, clinical crown failures have been reported in diverse locations, such as chipping at the occlusal area, fracture at the interface of veneer/core interface of bilayered crowns, etc. (Silva et al., 2011; Scherrer et al., 2007, 2008; Quinn et al., 2005; Aboushelib et al., 2009). The influences of framework thickness (Lawn et al., 2002; Tsai et al., 1999; Zhang and Lawn, 2004; Lohbauer et al., 2002) and clinical crown failures have been considered, with efforts focused on understanding the discrepancy between clinical and laboratory results. In recent decades, dental ceramics with high strength and toughness have been developed to meet the requirement of routine functions similar to teeth. Despite their general success, some all-ceramic crowns undergo failure after years of service (Beier et al., 2012). As indicated in the clinical survey, the main cause of failure is due to the fracture of ceramics. Since the estimated survival rate of all-ceramic crowns was 97.3% after 5 years, 93.5% at 10 years, and 78.5% at 20 years, the long-term success is still a major concern for restorative dentistry.

Dynamic fatigue test provides an efficient means to evaluate the long-term mechanical properties of materials under a constant cyclic stress ratio. Mechanical degradation in flexural stress and toughness has been realized in multiple dental ceramics (Zhang and Lawn, 2004; Lohbauer et al., 2002) single ceramic crowns (Borges et al., 2009) and dental bridges (Kohorst et al., 2008; Studart et al., 2007). The resin cement also plays an important role in the restorative process (Vaidyanathan and Vaidyanathan, 2009). For example, poor initial bond quality can significantly reduce the initial fracture load-bearing capacity of glass ceramics (Clelland et al., 2007). Previous studies have demonstrated that proper choice of dental cements can effectively improve the fracture resistance of all-ceramic restorations (Burke et al., 2002; Rekow et al., 2006). Numerical simulation suggested that the cement agent with greater Young’s modulus, such as Variolink, can to some extent reduce the magnitude of stress within the ceramic dental crown (Liu et al., 2011). The recent clinical survey also suggested that all-ceramic crown restorations with Variolink showed significantly fewer failures than other cements types such as Opttec Cement and Dual Cement (Beier et al., 2012). In a moist environment, resin cements absorb water and swell (Hirasawa et al., 1983), which decreases the elastic modulus and hardness (Oysaed and Ruyter, 1986). The micro-tensile test studies have shown that the bonding strength of some resin cements decrease due to water aging (Holderereger et al., 2008; Ozcay et al., 2009; Oyague et al., 2009). Retrospective and clinical follow-up studies have stated that all-ceramic crowns could lose retention over time (Ortorp et al., 2009, 2012; Wolfart et al., 2009). Hence, this problem appears to be related to the loss of bond strength of resin cements due to aging.

The aim of this study was to evaluate effects of water aging of the resin cement on the fracture behaviors of layered lithium disilicate and zirconia crowns using a laboratory and numerical study. Nanoindentation was conducted to evaluate Young’s modulus of resin cement before and after water aging. Two types of sectioned ceramic crowns were subjected to monotonic load to failure. The fracture modes were captured with digital image correlation and comparisons were made before and after cement aging. A 3-D finite element analysis was also conducted on the single all-ceramic crown to demonstrate the change in stress distribution and magnitude in the restoration due to cement aging. The null hypothesis was that water aging of the resin cement has no effects on the fracture load of bonded all ceramic crowns.

2. Materials and methods

Two types of laboratory evaluations were conducted. The first was to examine the degradation in Young’s modulus of a selected type of resin cement after water aging. Then, sectioned restored teeth with ceramic crowns were subjected to monotonic occlusal loads to fracture. The initiation and growth of cracks resulting from loading were monitored with a video system and then analyzed with an optical technique that enabled a quantification of the displacement and strain distribution.

