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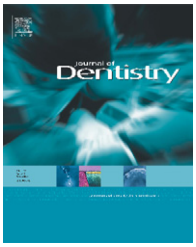

Effects of extreme cooling methods on mechanical properties and shear bond strength of bilayered porcelain/3Y-TZP specimens

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ABSTRACT

Objectives: This study investigated the effect of extreme cooling methods on the flexural strength, reliability and shear bond strength of veneer porcelain for zirconia.

Methods: Vita VM9 porcelain was sintered on zirconia bar specimens and cooled by one of the following methods: inside a switched-off furnace (slow), at room temperature (normal) or immediately by compressed air (fast). Three-point flexural strength tests (FS) were performed on specimens with porcelain under tension (PT, $n = 30$) and zirconia under tension (ZT, $n = 30$). Shear bond strength tests (SBS, $n = 15$) were performed on cylindrical blocks of porcelain, which were applied on zirconia plates. Data were submitted to one-way ANOVA and Tukey's post hoc tests ($p < 0.05$). Weibull analysis was performed on the PT and ZT configurations.

Results: One-way ANOVA for the PT configuration was significant, and Tukey's test revealed that fast cooling leads to significantly higher values ($p < 0.01$) than the other cooling methods. One-way ANOVA for the ZT configuration was not significant ($p = 0.06$). Weibull analysis showed that normal cooling had slightly higher reliability for both the PT and ZT configurations. Statistical tests showed that slow cooling decreased the SBS value ($p < 0.01$) and showed less adhesive fracture modes than the other cooling methods.

Clinical Significance: Slow cooling seems to affect the veneer resistance and adhesion to the zirconia core; however, the reliability of fast cooling was slightly lower than that of the other methods.

1. Introduction

A mismatch of the thermal expansion coefficient (CTE) between feldspathic porcelain and zirconia, as well as the effect of thermal diffusivity and thermal conductivity upon cooling after sintering, can generate transient and residual stresses and increase the clinical failure rates of zirconia-based restorations.[1–9] Below the glass transition temperature (Tg), the porcelain acquires a solid state in which structural

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rearrangements are impossible and residual stress can develop within the porcelain layer. Stress intensity is directly proportional to the differences in the CTE of the two materials from Tg to room temperature.[10] Furthermore, residual stresses in zirconia/porcelain bilayer specimens may be modified by thermal treatment at the Tg interval, variation in cooling rates or the temperature gradient of the internal and external layers of the veneer.[4,5,7,11–13]

In contrast to metals in metal–ceramic restorations, zirconia has thermal diffusivity lower than that of dental porcelain, and a slow cooling of zirconia retards the balance between the internal and external temperatures. Moreover, the thermal conductivity of zirconia is approximately 15 times smaller than that of alumina and approximately 100 times smaller than that of gold alloys.[5,12] Consequently, the cooling process after the firing of porcelain in zirconia-based restorations is very slow, resulting in high transitional temperature differences throughout the restoration, especially at the thicker and irregular layers and upon fast cooling. The temperature gradient between the veneer and zirconia core in the fast cooling method may reach up to 140 °C.[14] During fast cooling, the temperature of the veneer porcelain in contact with the zirconia core may remain above Tg for a longer period of time, while the surface of the veneer cools at a faster rate. This cooling introduces a high transient thermal gradient between the outer and inner surface. This process results in a high residual tensile stress within the porcelain layer and high tempering/compressive residual stresses on the surface.[5,11,12,14]

To address these concerns, after March 2009, manufacturers have recommended slow cooling after porcelain firing to reduce thermal gradients and residual stresses in the porcelain sintering[5,7,14] and to decrease the risk for early ceramic chipping.[6] The literature provides no standardization in the many different protocols for cooling,[3,6,7,11,13–18] and this wide variability among cooling methods produces a confusing nomenclature. For example, slow cooling for one author may be similar to regular cooling for other authors.

Therefore, the aim of this study is to investigate how the extreme slow or fast cooling methods influence the flexural strength and shear bond strength of dental feldspathic veneer porcelain for zirconia. In addition, the reliability of the flexural strength was investigated by Weibull analysis. The null hypothesis was that there would be no significant differences in the studied properties of the porcelain when different cooling conditions were used.

