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The Effect of Core Material, Veneering Porcelain, and Fabrication Technique on the Biaxial Flexural Strength and Weibull Analysis of Selected Dental Ceramics

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Abstract

Purpose: The objective of this study was to compare the effect of veneering porcelain (monolithic or bilayer specimens) and core fabrication technique (heat-pressed or CAD/CAM) on the biaxial flexural strength and Weibull modulus of leucite-reinforced and lithium-disilicate glass ceramics. In addition, the effect of veneering technique (heat-pressed or powder/liquid layering) for zirconia ceramics on the biaxial flexural strength and Weibull modulus was studied.

Materials and Methods: Five ceramic core materials (IPS Empress Esthetic, IPS Empress CAD, IPS e.max Press, IPS e.max CAD, IPS e.max ZirCAD) and three corresponding veneering porcelains (IPS Empress Esthetic Veneer, IPS e.max Ceram, IPS e.max ZirPress) were selected for this study. Each core material group contained three subgroups based on the core material thickness and the presence of corresponding veneering porcelain as follows: 1.5 mm core material only (subgroup 1.5C), 0.8 mm core material only (subgroup 0.8C), and 1.5 mm core/veneer group: 0.8 mm core with 0.7 mm corresponding veneering porcelain with a powder/liquid layering technique (subgroup 0.8C-0.7VL). The ZirCAD group had one additional 1.5 mm core/veneer subgroup with 0.7 mm heat-pressed veneering porcelain (subgroup 0.8C-0.7VP). The biaxial flexural strengths were compared for each subgroup ($n = 10$) according to ISO standard 6872:2008 with ANOVA and Tukey's post hoc multiple comparison test ($p \leq 0.05$). The reliability of strength was analyzed with the Weibull distribution.

Results: For all core materials, the 1.5 mm core/veneer subgroups (0.8C-0.7VL, 0.8C-0.7VP) had significantly lower mean biaxial flexural strengths ($p < 0.0001$) than the other two subgroups (subgroups 1.5C and 0.8C). For the ZirCAD group, the 0.8C-0.7VL subgroup had significantly lower flexural strength ($p = 0.004$) than subgroup 0.8C-0.7VP. Nonetheless, both veneered ZirCAD groups showed greater flexural strength than the monolithic Empress and e.max groups, regardless of core thickness and fabrication techniques. Comparing fabrication techniques, Empress Esthetic/CAD, e.max Press/CAD had similar biaxial flexural strength ($p = 0.28$ for Empress pair; $p = 0.87$ for e.max pair); however, e.max CAD/Press groups had significantly higher flexural strength ($p < 0.0001$) than Empress Esthetic/CAD groups. Monolithic core specimens presented with higher Weibull modulus with all selected core materials. For the ZirCAD group, although the bilayer 0.8C-0.7VL subgroup exhibited significantly lower flexural strength, it had highest Weibull modulus than the 0.8C-0.7VP subgroup.

Conclusions: The present study suggests that veneering porcelain onto a ceramic core material diminishes the flexural strength and the reliability of the bilayer specimens. Leucite-reinforced glass-ceramic cores have lower flexural strength than lithium-disilicate ones, while fabrication techniques (heat-pressed or CAD/CAM) and specimen thicknesses do not affect the flexural strength of all glass ceramics. Compared with the heat-pressed veneering technique, the powder/liquid veneering technique exhibited lower flexural strength but increased reliability with a higher Weibull modulus for zirconia bilayer specimens. Zirconia-veneered ceramics exhibited greater flexural strength than monolithic leucite-reinforced and lithium-disilicate ceramics regardless of zirconia veneering techniques (heat-pressed or powder/liquid technique).

In recent years, several all-ceramic core materials have been developed in an attempt to increase their toughness while maintaining adequate esthetics.[1] The most commonly used systems can be classified according to the laboratory procedure used to obtain the core or restoration (pressable, slipcasting, milling, or sintering) and chemical composition (feldspar: High leucite and low leucite; glass ceramic: lithium disilicate and mica; core reinforced: alumina, magnesia, and zirconia).[2-4] For the leucite-reinforced and lithium-disilicate glass ceramic, in addition to the traditional heat-pressed technique, CAD/CAM fabrication techniques are available in today's market.[5] With similar material composition, the fabrication technique may have an effect on the mechanical properties. For example, glass-infiltrated zirconia-reinforced ceramics for the CAD/CAM technique were shown to have better mechanical properties due to more consistent processing and less porosity compared to the slip-cast technique.[6] Conversely, one study reported the opposite results with the same ceramic material. A more standardized processing does not necessarily mean better mechanical properties as previously hypothesized.[7] Based on these findings, the effect of different fabrication techniques for the strength of all-ceramic restorations still remains unclear.