2.1. Nanoindentation

Cubic pieces (n=6) of the resin cement, Rely X ARC (3M-ESPE St. Paul, MN), which was used for bonding the ceramic crown and the dummy tooth substrate, were prepared according to the manufacturer’s instructions. One surface of the cement was polished to 200 μm thickness using abrasive papers from #2000 to #5000 mesh (Matador, Wasserfert, Germany) until a mirror-like surface was achieved. The specimens were randomly divided into two groups and stored in air or distilled water for 30 days. The Young modulus of the resin cement was evaluated with Hysitron Triboscope nanoindentor In-Situ Nanomechanical Test System (Hysitron, Minneapolis, MN, USA) with a Berkovich indenter (TI-039, Hysitron Inc., Minneapolis, MN, USA). Loading and unloading were performed at a rate of 0.6 mN/s to the maximum of 4 mN, and with a 5-s hold period. The reduced Young’s modulus was estimated from the unloading curves according to the conventional Oliver and Pharr method of evaluation (Oliver and Pharr, 1992).

2.2. Monotonic contact load

The ceramic crowns evaluated in this investigation consisted of (1) the pressable ceramic IPS e.max Press (Ivoclar-Vivadent, Schaan, Liechtenstein) prepared by the layering technique with IPS e.max Ceram (Ivoclar-Vivadent, Schaan, Liechtenstein) as the veneer (CP crowns), and (2) Cercon zirconia
Degudent, Frankfurt, Germany) prepared by computer aided machining (CAM) with Vita VM9 (Zahnfabrik, Bad Sackingen, Germany) as the veneering ceramic (VZ crowns). The sectioned crowns with a thickness of 2 mm were fabricated in bucco-lingual plane according to the geometry and size of a standard first right mandibular molar (DS0-500A, Nissin Dental Products Co., Ltd.) and involved a series of detailed procedures described in an earlier study [Zhang et al., 2008]. Briefly, 20 dummy tooth substrates were prepared with z100 resin (3M ESPE, USA), and then tapered at 8° with a chamfer of 135°. The cement Rely X ARC (3M-ESPE St. Paul, MN) was used to bond the ceramic crowns onto the dummy substrate, as shown in Fig. 1. The bonding process was completed in accordance with the manufacturer’s instructions. As the IPS e.max and Cercon zirconia are clinically placed with different bonding processes, the crowns were prepared using separate procedures. Specifically, the inner surfaces of the IPS e.max crowns were etched with 4.5% hydrofluoric acid for 20 s, rinsed with plenty of water and silanized. Then the resin surfaces were etched for 30 s with 35% phosphoric acid, rinsed, coated with Single Bond 2 and light cured for 10 s. At last, the ceramic crowns were cemented to the dummy tooth substrate. For the Cercon zirconia, Vita VM9 with maximum thickness of 1.4 mm was veneered on the framework with a uniform thickness of 0.6 mm. The internal surface of the zirconia crown was roughened with 600-grit silicon carbide papers and cemented (Rely X ARC) to the dummy tooth substrate. Ten specimens of each type were prepared and randomly divided into two groups. One group was stored in air and the other was stored in 37°C distilled water for 30 days before testing.

Due to the opacity of all-ceramic crowns, the crack initiation and growth cannot be directly observed while loading. Fractography has been introduced to determine the crack origin and growth path in fractured crowns by identifying fractographic features such as hackle, wake hackle, twist hackle, arrest lines, and mirrors. These evaluations are conducted post-fracture, and while they can often identify the origin of fracture, they often cannot distinguish some of the major contributing factors with variation of loading. One approach for monitoring the initiation and evolution of cracks in restored crowns utilizes a sectioned tooth-like specimen that is monitored using digital image correlation (Zhang et al., 2008). This approach can and has been successful in the identification of cracks and other defects in hard tissues and biomaterials (Zhang and Arola, 2004; Zhang et al., 2007; Zhang and An, 2012).

Fig. 1 – Schematic diagram of the sectioned CP crown restoration along the bucco-lingual direction. The thickness of zirconia core was 0.6 mm. The thickness reduction of 0.2 mm was replaced by the veneer material.