2. Materials and methods

2.1. *Processing and three-point flexural testing*

The materials used in this study are described in Table 1. Presintered 3Y-TZP blocks were cut with a diamond disc in a precision cutting machine (Isomet 1000, Buehler, Lake Bluff, USA) and finished using 600-grit size SiC papers in a polishing machine (Metaserv 2000, Buehler, Buehler UK Ltd., Coventry, England). After sintering in a $MoSi_2$ furnace (FE 1800, Maitec, São Carlos, SP, Brazil) at 1530 °C for 2 h, bar-shaped framework specimens had an average final dimension of 22 mm in length × 4.0 mm in width × 0.7 mm in thickness. The dimensions of each specimen were measured with a digital caliper (Mitutoyo Corporation, Tokyo, Japan) with precision of 0.01 mm for the calculation of flexural strength.

One side of the zirconia framework bars was veneered with Vita VM9. The powder and liquid (VITA Modeling Liquid, VitavZahnfabrik, BadSäckingen, Germany) were mixed to obtain a thin aqueous mixture (washbake layer), which was applied very thinly on the cleaned framework and sintered in the ceramic oven (Aluminipress, EDG, Sao Carlos, SP, Brazil) following the manufacturer's recommendations. A slurry of porcelain (dentine layer) was prepared by mixing the powder and liquid in a ratio of 2.5:1 and inserted into a polyether mold (Impregum F, 3M ESPE, Seefeld, Germany) that was adapted around the zirconia bars. Excess liquid was blotted with absorbent paper before the specimens were removed from the mold. The specimens were sintered in the oven according to the manufacturer's instructions. At the end of firing, cooling was performed according to the following experimental protocol:

- **Slow** – samples were left inside the closed, turned-off furnace until they reached room temperature (about 8 h);
- **Normal** – the elevator of the furnace was lowered, and when the temperature inside the furnace reached 500 °C, the samples were removed and cooled at room temperature (about 20 min);
- **Fast** – samples were removed from the furnace immediately after the holding time and blasted by compressed air (less than 10 s).

After cooling, the porcelain surface of the specimens was sequentially grounded using 120- to 1200-grit wet SiC paper

Table 1 – Materials.

Material	Manufacturer	Main components (mass%)	Batch number	Elastic modulus (GPa)	CTE (10^{-6} °C^{-1})
ZRHP	ProtMat Materiais Avançados, Guaratinguetá, São Paulo, Brazil	ZrO_2 (94,8); Y_2O_3 (5.2)	S09-011B	210[a]	10,1[a]
Vita VM9 Dentin	Vita Zahnfabrik, Bad Sackingen, Germany	SiO_2 (60–64); Al_2O_3 (13–15); K_2O (7–10); Na_2O (4–6); B_2O_3 (3–5) [b]	30830	65[b]	9,2[b]

[a] According to the manufacturer.

[b] According to Guess et al.[12]

discs (Norton Abrasivos, Sao Paulo, SP, Brazil) in a polishing machine (Metaserv 2000, Buehler) until achieving final dimensions of 4 ± 0.25 mm in width, 1.2 ± 0.2 mm in thickness and 22 mm in length. The dimensions of the specimens were measured with a digital caliper.

Three-point flexural strength testing was carried out in distilled water at 37 °C (±1.0 °C). The sample holder had a 15-mm span between the two rounded steel knife-edge bearers of 0.8-mm radius. The specimens were loaded on the center point by a rounded steel knife edge piston (1.6 mm radius) in a universal testing machine (DL 2000, EMIC, São José dos Pinhais, PR, Brazil) with a 5.0-kN load cell and at a cross head speed of 1.0 mm/min until failure. Specimens were randomly divided into two configurations, according to the cooling method:

1 porcelain side on the sample holder, i.e., porcelain under tensile stress and zirconia under compression stress (PT) (slow $n = 30$; normal $n = 30$; fast $n = 30$);
2 zirconia side on the sample holder, i.e., zirconia under tensile stress and porcelain under compression stress (ZT) (slow $n = 30$; normal $n = 30$; fast $n = 30$).