Porcelain-veneered core prostheses have been used for several applications (anterior and posterior restorations), and these combine the strength and toughness of ceramic cores with the esthetics of the veneering porcelains.[8,9] Although the mechanical characteristics of core materials have continuously been improved (i.e., increased toughness), veneering material mechanical properties have largely remained unchanged.[10] For porcelain-veneered zirconia prostheses, bulk fracture of the zirconia framework appears to be quite uncommon, and the most commonly reported complication is chipping or cracking limited to the porcelain veneer.[11-13] A recent 4-year clinical study with a sample size of 99 showed that Cercon base zirconia 3- to 4-unit FPDs demonstrated a 13% porcelain fracture rate during the follow-up period; however, the zirconia framework fracture rate was only 1%.[13] It is therefore uncertain whether enhanced mechanical properties of the core material would necessarily result in an overall enhanced clinical performance of ceramic core/veneering ceramic systems.[9] Indeed, studies have shown that a thin layer of veneering porcelain fired onto a ceramic core material significantly diminishes the strength of the bilayer specimens.[9,14] Although one in vitro study concluded that the critical load for radial fracture is strongly influenced by the total crown thickness (quadratically) and is much less dependent on the relative veneer/core ceramic layer thickness, particularly when the veneer/core thickness ratio is 1, the veneering porcelain is still likely to be the weakest link, compromising the strength of the entire bilayer system.[15]

Dental ceramics are brittle materials and sensitive to tensile stress. Different test methods have been established to evaluate the mechanical properties of ceramics.[2,14,16-42,44-46] Test designs for mechanical properties of monolithic specimens and bond strength of bilayer specimens can be based on three-point flexural test (nonuniform central stress field), four-point flexural test (uniform central stress field), biaxial flexural test (reduced edge failures associated with the previous two test designs), microtensile test (not adaptable to metal ceramic or ceramic-ceramic structures), shear bond test (associated with inconsistent location of crack initiation), fatigue test (aging or thermocycling), and interfacial fracture toughness test. Each of these tests has advantages and limitations, and the methods of reporting results have led to a great deal of confusion on how these results should be interpreted.[45-49] The standard for testing the strength of dental ceramics has been the three-point flexural test, but one problem has been the sensitivity of the test to flaws along the specimen edges.[18] The three-point bending test is largely dependent on the surface finish of the edges of the specimen. Therefore, the measurement of strength of brittle materials under biaxial flexural conditions rather than uniaxial flexural is often considered more reliable, because the maximum tensile stresses occur within the central loading area, and spurious edge failures are eliminated. This allows slightly warped specimens to be tested and produces results unaffected by the edge condition of the specimen. The biaxial flexural test should produce less variation in data for strength determination.[2,16,25-37] The failure stresses of brittle materials are statistically distributed as a function of the flaw size distribution in the material.[16] The variability of the strength and, consequently, the homogeneity of the materials, can then be appraised through a calculation of the Weibull modulus (m), which is related to the flaw size distribution.[32,35-37]

The purposes of this study were to compare the effect of veneering porcelain (monolithic or bilayer specimens), and core fabrication techniques (heat-pressed or CAD/CAM) on the biaxial flexural strength and Weibull modulus of leucite-reinforced and lithium-disilicate glass ceramics. In addition, the effect of veneering techniques (heat-pressed or powder/liquid layering) for zirconia ceramics on the biaxial flexural strength and Weibull modulus is to be studied. The hypotheses tested were that veneering porcelain has an adverse effect on the biaxial strength of ceramics; on the other hand, core fabrication techniques and porcelain veneering techniques have no effect on the biaxial strength of ceramics.

Materials and methods

Five all-ceramic core materials (IPS Empress Esthetic, IPS Empress CAD, IPS e.max Press, IPS e.max CAD, IPS e.max ZirCAD) and three corresponding veneering porcelains (IPS Empress Esthetic Veneer, IPS e.max Ceram, IPS e.max ZirPress) were selected for this study (Table 1). Each core material group contained three subgroups based on the core material thickness and the presence of corresponding veneering porcelain as follows: 1.5 mm core material only (subgroup 1.5C), 0.8 mm core material only (subgroup 0.8C), and 1.5 mm core/veneer group: 0.8 mm core material with 0.7 mm corresponding veneering porcelain with the powder/liquid layering technique (subgroup 0.8C-0.7VL). The ZirCAD group had one additional 1.5 mm core/veneer subgroup with 0.7 mm heat-pressed veneering porcelain (subgroup 0.8C-0.7VP) (Fig 1). For each subgroup ($n = 10$), the biaxial flexural strength, according to ISO standard 6872,[41] was compared with two-way ANOVA and Tukey's post hoc multiple comparison method. The two-sample t-test was used to compare the 0.8C-0.7VP subgroup and 0.8C-0.7VL subgroup for the ZirCAD group. The level of statistical significance was set at 0.05. All statistical analyses were implemented with SAS 9.2 (SAS Institute Inc, Cary, NC).