Fig. 2 – Experimental setup and loading condition. The surface of the specimen was sprayed with arbitrarily distributed black speckles.
The sectioned all-ceramic crown restoration was mounted onto the tooth substrate and clamped in a special fixture. The concentrated contact force was applied at the cusp of the restoration with a tungsten carbide sphere with a diameter of 6 mm as shown in Fig. 2. The monotonic load was achieved by a universal test machine (BZ2.5/TS1S, Zwick/Roell, Germany) at a rate of 0.05 mm/min until failure of the crown. A video camera (CV-A1, JAI, Japan) was placed normal to the crown section surface to document sequential images while loading. The corresponding deformation developed in the trilayered all-ceramic crown restoration was evaluated using Digital Image Correlation (DIC), a non-contact optical method for displacement and strain measurement that requires only two digital images acquired before and after deformation. This provides a way to evaluate the displacement and strain components over the entire field of view. The distribution of the displacements or strains can be visualized by transforming the magnitude of the displacement components to grayscales. For instance, since the displacement distribution is not continuous across the edge of a crack, the crack can be easily identified by an apparent discontinuity in the grayscale map. Prior to the tests, a thin speckle coating was sprayed onto the specimen surface to facilitate DIC (Zhang and Lawn, 2004). Sequential images were acquired at a constant frequency of 2 Hz and were triggered at the onset of the loading. According to the image resolution (1376 × 1035 pixels), one pixel length represented approximately 10 μm. Using sub-pixel correlation, the precision of the displacement measurement reached 0.01 pixels, i.e. 0.1 μm in this case. Once a crack was identified by an apparent discontinuity in grayscale of the displacement field, the corresponding load was distinguished. The documented fracture loads for each group of specimens were analyzed using one-way ANOVA with significance defined by p ≤ 0.05.

2.3. Numerical modeling

A plaster crown restoration of the first right mandibular molar was prepared according to standard clinical protocol as described in a previous study and then modeled using FEA (Liu et al., 2011). The numerical model was comprised of a veneer layer with thickness of 1.2 mm at the occlusal facet and gradually reduced to 0.2 mm at gingival margin, a core layer (0.8 mm), a cement layer (90 μm) and the dentin substrate (Fig. 3). The model was imported into the commercial finite element software (ANSYS 11.0, ANSYS Inc., USA), free meshed using brick elements (Solid92) and tested for convergence (~530,000 elements). All layers were assumed to be homogeneous, isotropic and linear elastic with material properties listed in Table 1 (Albakry et al., 2003; Isgro et al., 2011; He and Swain, 2007; Swain, 2009; Yilmaz et al., 2011). As studies have demonstrated that the effects of periodontal tissues on the stresses in the crown of the molar are negligible (Goel et al., 1991; Ko et al., 1992), the influence of the periodontal ligament on the stresses was not considered in this study. The root of the dental substrate was constrained such that displacement components in all directions were equal to zero. A 600 N maximum load was applied at the tip of the buccal cusp ridge on the veneer layer (Fig. 3).

As cement aging could result in the reduction in mechanical properties (Oysaed and Ruyter, 1986; Holderegger et al., 2008; Ozcan et al., 2009; Oyague et al., 2009), two cases were evaluated. The first was to study the influence of a reduction in Young’s modulus of the cement on the stress distribution of the restored crown. In this case the interface between the core and tooth substrate was perfectly bonded together, while Young’s modulus was assigned from magnitudes that were determined from the experimental results (via nanoindentation). The second was to study the loss of bond strength on the stress distribution. In this case, the interface between the core and cement was totally debonded and contact elements were defined in order to simulate complete debonding or loss of retention.