The flexural strength (FS) was calculated according to Eq. (1):

$$\sigma_f = \frac{6M}{wt_t^2 K}\left(2 + \frac{t_c}{t_t} + \frac{E_t t_c}{E_c t_c}\right) \tag{1}$$

where M and K are obtained by Eqs. (2) and (3).

$$M = \frac{PL}{4} \tag{2}$$

$$K = 4 + 6\left(\frac{t_c}{t_t}\right)^2 + \frac{E_c}{E_t}\left(\frac{t_c}{t_t}\right)^3 + \frac{E_t t_t}{E_c t_c} \tag{3}$$

Replacing M and K in Eq. (1), the Eq. (4) is obtained for the calculation of the bilayer specimens FS[19,20]:

$$\sigma_f = \frac{3E_t LP(E_c t_c^2 + 2E_c t_c t_t + E_t t_c^2)}{2w(E_c^2 t_c^2 + 4E_c E_t t_c^3 t_t + 6E_c E_t t_c^2 t_t^2 + 4E_c E_t t_c t_t^3 + Et_c^2 t_t^4)} \tag{4}$$

where σ_f is the maximum center tensile stress (MPa), P is the load at fracture (N), L is the distance between the supports (mm), E_t is the elastic modulus of the material under tensile stress (GPa), E_c is the elastic modulus of the material under compression (GPa), t_t is the thickness of the material under tensile stress (mm), t_c is the thickness of the material under compression (mm), and w is the specimen's width (mm).

2.2. *Weibull analysis*

To assess the reliability of the specimens in each configuration test according to the cooling conditions, a Weibull regression analysis was performed on the flexural strength data to determine the Weibull modulus (m) and the characteristic strength (σ_0). Eq. (5) describes the Weibull distribution:

$$P = 1 - \exp\left[\left(-\frac{\sigma}{\sigma_0}\right)^m\right] \tag{5}$$

where P is the probability of failure, σ is the flexural strength, σ_0 is the characteristic strength at the fracture probability of 63.21%, and m is the Weibull modulus, which is the slope of the line plotted in the "$\ln[\ln(1/(1 - P))]$ vs $\ln \sigma$" Cartesian plane.

2.3. *Shear bond strength test*

Square zirconia specimens, 9 mm in length and 2 mm in thickness, were cut and sintered as described above. A wash bake layer was applied and sintered on the surface, and a cylindrical metal mold, 5 mm in diameter and 3 mm in height, was used to build the porcelain layer. Dentine porcelain was sintered according to the manufacturer's instructions and cooled as previously described ($n = 15$).

After cooling, the zirconia segment of the specimen was embedded in a polyvinyl chloride (PVC) tube with PMMA resin, ensuring that the zirconia/porcelain interface was at the same level as the resin surface. The diameter of porcelain layer of the specimens was measured with digital caliper to calculate the bond area. The specimens were held in a metal device in a universal testing machine (DL 2000, EMIC, São José dos Pinhais, PR, Brazil). The load was applied parallel to the long axis of the specimen via a knife-edge shearing rod at the zirconia/porcelain interface, with a 5.0 kN load cell at a crosshead speed of 1.0 mm/min, until fracture of the sample was achieved. The maximum load at failure was recorded, and the shear bond strength (σ_{SBS} – MPa) was calculated according to Eq. (6):

$$\sigma_{SBS} = \frac{P}{\pi r^2} \tag{6}$$

where P is the maximum failure load (N) and r is the ratio of porcelain circumference (mm^2).

Failure modes of the SBS test were classified according to: (1) adhesive failure at the veneering porcelain/substrate interface (AD); (2) cohesive failure within the veneering porcelain (CO); and (3) the combination of adhesive and cohesive failures (AC).[2]

2.4. *Statistics*

Statistical analyses for flexural strength and shear bond strength were performed by one-way ANOVA ($\alpha < 0.05$) and Tukey's post hoc test for multiple comparisons.

3. Results

The means of the three-point flexural strength measures (σ_f), the standard deviations (SD), and the coefficients of variation (CV) of specimens with porcelain under tension (PT) and zirconia under tension (ZT) according to cooling method are shown in Table 2. One-way ANOVA for the PT specimen configuration was significant ($F_{2,87} = 10.46$, $p < 0.01$), and Tukey's post hoc test showed that fast cooling leads to significantly higher mean σ_f values than the slow and normal cooling methods, which were not different from each other. On the other hand, one-way ANOVA for the ZT specimen configuration was not significant ($F_{2,87} = 2.90$, $p = 0.06$).

The Weibull statistical analyses (Table 2) showed that the normal cooling specimens exhibited slightly higher values than those that underwent fast or slow cooling, for both

Table 2 – Means of flexural strength (σ_f, MPa), standard deviations (SD), coefficients of variation (CV, %), Weibull modulus (m), characteristic strengths (σ_0, MPa) and R-values of specimens with porcelain under tension (PT configuration) and specimens with zirconia under tension (ZT configuration) according to cooling method.