Table 1 Materials used for core and veneering porcelain

Product	Material/technique	Manufacturer	Batch number
IPS Empress Esthetic	Heat-pressed; leucite-reinforced glass ceramic	Ivoclar Vivadent, Schaan, Lichtenstein	F41198
IPS Empress CAD	CAD/CAM; leucite-reinforced glass ceramic	Ivoclar Vivadent, Schaan, Lichtenstein	L35873
IPS e.max Press	Heat-pressed; lithium disilicate glass-ceramic	Ivoclar Vivadent, Schaan, Lichtenstein	K03585
IPS e.max CAD	CAD/CAM; lithium disilicate glass-ceramic	Ivoclar Vivadent, Schaan, Lichtenstein	K11234
IPS e.max ZirCAD	CAD/CAM; Yttrium-stabilized zirconia ceramic	Ivoclar Vivadent, Schaan, Lichtenstein	K30504
IPS e.max Ceram	Veneering porcelain; low-fusing nano-fluorapatite glass-ceramic	Ivoclar Vivadent, Schaan, Lichtenstein	L24237
IPS Empress Esthetic Veneer	Veneering porcelain; feldspathic porcelain	Ivoclar Vivadent, Schaan, Lichtenstein	G06939
IPS e.max ZirPress	Heat-pressed fluorapatite glass-ceramic ingots	Ivoclar Vivadent, Schaan, Lichtenstein	J14729

Preparation of the core only specimens (subgroups 0.8C and 1.5C)

Twenty disk-shaped specimens for each core material (five groups of 20; N = 100) with a 12.5 mm diameter were prepared according to ISO specification 6872 and divided into two subgroups (n = 10), 1.5 mm and 0.8 mm in thickness. For the heat-pressed groups (IPS Empress Esthetic and IPS e.max Press), pressing was done according to manufacturer's recommendations. The IPS Empress Esthetic group was pressed under 1075°C for 20 minutes. The IPS e.max Press group was pressed under 915°C for 15 minutes. The investment was removed from the disks with an air particle abrasion unit with 50 μm glass beads at a pressure of 4 bar for the initial divestment and 2 bar for the final divestment. The reaction layer formed during the pressing procedure on the IPS e.max press specimens was removed by immersing the specimens in the HF solution (IPS e.max Press Invex Liquid, Ivoclar Vivadent) for 20 minutes followed by Al_2O_3 air particle abrading under 2 bar pressure. For the IPS Empress CAD, IPS e.max CAD, and IPS e.max ZirCAD groups, the wax disks (12.5 mm diameter, 1 and 1.7 mm thick) were fabricated with casting wax (Corning Waxes, Ronkonkoma, NY). The wax disks were then sprayed with contrast spray (IPS Contrast Spray, Ivoclar Vivadent) and scanned with a CAD/CAM system (Sirona inLab, Sirona Dental Systems, Inc. Charlotte, NC). The data thus obtained were used to produce the ceramic core specimens with the CAD/CAM system (Sirona inLab) (Fig 2). For the IPS e.max ZirCAD groups, the specimens were dried prior to the sintering procedure. Based on the manufacture's recommendation, moist IPS e.max ZirCAD frameworks must not be sintered. Therefore, the specimens were stored at room temperature for 1 week to allow complete dryness of all IPS e.max ZirCAD core specimens. Once the specimens were completely dry, the sintering procedure was conducted at a temperature of 1500°C. All specimens were then serially wet ground with 220, 320, 500, 600, and 800 grit silicon carbide papers (Metlab Corp., Niagara Falls, Canada) to the definitive dimensions of 12.5 × 1.5 mm^2 and 12.5 × 0.8 mm^2 for each group. The crystallization for IPS e.max CAD specimens was done according to manufacturer recommendations without application of any glaze materials. The speed crystallization cycle was used, and specimens were crystallized under 840°C holding temperature for 7 minutes.

Finally, all IPS Empress CAD and IPS e.max CAD specimens were refired in a porcelain furnace (Programat P300; Ivoclar Vivadent) according to the manufacturer's recommended glazing cycles (840°C holding temperature 3 minutes) to simulate laboratory procedures and release stresses associated with the grinding and polishing procedures. For the IPS e.max ZirCAD groups, specimens were fired under a regeneration firing cycle to reverse changes in the sintered zirconia according to manufacturer's recommendation (at a 1050°C holding temperature for 15 minutes).