3. Results

3.1. Nanoindentation of cement

The average Young’s modulus reduced from 6.48 ± 0.41 GPa to 4.97 ± 0.36 GPa after water aging for 30 days. The reduced Young’s modulus obtained from nanoindentation indicated that water aging caused a significant degradation of cement stiffness (p = 0.000).
3.2. Contact loading to fracture

For CP crowns stored in air, fracture occurred at comparatively large loads without any indication of debonding between the cement and crown in the grayscale images obtained from the DIC analysis. It was found that cracking initiated from the loading zone and propagated transiently forming a chip at the veneer layer (Fig. 4). In contrast, an apparent debonding between the core and dummy tooth substrate was detected at the early loading stage in specimens stored in water (Fig. 5). With increasing load, radial cracks initiated at the lower side of the coping layer and subsequently caused bulk fracture of the crown (Fig. 6). A detail description of the fracture load and corresponding fracture mode for the CP specimens is presented in Table 2. According to the displacement discontinuity identified using DIC, the average load at the onset of debonding was \(297 \pm 20\) N. The average fracture load for the dry specimens was \(542 \pm 71\) N, while the fracture load reduced to \(345 \pm 21\) N after water aging, which was significantly \((p<0.001)\) smaller than that in the dry CP crowns.

For the VZ crowns, specimens stored in air were fractured in the form of chips at an average load of \(1163 \pm 114\) N. Although debonding at the interface of the core and dummy tooth substrate was also identified at an early stage of loading \((393 \pm 46\) N\) in the water aging group, the sectioned crown specimens fractured at comparatively high contact loads \((1074 \pm 117\) N\). In addition, the specimens fractured by the same mode, i.e. in the form of chipping around the contact area (Fig. 7). There was no significant influence of water aging on the fracture loads for the zirconia crowns \((p=0.257)\).

3.3. Finite element analysis

As ceramic crowns are comprised of brittle materials, only the tensile stresses were examined in the ceramic layers. For both all-ceramic restoration systems the stress distribution in the ceramic crown was essentially identical when using a Young's modulus of 4.97 GPa, a reduction from 6.48 GPa after water aging. There were variable reductions in the magnitude of the maximum principal stresses in the two ceramic systems. For IPS e.max Press core, the stress rose from 115 MPa to 121 MPa, and for zirconia core from 195 MPa to 206 MPa. However, the loss of bonding strength contributed more to the stress distribution as well as the magnitude of stress. It was found the maximum principal stress at the bottom surface of the core layer increased to 247 MPa for IPS e.max Press and to 303 MPa for the zirconia. The comparison of the stress distribution in the bucco-lingual section before and after the loss of bonding strength is shown in Fig. 8. Note that the degree of stress concentration becomes more severe and that the stress distribution at the bucco-lingual marginal region is no longer continuous in this condition.

4. Discussion

Although previous research demonstrates that resin cements improve the immediate fracture resistance of all-ceramic restorations, the effect of bond degradation is not completely understood (Burke et al., 2002; Liu et al., 2011). The laboratory study was designed to illustrate the effect of water aging on the load bearing capabilities of the lithium disilicate and zirconia ceramic restorations. The resin cement Rely X ARC was used as the bonding agent. The nanoindentation test has revealed that...
Young's modulus of the cement decreased from 6.48 GPa to 4.97 GPa due to water aging, which represents a 23% reduction. Meanwhile, micro-tensile tests also reported that the bonding strength of Rely X ARC decreases due to water aging (Holderegger et al., 2008). The mechanical degradation in both stiffness and bond strength of Rely X ARC resin cement may potentially affect the longevity of the all-ceramic crown restorations. A relevant study suggested a slight reduction in the elastic modulus of the EverStick and Vectris Pontic after water storage (Bouillaguet et al., 2006). From the micro-tensile test, deterioration in bonding strength has been widely observed in many types of cement agents (Holderegger et al., 2008; Ozcan et al., 2009; Oyague et al., 2009). It is rational to deduce that the cement due to water aging could be an important factor contributing to the overall mechanical performance of the all-ceramic restoration in a long-term evaluation.