Parameters	Flexural strength		Weibull analysis		
	σ_f (SD)	CV	m	σ_0	R-value
PT configuration					
PT-SLOW	50.4 (11.8)^B	23.5%	4.7	54.8	0.973
PT-NORMAL	52.3 (9.5)^B	18.1%	6.2	56.1	0.956
PT-FAST	64.2 (15.0)^A	23.3%	4.7	69.9	0.987
ZT configuration					
ZT-SLOW	611.6 (127.3)^{ns}	20.8%	5.2	661.3	0.966
ZT-NORMAL	612.8 (125.6)^{ns}	20.5%	5.4	663.9	0.974
ZT-FAST	685.2 (151.7)^{ns}	22.1%	4.7	747.5	0.989

Different letters within the PT configuration and ZT configurations indicate that flexural strength was significantly different between groups ($p < 0.05$).

specimen configurations. In the PT configuration, slow and fast were equal, but in the ZT configuration, slow cooling specimens exhibited a higher Weibull modulus than fast-cooling specimens.

The mean shear bond strength of porcelain bonded to zirconia that underwent slow cooling was 15.9 (4.5) MPa; normal cooling was 19.5 (4.6) MPa; and fast cooling was 20.9 (4.4) MPa. One-way ANOVA showed a significant difference for the shear bond strengths among the cooling methods tested ($F_{2,42} = 5.430$, $p < 0.01$). Tukey's post hoc test for multiple comparisons showed that the mean SBS of the slow-cooling method was lower than those of the normal- and fast-cooling methods, which were similar to each other. After the SBS test, the following failure modes were observed for slow (AD 40%; CO 33%; AC 27%), normal (AD 67%; AC 33%), and fast cooling (AD 67%; CO 13%; AC 20%).

4. Discussion

The final dimensions of the utilized bilayer flexural strength specimens were chosen based on the monolayer specimen tests (ISO 6972:2008) with a thickness ratio of 1:1. This study conducted two flexural strength test configurations (porcelain or zirconia under tension), submerged in water at 37 °C. The results indicated that the material on the bottom surface determines the strength and failure mode of the system.[19–24] According to the selected mathematic equation, flexural strength depends directly on the elastic modulus of the material under tension[21–23] because the maximum load is concentrated on the bottom surface of the sample. Therefore, a higher flexural strength was achieved when zirconia was under tension. Nevertheless, there were two distinct failure modes according to the test configurations. When porcelain was under tension (PT), flaws initiated in the bottom surface and propagated throughout the porcelain until they reached the interface. At this moment, the tests were stopped and the zirconia layer was not impaired. When the zirconia was under tension (ZT), the porcelain delaminated before the fracture of the zirconia due to lateral flaw formation and the crushing of the loading area on the porcelain.[20,25]

The flexural strength values of ZT specimens are lower compared to the published values for zirconia monolayer specimens[12,20,24,26,27] because the compression stress induces failure of the porcelain before the zirconia under tension. Nevertheless, the ZT test configuration was performed because it is believed that failures originate at the internal surfaces of crowns.[19,24,27] To decrease the failure rate, studies[20,24] have suggested that the areas of restorations or fixed partial dentures that are submitted to a high concentration of tensile stress where esthetics is not needed (such as the bottom of the pontic and connectors) should be free of the veneered layer to increase the mechanical performance. However, zirconia is susceptible to degradation at low temperatures when exposed to a humid environment.[28]

Special attention should be paid to the great variability of cooling methods that are described in the literature with no standardization[3,6,7,11,13–18] (Table 3). These differences lead to difficulties in comparing results and do not allow a consensual conclusion for which cooling method must be used. For example, some studies refer to a specific method as "slow," but this method is actually similar to normal in our and other studies. Furthermore, porcelain manufacturers are unclear about the ideal cooling method, referring only to "slow." In our study, extreme cooling protocols (fast and slow) were performed to identify the changes in the properties of veneer and zirconia bilayer specimens. In the fast method, the specimens were cooled by blasting compressed air immediately after the holding time of sintering, that is, from 910 °C to room temperature in less than 10 s. In the slow-cooling method, the specimens were left inside the switched-off furnace for more than 8 h.