Preparation of the core-veneered specimens (subgroups 0.8C-0.7VL, 0.8C-0.7VP)

Ten disk-shaped specimens for all five core materials (n = 50) were assigned to subgroup 0.8C-0.7VL (veneering porcelain with powder/liquid layering technique), and 10 additional specimens for zirconia ceramic core material (IPS e.max ZirCAD) were assigned to subgroup 0.8C-0.7VP (veneering porcelain with heat-pressed layering technique). All disk specimens (12.5 mm diameter, 0.8 mm thick) were prepared according to the manufacturer's recommendations and fabrication procedure. After all specimens were serially wet ground with 220, 320, 500, 600, and 800 grit silicon carbide papers (Metlab Corporation) to the definitive dimensions of 12.5 × 0.8 mm^2, the sides of the specimens to be veneered were further manually ground with a fine-grit round-end tapered diamond bur (854R, Brasseler, Savannah, GA). After ultrasonic cleaning in acetone (Thomas Scientific, Swedesboro, NJ), the specimens were dried with a paper towel (Kimberley-Clark Global Sales, LLC, Neenah, WI). A thin layer of liner material (IPS e.max Ceram ZirLiner, [Ivoclar Vivadent]) was applied on all 20 zirconia ceramic disk specimens (IPS e.max ZirCAD) according the manufacturer's recommendations. For the 0.8C-0.7VL subgroup, 50 core specimens were individually seated in a vinyl(poly siloxane) (VPS) mold (Aquasil Ultra LV Fast Set, Dentsply Caulk, Milford, DE) with its depth adjusted to provide a 1.0 mm layer of porcelain veneering material. A compatible feldspathic veneering ceramic (IPS Empress Esthetic Veneer) was used as veneering material for leucite-reinforced glass ceramic (IPS Empress Esthetic and IPS Empress) and was fired at a 790°C holding temperature for 2 minutes for all corresponding specimens. Fluorapatite veneering ceramic

Figure 1 Each core material group contained three or four subgroups based on core material thickness and the presence of corresponding veneering porcelain. ZirCAD group had one additional subgroup with a different veneering technique.

(IPS e.max Ceram) was used as veneering material for the lithium-disilicate-reinforced glass ceramics (IPS e.max Press, IPS e.max CAD) and zirconia ceramic (IPS e.max ZirCAD), and was fired at a 790°C holding temperature for 2 minutes for all corresponding specimens. For all specimens, a thin wash layer of veneering porcelain was first applied and fired, followed by first and second dentin application and firing to achieve a porcelain thickness of 1.0 mm. For the first dentin layer

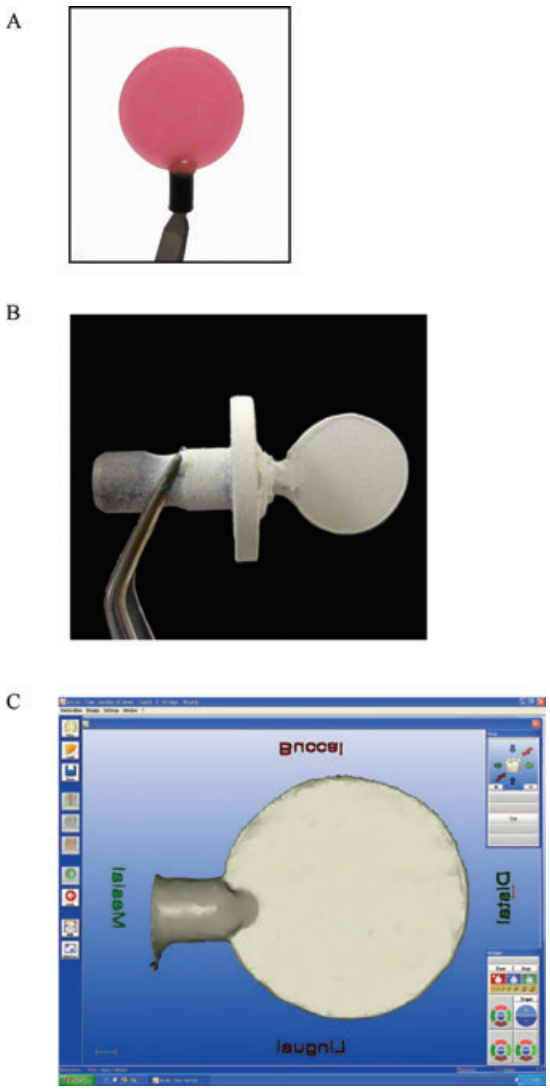

Figure 2 (A) Wax disks with a diameter of 12.5 mm, 1.0 mm and 1.8 mm thickness were fabricated with wax. (B) The wax disks were then sprayed with contrast spray and scanned with a CAD/CAM system. (C) The scan data were used to produce the ceramic core specimens.

application, porcelain powder/liquid mix was condensed with a flat-end dental spatula (Cement spatula standard flexible blade, Pearson Dental, Sylmar, CA) under hand pressure onto the core specimens, and excess moisture was removed by adapting facial tissue on the porcelain surface. The same procedure was repeated for the second dentin porcelain application. For the 0.8C-0.7VP subgroup, 10 zirconia ceramic specimens were individually seated in a VPS mold (Aquasil Ultra LV Fast Set) with its depth adjusted to provide a 1.0 mm layer of wax material (casting wax, Corning Waxes), and the specimens were sprued and invested according to manufacturer's recommendations. Heat-pressed fluorapatite glass-ceramic ingots (IPS e.max ZirPress) were then used for veneering porcelain and were pressed at a 900°C holding temperature for 15 minutes. All specimens were then serially wet ground to the definitive dimensions of