In the monotonic contact compressive experiment, distinctions have been made both from the maximum fracture load, fracture mode and from the deformation distribution among layers before and after water aging for lithium disilicate crowns. For the CP crowns, the load-bearing capacity to interfacial debonding and to fracture reduced 45% and 36%, respectively. The results are in agreement with an early study (Clelland et al., 2007). Thus, the null hypothesis must be rejected when applied to results of the CP crowns. Furthermore, the fracture mode transitioned from surface chipping to radial cracking, which is detrimental to all-ceramic crowns. However, for dental ceramics with very high flexural strength and toughness like zirconia, the onset of debonding between the coping and substrate was observed at 393 N, which represented a 66% reduction of the total load-bearing capacity to interfacial failure. Yet, the load at chipping fracture reduced merely from 1163 N to 1074 N, a trivial percent loss of the total load-bearing capacity. This small reduction in fracture load may reduce the durability of the crown (depending on other intrinsic and processing defects), but it is more likely to result in other forms of premature failure. Thus, the null hypothesis is accepted when applied to results of the zirconia crowns, but the importance of the increase in stress and debonding should not be overlooked. Rekow et al. (2006) and Liu et al. (2011) reported that cement modulus in the restored crown is an important contributor to the stress level, while in different dental ceramic systems, the contribution varies. The presented experimental results support this statement. By comparing the mechanical properties between lithium disilicate and zirconia, it is concluded that cement deterioration due to water aging could be more serious for dental ceramics with low flexural strength.

Now that water aging causes the reduction in stiffness and bonding strength of cement, which factor is more critical in contribution to the fracture resistance of all-ceramic crowns? The 3D finite element analysis was performed to understand the fracture mechanism of all-ceramic crowns due to the water-aging related degradation of the cement. The degradation included two aspects, i.e. a reduction in elastic modulus and loss of bonding strength. In both conditions, the maximum tensile stress in the layered ceramics increased, regardless of the ceramic type. Consequently, it is reasonable to conclude that the water aging of the resin cement

![Radial crack at the bottom of the e.max Press core layer.](image)

Table 2 – Fracture loads and modes documented in the experimental evaluation of the crowns.

<table>
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<th>4</th>
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<td></td>
<td>FL (N)</td>
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<td>514</td>
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<td>297 (20)/345</td>
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increases the stress level of the all-ceramic crowns. However, the degree of influence caused by reduction of stiffness and debonding is quite different. The reduction in Young's modulus did not change the stress distribution of the ceramic crown subjected to occlusal loads. In addition, although there was an increase in the maximum stress concentrated at the cement/core interface for both crown types, the contribution was limited (5%). In contrast, the loss of bonding strength of the resin cement would cause substantial problems. Note that debonding was visualized in the experiment by the discontinuity in displacement field at the interface of the core and substrate (Figs. 5 and 7). It not only changed the stress distribution in the ceramic layers, but also significantly increased the magnitude of tensile stress at the lower surface of the core. From the numerical simulation, it was found that the maximum principal stress increased by 115% for CP crowns and 55% for the VZ crowns due to the loss of bonding strength. The rise of flexural stress would increase the risk of fracture initiating at the interior of the core for ceramics with low fracture strength.

Clinical studies have rarely reported failure of high-strength zirconia cores in the form of bulk fracture (Beier et al., 2012; Ortorp et al., 2009; Wolfart et al., 2009; Ortorp et al., 2012; Cehreli et al., 2009). Indeed, fracture of the zirconia is unexpected as the flexural strength is up to 1400 MPa and resistant to fatigue (Zhang and Lawn, 2004; Yilmaz et al., 2011). Results from the numerical simulation showed that the maximum flexural stress increased from 195 MPa to 303 MPa after loss of retention. While this is more than a 50% increase in stress level, it is far below the flexural strength of the zirconia core. Nevertheless, cement degradation cannot be ignored in zirconia crowns. Although bulk failure did not happen to the VZ specimens, debonding due to water aging was evident (Fig. 7) and could lead to a complete loss of retention of the restored crown over time. In this condition, a secondary restoration might be required to maintain the masticatory function of patients. Bacteria in the oral environment might also infiltrate the trimmed tooth substrate through the debonded gingival margin and facilitate the development of secondary caries (Pak et al., 2010). Therefore, the importance of developing adhesives that are durable under water absorption and that are capable of maintaining adhesive strength is critical to the success of all-ceramic crowns.