The null hypothesis that the flexural strength and reliability would not be influenced by the cooling method was partially rejected. The higher flexural strength observed for PT-FAST may be related to the tempering of the porcelain due to a high cooling rate and a large difference in the thermal gradient. This may induce a non-uniform solidification from the surface to the center, leading to residual compressive stress on the veneer surface[5,6,29,30] and increasing the strength.[4,6] On the other hand, in this study, it was observed that the PT-NORMAL showed a slightly higher Weibull modulus (m). The clinical success of ceramic restorations depends on the structural reliability of the dental ceramics. Higher Weibull modulus (m) values represent a more homogenous distribution of flaws, a lower dispersion of values, and a higher reliability of the material.[19,24,27] In this study, in spite of the fact that the PT-FAST group exhibited a higher flexural strength, this group presented higher dispersion values and, consequently, lower reliability. This might be related to the possible increase in the incidence of cracks when fast cooling is performed. Guazzato et al.[7] observed an increase in the crack rate in porcelain cooled with a fast cooling rate, which affected adversely its strength, despite their cooling method had not been as extreme as the fast method employed in our study (Table 3). Moreover, Belli et al.[31] performed cyclic fatigue test on pre-molar crowns submitted to fast and slow cooling and observed that cracks on VM9

Table 3 – Comparison among studies that evaluated different cooling methods in porcelain/zirconia specimens.

Authors (year)	Design of specimens (v:c thickness ratio)	Cooling method	Classified	Compared to our study
Taskonak et al. (2008)[13]	Bilayer disks (6:10)	Immediate	Fast	Fast
	Monolayer disks	Inside the furnace	Slow	Slow
Zhang et al. (2009)[11]	Monolayer disks	Inside the furnace	Slow	Slow
	Bilayer plates (6:1)	In ambient air at room temperature	Normal	Normal
		Tempered by blasting compressed air	Fast	Fast
Gostemeyer et al. (2010)[6]	Bilayer rectangular plate (1:1)	Inside the furnace for 5 min	Slow	Normal?
		Immediately in ambient air	Rapid	?
Guazzato et al. (2010)[7]	Bilayer spheres (1:2; 1:1)	Immediately moved to the furnace bench	Fast	?
		According to the manufacturer's recommendations	Normal	?
Komine et al. (2010)[3]	Bilayer disks	Outside the furnace for 4 min until reaching Tg	Slow	Normal
		Immediately in ambient air	Rapid	?
Rues et al. (2010)[15]	Central incisor crowns	Conventional firing	Protocol 1	Normal?
		Extra cooling time of 6 min after glaze firing	Protocol 2	?
		Extra cooling time of 6 min after all firings	Protocol 3	?
Choi et al. (2011)[16]	Bilayer plate (1:1; 2:1)	Force cooled with compressed air	Fast	Fast
	Porcelain Monolayer plate	Removed when the temperature of furnace dropped	Normal	Normal
		Stopped the descent of the muffle and waited until 100 ◦C.	Slow	Slow
Mainjot et al. (2011)[17]	Bilayer disks (2:1)	Opened furnace	Classic	Normal
		Inside the switched-off furnace from 900 °C to 600 °C	Modified	Slow
		At a rate of 2 °C/min in special furnace	Slow	?
Tholey et al. (2011)[14]	Crowns with uniform and anatomical frameworks	Inside the furnace until 600 °C	Slow	?
		Opened the chamber directly and switched off the furnace	Fast	Normal?
Tan et al. (2012)[18]	Beam of zirconia with porcelain button (3:1)	Removed as soon as the muffle had fully descended	Fast	?
		Left in the muffle for 7.5 min until reaching 500 °C	Moderate	Normal
		Left in the partially (30%) open muffle for 15 min until reaching a muffle temperature of 500 °C.	Slow	?
Belli et al.[31]	Premolar crowns	Immediately in ambient air	Fast	?
		Left in the partially (10%) open muffle until reaching a muffle temperature of 200 °C.	Slow	?

specimens grew less under slow regimen and it increased the lifetime of zirconia–porcelain prostheses.

Despite the statistical similarities among the flexural strength values of the ZT configuration groups according to the different methods, ZT-NORMAL exhibited a higher m value than ZT-SLOW and ZT-FAST. Although the strength value is important, it may not be extrapolated to predict the structural performance of the ceramic.