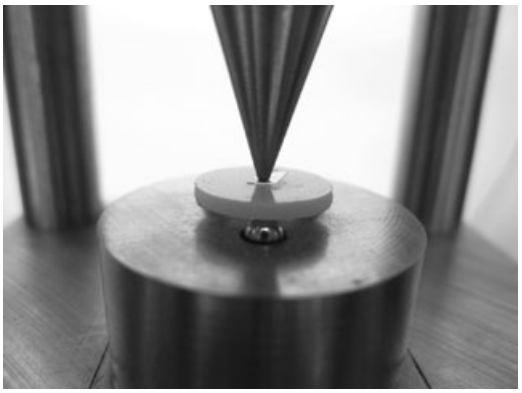

Figure 3 Biaxial flexural strength test on the Instron machine with specimen in place.

12.5 × 1.5 mm^2 and refired in a porcelain furnace (Programat P300) according to the manufacturer's recommended glazing cycles (750°C holding temperature, 1 minute).

Biaxial flexural strength test

Strength was measured with the biaxial flexural strength test (piston on three balls) following ISO standard 6872 for dental ceramics.[30,31,34,41] The parallelism and the flatness of opposing surfaces of each specimen were verified with a micrometer (Northeast Metrology Corp, Buffalo, NY) to a tolerance within ± 0.05 mm. The test was carried out using a universal testing machine (Instron, Norwood, MA) at a 0.5 mm/min crosshead speed until failure. A thin plastic sheet (0.05 mm thick) was placed between the piston (1.2 mm diameter) and the specimen to facilitate even load distribution and minimize stress concentration (Fig 3). Testing was performed at room conditions (22°C, 66% relative humidity). The load at fracture was recorded, and the biaxial flexural strength for each specimen was calculated with the following equation:

$$S = -0.2387P(X - Y)/d^2$$

where S is the maximum center tensile stress (MPa) (the flexural strength at fracture); P is the total load at fracture (N); and d is the thickness of the specimens. X and Y were determined as follows:

$$X = (1+\nu)\log\left(\frac{B}{C}\right)^2 + [(1-\nu)/2]\left(\frac{B}{C}\right)^2,$$
$$Y = (1+\nu)\left[1+\log\left(\frac{A}{C}\right)^2\right] + (1-\nu)\left(\frac{A}{C}\right)^2,$$

where ν is Poisson's ratio (if the value for the ceramic concerned is not known, Poisson's ratio of 0.25 is used); A is the radius of the support circle (5 mm); B is the radius of the tip of the piston (0.6 mm); and C is the radius of the specimen (6.25 mm). This equation assumes a uniform elastic modulus and Poisson's ratio throughout the entire disk, and for this reason, it could not be used in this form to calculate the BFS of the two-layer disks. Therefore, laminated plate theory was applied.[42] R is an equivalent radius determined as follows: $R = \sqrt{1.6B^2 + d^2} - 0.675d$, where B is the radius of the tip of the piston, and d is the thickness of specimens (1.5 mm). Maximum bending moment (M) was calculated as $M = \frac{W}{4\pi}[(1+\nu)\log\frac{A}{R} + 1]$, where W is

the load; R is the equivalent radius of loading; and A is the radius of the circle of support points.

$$K_{2p} = 1 + \frac{E_b t_b^3 (1 - \nu_a^2)}{E_a t_a^3 (1 - \nu_b^2)} + \frac{3(1 - \nu_a^2)\left(1 + \frac{t_b}{t_a}\right)^2 \left(1 + \frac{E_a t_a}{E_b t_b}\right)}{\left(1 + \frac{E_a t_a}{E_b t_b}\right)^2 - \left(\nu_a + \frac{\nu b E_a t_a}{E_b t_b}\right)^2}$$

where t_a and t_b are the thicknesses of the two material layers; material a is at the top, and material b is at the bottom. E_a and E_b are the Young's moduli of the two materials a and b, respectively. The Young's modulus for IPS Empress is 60, for IPS e.max is 95, for IPS ZirCAD is 210, for IPS empress Esthetic Veneer is 60, for IPS e.max Ceram is 60, and for IPS e.max ZirPress is 70. Poisson's ratio, v, is 0.25 for all materials. The biaxial flexural stress (σ) was then calculated as

$$\sigma = \frac{6M}{t_a^2 K_{2p}} \left[\frac{E_b t_b (1 - \nu_a^2)}{E_b t_b (1 - \nu_a^2)} + \frac{t_a (1 - \nu_a^2)\left(1 + \frac{t_b}{t_a}\right)\left(1 + \frac{E_a t_a}{E_b t_b}\right)}{t_b \left(1 + \frac{E_a t_a}{E_b t_b}\right)^2 - \left(\nu_a \frac{E_a t_a}{E_b t_b}\right)^2} \right]$$

Mean values for biaxial flexural strength were analyzed by two-way ANOVA, with strength as the dependent variable. The material (IPS Empress Esthetic, IPS Empress CAD, IPS e.max Press, IPS e.max CAD, ZirCAD) was the first between-subjects factor, and the thickness (1.5 mm core material, 0.8 mm core material, 1.5 mm core/veneer material) was the second. For all analyses, the results were considered significant for $p \leq 0.05$. Tukey's multiple comparison method was used to look for specific differences between pairs of groups.