Recently, the importance of aging effect of resin cement has been recognized in the restorative dentistry. Some conditioning methods such as silane treatment have been introduced to reinforce the bonding strength between the ceramics and cement agents. It has been pointed out that hydrolytic stability of the repair method based on silica coating and silanization was superior to the other repair strategies (Ozcan et al., 2009). The chemical bonds generated at the interface between the Alumina-reinforced feldspathic ceramic and resin cement from the conditioning is helpful to enhance the bonding capacity of the structure. It was also reported that due to the differences in coefficients of thermal expansion (CTE) of resin composites and ceramics (Y-TZP), the shear bond strength reduced considerably after thermocycling (Heikkinen et al., 2009a,b). In the short-term laboratory evaluation, hydrolytic stability of acrylate silane was believed to be superior to methacrylate silane. In the present laboratory study, it was found the water aging can cause degradation of cement in loss of Young's modulus and bonding strength for IPS e.max crowns even after silanization which cause the reduction of load bearing capacity of the restored crown. This suggested that the silanization could be helpful to some specified ceramics. In comparison, the present laboratory study provided a new routine to evaluate the overall load capacity of restored ceramic crowns. The effects of reduction in Young's modulus and the bonding strength of the cement were all observed and quantitatively analyzed.

As with all investigations, there are important limitations that should be recognized. Firstly, in order to emphasize the role of cement due to water aging, the mechanical degradation
of ceramics and cement under cyclic loading was not considered in this study. Cyclic loading could cause mechanical degradation in some dental ceramics, thereby resulting in a slight decrease of both the flexural strength and fracture toughness (Zhang and Lawn, 2004; Yilmaz et al., 2011; Kassem et al., 2012). Secondly, current ceramic systems and adhesive technology have ensured immediate fracture resistance of all-ceramic restorations, while failures were reported after years of service (Beier et al., 2012). In actual moist oral environment, resin cements can undergo fluid absorption from the dentin tubules and saliva at the crown margin. In the study, the water aging was simulated by emerging the sectioned crowns into the 37°C distilled water for 30 days. The study only provides understandings that water aging of cements can potentially reduce the load-bearing capacity of all-ceramic crowns. How the emerging duration relates to the actual oral service time is not discussed. Lastly, the sectioned crown was used in the experiment so that the debonding and fracture of the crown could be monitored with DIC. The true stress distribution in the restored crown has been analyzed with a 3D numerical simulation.

5. Conclusion

Water aging resulted in a reduction of Young’s modulus of the cement (Rely X ARC) as well as an apparent reduction of bonding strength. Degradation in bonding strength and stiffness could potentially lead to stress redistribution in the restored crown and consequently reduce the load-bearing capacity of all-ceramic restorations after years of service. Cement deterioration due to water aging could be more serious for dental ceramics with low flexural strength.

Acknowledgments

This research was supported by the National Science Foundation of China Grant no. 11172161, the Science and Technology Commission of Shanghai Municipality Grant nos. 11195820900 and 10zr1423400, the Innovation Program of Shanghai Municipal Education Commission No. 12ZZ092, the State Key Laboratory of Oral Diseases (Sichuan University) by Grant no. SKLODSCU2009KF03, the Shanghai Leading Academic Discipline Project No. S30106, and the Graduate Innovation Fund of Shanghai University No. Shucx101077.

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