Chipping and delaminating of porcelain in zirconia-based restorations has occurred clinically, and these processes are considered to be the most common clinical failures.[8,9] The bond strength may be explained by the inherent fragility of the interface between the core and veneer, or it may be simply due to the weak strength of the porcelain layer and can be influenced by the materials,[3,6] surface treatments of zirconia[32], cooling rate after sintering[3,6,14] or bond strength tests.[3,6,14] In this study, fast and normal cooling methods led to significantly higher SBS values and showed predominantly adhesive failure mode between VM9 porcelain and zirconia. These results may be attributed to compressive/tempering stresses in the porcelain layer under faster cooling, which can improve the resistance of the surface layer[6] and to develop high residual tension on the zirconia/porcelain interface,[5,7,14] which led to the predominance of adhesive failure mode. In contrast, the slow cooling method had lower SBS value and higher incidence of cohesive and combination failure modes. However, a direct comparison to other studies is difficult once, to the authors' knowledge, there is any published bond strength investigation that used slow cooling method comparable to that used in this study. The cohesive failure mode is more related to porcelain strength than to its adhesion to the zirconia core.[1] In slower cooling regimen, the tempering does not occur because tensile stresses are generated in the porcelain due to structural relaxation of the glass above and around the Tg.[5,6,13,29] Moreover, as discussed before, PT-SLOW group in flexural strength test showed lower mean value than PT-FAST. It is possible that porcelain in slow cooling method had resistance below than that for the adhesion between veneer and zirconia.

Komine et al.[3] observed that depending on porcelain material, slow cooling increased the SBS between veneer and zirconia, and all specimens showed cohesive fracture, however they used other porcelain brand marks (CZR and e.Max Ceram), the surface of zirconia specimens was air-blasted with Al_2O_3 and the slow cooling used was similar to our normal cooling (Table 3). Despite Gostemeyer et al.[6] also had observed the dependence on porcelain material, they showed that slow cooling method (similar to our normal cooling – Table 3) adversely affected the strain energy release in four-point bending test and prevailed the combination fracture mode for VM9 and Triceram but there were no effect of cooling methods on Zirox and Lava Ceram. Tan et al.,[14] using modified four-point flexural technique with VM9 porcelain button under beams of zirconia, observed that slow cooling (intermediary to our normal and slow cooling method) increased the fracture load and the visual fracture analysis owed a thin layer of porcelain on the zirconia, classified as cohesive mode.

Nevertheless, no direct clinical correlation should be made between failures in shear bond studies with the failure mechanisms of restorations because the testing methods do not reproduce clinical conditions.[33] Ideally, long-term clinical trials should be used to determine the failure mechanisms for all-ceramic restorations. Moreover, while a fracture bond strength value higher than 25 MPa is accepted as adequate for metal–ceramics, the acceptable bond strength for all-ceramic materials has not yet been determined.[34] Moreover, the bonding mechanisms between zirconia and porcelain are unclear.[2,12] Surface treatments seem to damage the structure of zirconia due to its martensitic transformation from the tetragonal to monoclinic phase.[26,28] Some porcelain brands require a surface liner before porcelain application; the porcelain samples used in this study necessitated a washbake layer. Thus, the effects of chemical bonding and micromechanical retention, as well as the improvement of the wettability of zirconia, are active areas of research.

While a fracture bond strength value higher than 25 MPa is accepted as adequate for metal–ceramics, the acceptable bond strength for all-ceramic materials has not yet been determined.[34] Moreover, the bonding mechanisms between zirconia and porcelain are unclear.[2,12] Surface treatments seem to damage the structure of zirconia due to its martensitic transformation from the tetragonal to monoclinic phase.[26,28] Some porcelain brands require a surface liner before porcelain application; the porcelain samples used in this study necessitated a washbake layer. Thus, the effects of chemical bonding and micromechanical retention, as well as the improvement of the wettability of zirconia, are active areas of research.