Weibull modulus

Strength variation among each group was evaluated by calculating the Weibull modulus (m). A computer was used to rank the biaxial strength data in ascending order and appoint a rank over the range 1 to N (N is the number of specimens). A straight line was then fitted through the points using the median rank regression method. The following equation was used to calculate the Weibull modulus:[2,24,27,32]

$$P(\sigma) = 1 - \exp(-\sigma/\sigma_0)^m$$

where $P(\sigma)$ is the fracture probability; σ is the fracture strength at a given $P(\sigma)$; σ_o is the characteristic strength; and m is the Weibull modulus, which is the slope of the ln (ln 1/1-P) versus in σ plots.

Results

The results of the biaxial flexural strength tests are listed in Table 2. For all core materials, the 1.5 mm core/veneer subgroups (0.8C-0.7VL, 0.8C-0.7VP) had significantly lower mean biaxial flexural strength ($p < 0.0001$) than the other two subgroups (subgroups 1.5C and 0.8C). For ZirCAD groups, the 0.8C-0.7VL subgroup had significantly lower flexural strength ($p = 0.004$) than subgroup 0.8C-0.7VP. Nonetheless, both veneered ZirCAD groups showed greater flexural strength than the monolithic Empress and e.max groups, regardless of core thickness and fabrication techniques. Comparing fabrication techniques, Empress Esthetic and Empress CAD, e.max CAD and e.max Press had similar biaxial flexural strength ($p = 0.28$ for Empress pair; $p = 0.87$ for e.max pair); however, e.max CAD-Press groups had significantly higher flexural strength ($p < 0.0001$) than Empress Esthetic-CAD groups. Also, no difference in flexural strength was seen between the monolithic ceramics regardless of the material thickness (1.5 vs. 0.8 mm).

The Weibull statistical analysis of the biaxial flexural strength data is summarized in Table 3. Higher Weibull modulus values were obtained for monolithic core specimens with the all selected core materials. For the ZirCAD group, the bilayer 0.8C-0.7VL subgroup exhibited higher Weibull modulus than the 0.8C-0.7VP subgroup.

Table 2 Biaxial flexural strength

		Flexural strength (MPa)		
Core material	Subgroup	N	Mean	SD
IPS Empress Esthetic	1.5C[1]	10	142.77	31.09
	0.8C[1]	10	155.97	19.38
	0.8C-0.7VL[3]	10	119.28	26.23
IPS Empress CAD	1.5C[1]	10	163.95	30.13
	0.8C[1]	10	157.60	11.01
	0.8C-0.7VL[3]	10	135.29	22.10
IPS e.max Press	1.5C[2]	10	330.44	19.02
	0.8C[2]	10	355.17	36.38
	0.8C-0.7VL[4]	10	262.31	30.39
IPS e.max CAD	1.5C[2]	10	365.06	45.91
	0.8C[2]	10	367.90	37.76
	0.8C-0.7VL[4]	10	236.56	34.12
IPS e.max ZirCAD	1.5C[5]	10	1039.71	32.04
	0.8C[5]	10	1066.59	52.11
	0.8C-0.7VL[6]	10	628.79	28.35
	0.8C-0.7VP[7]	10	688.97	49.60

There is no significant statistical difference between materials with the same superscript number.

Discussion

All-ceramic systems can be broadly divided into the following categories with respect to the presence of veneering porcelain:[3–6] (1) characterized by using high strength ceramic core materials, veneered with feldspathic porcelain to simulate the esthetics of a natural tooth, and (2) fabricated completely of one specific all-ceramic material. These systems achieve a tooth-like appearance with the selection of an appropriately colored ceramic and the application of surface-coloring techniques. Because of the higher opacity of alumina-based ceramic and zirconia-based ceramic core material, they are required to be veneered with feldspathic porcelain to achieve an esthetic result. On the other hand, for the glass-ceramic materials (lithium-disilicate glass ceramic, leucite-reinforced glass ceramic), they can achieve desirable esthetic restorations with veneering porcelain or by custom staining and glazing because of their high translucency.[43] Although the mechanical characteristics of the core materials have continuously been improved