This study has some limitations that make it difficult to directly relate its results to clinical situations. The temperature distribution of specimens is complex and depends on the thermal proprieties of the materials, the cooling rate, the gradient and distribution of temperature, the support of the materials inside the oven, and the thickness, preparation and design.[5,14,30] In this study, plate specimens were used to investigate the effect of extreme cooling methods under controlled conditions for the mechanical tests.[35] However, the geometry of dental crowns and FPDs is multifaceted, with a sphero-cylindrical form, heterogeneous contours and variations in the thickness of the veneer and core.[1,2,5,10,36] Furthermore, the microstructure of porcelain, the thickness ratio, the manufacturing process, the flaw population (number, distribution, and size), the occlusal adjustment, moisture, thermal and load cycling, and individual habits also have influences on the fracture resistance of the veneering porcelain and its clinical reliability.[15,24,27,36] Therefore, in vitro thermal, chemical and mechanical fatigue studies should be conducted using complex specimens as crowns, which are submitted to various cooling methods with different zirconia ceramic/veneering porcelain systems; the thickness ratio in humid environments should also be further studied. Moreover, more randomized clinical trials are necessary to evaluate the actual performance of this zirconia-based method of restoration.[9]

5. Conclusion

The fast-cooling method showed a higher flexural strength but a lower reliability in porcelain under tension test configurations. The slow-cooling method decreased the shear bond strength and showed higher cohesive and combination failure modes. These results suggest that the cooling method may affect the longevity of zirconia-based restorations. Thus, other investigations are needed to establish the ideal cooling protocol.

REFERENCES

1. Fischer J, Stawarzcyk B, Trottmann A, Hammerle CH. Impact of thermal misfit on shear strength of veneering ceramic/zirconia composites. *Dental Materials* 2009;**25**:419–23.
2. Saito A, Komine F, Blatz MB, Matsumura H. A comparison of bond strength of layered veneering porcelains to zirconia and metal. *Journal of Prosthetic Dentistry* 2010;**104**:247–57.
3. Komine F, Saito A, Kobayashi K, Koizuka M, Koizumi H, Matsumura H. Effect of cooling rate on shear bond strength of veneering porcelain to a zirconia ceramic material. *Journal of Oral Science* 2010;**52**:647–52.
4. Taskonak B, Mecholsky Jr JJ, Anusavice KJ. Residual stresses in bilayer dental ceramics. *Biomaterials* 2005;**26**:3235–41.
5. Swain MV. Unstable cracking (chipping) of veneering porcelain on all-ceramic dental crowns and fixed partial dentures. *Acta Biomaterialia* 2009;**5**:1668–77.
6. Gostemeyer G, Jendras M, Dittmer MP, Bach FW, Stiesch M, Kohorst P. Influence of cooling rate on zirconia/veneer interfacial adhesion. *Acta Biomaterialia* 2010;**6**:4532–8.
7. Guazzato M, Walton TR, Franklin W, Davis G, Bohl C, Klineberg I. Influence of thickness and cooling rate on development of spontaneous cracks in porcelain/zirconia structures. *Australian Dental Journal* 2010;**55**:306–10.
8. Sailer I, Pjetursson BE, Zwahlen M, Hammerle CH. A systematic review of the survival and complication rates of all-ceramic and metal-ceramic reconstructions after an observation period of at least 3 years. Part II: fixed dental prostheses. *Clinical Oral Implants Research* 2007;**18**:86–96.
9. Raigrodski AJ, Hillstead MB, Meng GK, Chung KH. Survival and complications of zirconia-based fixed dental prostheses: a systematic review. *Journal of Prosthetic Dentistry* 2012;**107**:170–7.

10. Fairhurst CW, Hashinger DT, Twiggs SW. Glass transition temperatures of dental porcelain. *Journal Dental Research* 1981;**60**:995–8.
11. Zhang Z, Li Q, Li W, Swain M. Transient modelling of thermal processing for ceramic prostheses. *Journal of Australian Ceramic Society* 2009;**45**:40–8.
12. Guess PC, Kulis A, Witkowski S, Wolkewitz M, Zhang Y, Strub JR. Shear bond strengths between different zirconia cores and veneering ceramics and their susceptibility to thermocycling. *Dental Materials* 2008;**24**:1556–67.
13. Taskonak B, Borges GA, Mecholsky Jr JJ, Anusavice KJ, Moore BK, Yan J. The effects of viscoelastic parameters on residual stress development in a zirconia/glass bilayer dental ceramic. *Dental Materials* 2008;**24**:1149–55.
14. Tholey MJ, Swain MV, Thiel N. Thermal gradients and residual stresses in veneered Y-TZP frameworks. *Dental Materials* 2011;**27**:1102–10.
15. Rues S, Kroger E, Muller D, Schmitter M. Effect of firing protocols on cohesive failure of all-ceramic crowns. *Journal of Dentistry* 2010;**38**:987–94.
16. Choi JE, Waddell JN, Swain MV. Pressed ceramics onto zirconia part 2: indentation fracture and influence of cooling rate on residual stresses. *Dental Materials* 2011;**27**:1111–8.
17. Mainjot AK, Schajer GS, Vanheusden AJ, Sadoun MJ. Influence of cooling rate on residual stress profile in veneering ceramic: Measurement by hole-drilling. *Dental Materials* 2011;**27**:906–14.
18. Tan JP, Sederstrom D, Polansky JR, McLaren EA, White SN. The use of slow heating and slow cooling regimens to strengthen porcelain fused to zirconia. *Journal of Prosthetic Dentistry* 2012;**107**:163–9.
19. Della Bona A, Anusavice KJ, DeHoff PH. Weibull analysis and flexural strength of hot-pressed core and veneered ceramic structures. *Dental Materials* 2003;**19**:662–9.
20. Borba M, de Araujo MD, de Lima E, Yoshimura HN, Cesar PF, Griggs JA, *et al.* Flexural strength and failure modes of layered ceramic structures. *Dental Materials* 2011;**27**:1259–66.
21. Kelly JR, Perspectives on strength. *Dental Materials* 1995;**11**:103–10.
22. Fleming GJ, El-Lakwah SF, Harris JJ, Marquis PM. The effect of core:dentin thickness ratio on the bi-axial flexure strength and fracture mode and origin of bilayered dental ceramic composites. *Dental Materials* 2005;**21**:164–71.
23. Zeng K, Oden A, Rowcliffe D. Evaluation of mechanical properties of dental ceramic core materials in combination with porcelains. *International Journal of Prosthodontics* 1998;**11**:183–9.
24. Yilmaz H, Nemli SK, Aydin C, Bal BT, Tiras T. Effect of fatigue on biaxial flexural strength of bilayered porcelain/zirconia (Y-TZP) dental ceramics. *Dental Materials* 2011;**27**:786–95.
25. Guazzato M, Albakry M, Ringer SP, Swain MV. Strength, fracture toughness and microstructure of a selection of all-ceramic materials Part II. Zirconia-based dental ceramics. *Dental Materials* 2004;**20**:449–56.
26. Kosmac T, Oblak C, Jevnikar P, Funduk N, Marion L. The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic. *Dental Materials* 1999;**15**:426–33.
27. Lin WS, Ercoli C, Feng C, Morton D. The effect of core material, veneering porcelain, and fabrication technique on the biaxial flexural strength and weibull analysis of selected dental ceramics. *Journal of Prosthodontics* 2012.
28. Cattani-Lorente M, Scherrer SS, Ammann P, Jobin M, Wiskott HW. Low temperature degradation of a Y-TZP dental ceramic. *Acta Biomaterialia* 2011;**7**:858–65.
29. DeHoff PH, Anusavice KJ, Vontivillu SB. Analysis of tempering stresses in metal–ceramic disks. *Journal of Dental Reseaarch* 1996;**75**:743–51.
30. Mainjot AK, Schajer GS, Vanheusden AJ, Sadoun MJ. Influence of zirconia framework thickness on residual stress profile in veneering ceramic: Measurement by hole-drilling. *Dental Materials* 2012;**28**:378–84.
31. Belli R, Frankenberger R, Appelt A, Schmitt J, Baratieri LN, Greil P, *et al.* Thermal-induced residual stresses affect the lifetime of zirconia–veneer crowns. *Dental Materials* 2012.
32. Aboushelib MN, Kleverlaan CJ, Feilzer AJ. Effect of zirconia type on its bond strength with different veneer ceramics. *Journal of Prosthodontics* 2008;**17**:401–8.
33. Kelly JR. Clinically relevant approach to failure testing of all-ceramic restorations. *Journal of Prosthetic Dentistry* 1999;**81**:652–61.
34. Al-Dohan HM, Yaman P, Dennison JB, Razzoog ME, Lang BR. Shear strength of core-veneer interface in bi-layered ceramics. *Journal of Prosthetic Dentistry* 2004;**91**:349–55.
35. Aboushelib MN, de Jager N, Kleverlaan CJ, Feilzer AJ. Effect of loading method on the fracture mechanics of two layered all-ceramic restorative systems. *Dental Materials* 2007;**23**:952–9.
36. DeHoff PH, Anusavice KJ. Viscoelastic finite element stress analysis of the thermal compatibility of dental bilayer ceramic systems. *International Journal of Prosthodontics* 2009;**22**:56–61.