Table 3 Weibull analysis of strength

			m						
Core material	Thickness	Veneering	Estimate	SE	95% CI		$\sigma_{0.01}$	$\sigma_{0.05}$	$\sigma_{0.10}$
e.max CAD	0.8	N	12.4	3.2	7.5	20.6	247.9	282.6	299.4
e.max CAD	1.5	N	8.7	2.1	5.5	14.0	206.8	249.2	270.6
e.max CAD	1.5	V	6.7	1.5	4.3	10.5	107.4	136.9	152.4
e.max Press	0.8	N	12.3	3.1	7.5	20.1	238.2	271.9	288.3
e.max Press	1.5	N	20.7	5.1	12.8	33.6	260.8	282.1	292.1
e.max Press	1.5	V	11.0	2.8	6.6	18.1	167.6	194.4	207.6
Empress CAD	0.8	N	17.6	4.5	10.7	28.9	119.3	130.8	136.3
Empress CAD	1.5	N	6.7	1.7	4.1	11.0	78.1	99.7	111.0
Empress CAD	1.5	V	6.7	1.6	4.2	10.7	64.4	82.1	91.4
Empress Press	0.8	N	10.1	2.5	6.1	16.5	95.6	112.4	120.7
Empress Press	1.5	N	5.7	1.5	3.4	9.4	59.2	79.0	89.7
Empress Press	1.5	V	5.4	1.3	3.3	8.8	47.3	64.0	73.1
Zir CAD	0.8	N	22.6	5.4	14.1	36.2	857.4	921.6	951.5
Zir CAD	1.5	N	28.6	7.5	17.1	48.0	530.6	561.7	576.0
Zir CAD	1.5	L	21.4	5.4	13.0	35.1	827.4	892.9	923.4
Zir CAD	1.5	P	13.8	3.0	8.9	21.2	479.6	539.9	568.9

m value = Weibull modulus; $\sigma_{0.05}$ = stress levels at 5% probability of failure; $\sigma_{0.01}$ = stress levels at 1% probability of failure

in modern dentistry, veneering material mechanical properties have largely remained unchanged.[10] Studies have shown that a thin layer of veneering porcelain fired onto a ceramic core material significantly diminishes the strength of the bilayer specimens.[9,14] The decreased strength of the bilayer specimens is most likely related to the composition of the core materials and porcelain, the behavior of the interfaces between porcelain and adjacent ceramic cores, and the compatibility of porcelain and ceramic cores.[14]

In the current study, the ceramic core surfaces were selected as the tensile side for flexural testing of multilayer structures. Investigations of clinically failed all-ceramic restorations have shown that the fracture origin is typically located at the internal (tensile) surface of the crowns, and these results justified our selection.[34,35] Cheng et al[43] reported that the thickness of the specimen had no effect on the failure distribution of the piston-on-3-ball test. Therefore, it was deemed that a reasonable thickness of the specimen disk could be selected for the piston-on-3-ball test. When it is beyond a specific core thickness for each ceramic material, increase in thickness had little effect on overall flexural strength of the material. The results of the current study showed consistent findings with similar biaxial flexural strength in the same monolithic ceramic material specimens fabricated with the same technique regardless of the material thickness. The biaxial flexural strength is an important property of dental ceramic materials, and it is recorded as tensile stress (MPa). The biaxial flexural strength is calculated with the following equation:

$$S = -0.2387P(X - Y)/d^2$$

where S is the maximum center tensile stress (MPa) (the flexural strength at fracture); P is the total load at fracture (N); and d is the thickness of the specimens. The fracture load (P) recorded in the current study was in proportion with the specimen's thickness, and it was influenced by the thickness of specimens. With thicker specimens, the fracture load was higher; however, the biaxial flexural strength is heavily governed and inversely proportional to the square of the specimens' thickness based on the calculation formula. Using the current study as an example, the fracture load recorded for monolithic Empress CAD 1.5 mm specimens was much higher than those of 0.8 mm specimens; however, the biaxial flexural strengths for both groups were similar.

Cattell and Palumbo[30] revealed that reduction of the Empress 2 core material from 2 to 1 mm to accommodate the application of the veneering porcelain did not result in a lower biaxial flexural strength and still maintained the reliability with a high Weibull modulus (14.8). Conversely, the results in the current study reveal the 1.5 mm core/veneer group had a significantly lower mean flexural strength value than the other two core groups (0.8 mm, 1.5 mm) with all five tested core materials. The findings of this current study showed that veneering porcelain onto the ceramic core material diminishes the strength of the bilayer specimens and decreases the reliability of ceramics with lower Weibull moduli. The results of this current study are consistent with those of Isgró et al,[9] who tested the influence of the veneering porcelain and different surface treatments on the biaxial flexural strength of a heat-pressed ceramic (Carrara Press System; Elephant Dental BV, Hoorn, The Netherlands). The results showed that veneering porcelain significantly decreased the strength of two-layer specimens when tested with the ground ceramic core surface in tension. The possible explanation for this result may be because of the inconsistent property of veneering porcelain. The lower Weibull modulus in this current study for bilayer core/veneer specimens may confirm this possibility. Comparing the heat-pressed technique and CAD/CAM technology with a commercially available block, the veneering layer with a traditional powder/liquid technique may have a less homogenous structure. The strength of a

ceramic material is dependent on the size of the preexisting initiating crack present in a particular specimen or component.[36] The large number of preexisting ceramic cracks, coupled with low fracture toughness, limits the strength of ceramics and causes large variability in strength.[37]

With similar material composition, fabrication techniques may have an effect on the mechanical properties. Guazzato et al reported a significantly higher flexural strength for In-Ceram® Zirconia® processed by slip-casting (630 ± 58 MPa) compared to the machined material (476 ± 50 MPa).[7] The results of this current study for leucite-reinforced glass ceramic and lithium-disilicate glass ceramic, the heat-pressed technique, and the CAD/CAM technique showed similar mean biaxial flexural strength with no significant difference ($P = 0.87$, 0.28, respectively). These findings suggested that for both leucite-reinforced and lithium-disilicate glass-ceramic materials, different fabrication techniques (heat-pressed and CAD/CAM) do not have an effect on the biaxial flexural strength. Furthermore, for the leucite-reinforced glass ceramic, the heat-pressed technique and the CAD/CAM technique showed a similar Weibull modulus, which may also indicate similar homogenous structure from both techniques; however, in the lithium-disilicate glass-ceramic groups, the heat-pressed technique exhibited a higher Weibull modulus when compared with the CAD/CAM technique. The results implied that the CAD/CAM techniques may produce specimens with lower reliability. A more consistent processing, as in the case of CAD/CAM technique over heat-pressed technique, does not necessarily mean better mechanical properties. Other factors such as grain size and shape and porosity should also be considered and can be further investigated in future studies.

For the zirconia core material layered with conventional powder/liquid layering technique, the current study showed a biaxial flexural strength of 628.79 MPa with a high Weibull modulus ($m = 21.4$). This result is consistent with one previous publication. Yilmaz et al[47] showed a similar biaxial flexural strength recorded at the bottom surface of bilayer zirconia specimens. In their study, the thickness of zirconia core and veneering porcelain were both 1 mm with a thickness ratio of 1 to 1, similar to the ratio of core/veneering porcelain thickness in the current study. Yilmaz et al[47] showed the biaxial flexural strengths for bilayer zirconia specimen were 591 MPa for Cercon (Cercon, DeguDent, Hanau, Germany) and 804 MPa for Lava (Lava, 3M ESPE, Seefeld, Germany), with Weibull moduli of 16.2 and 20.6 respectively.

Compared with the conventional powder/liquid layering technique for zirconia core material, Aboushelib et al[40] showed that heat-pressed veneering porcelain produces significantly higher fracture strength and microtensile bond strength between zirconia core and veneering porcelain. The current study showed a similar result with the heat-pressed technique providing significantly higher flexural strength for the zirconia bilayer specimens. The possible explanation is the molten ceramic pellet is brought into contact with the zirconia framework during heat pressing under pressure and in a vacuum, resulting in improved wetting and contact between the two materials.[40] The zirconia core materials also showed the highest Weibull modulus among all different core materials in this study, which may imply the high reliability of zirconia core material; however, the finding of a higher Weibull modulus for the conventional powder/liquid layering technique in this current study is somewhat difficult to explain. In all-ceramic systems, the flaw population (size, number, and distribution) can be related to the material or be affected by the fabrication process. Thus, it might be expected that the heat-pressed veneering technique introduces fewer flaws than the conventional powder/liquid layering technique, resulting in more homogeneous material, as it is a more-controlled procedure. By comparison, the conventional powder/liquid layering technique is more sensitive and subject to variability due to the individual building and firing procedures.[39] Two other in vitro studies[38,39] reported different results with no difference in the fatigue properties and failure load of the zirconia core material following conventional technique or heat pressing of the veneering material. More studies with larger sample sizes and different zirconia ceramic/veneering porcelain systems may be needed to fully investigate the mechanical properties of multi-layer zirconia specimens.

It is nonetheless interesting to note that the veneered zirconia specimens exhibited a greater flexural strength than the monolithic leucite and lithium disilicate ceramics. Within the limitations of the current methodology, it could be argued that, while the veneering material significantly decreases the flexural strength of zirconia restorations (as compared to monolithic thicknesses of 1.5 and 0.8 mm), these specimens still exhibited greater flexural strength than monolithic leucite and lithium disilicate specimens at the 1.5 mm thickness; however, Guess et al[48] reported that the application of CAD/CAM lithium disilicate ceramic in a monolithic/fully anatomical configuration with a 2 mm thickness resulted in fatigue-resistant crowns, whereas hand-layer-veneered zirconia crowns revealed a high susceptibility to mouth-motion cyclic loading with early veneer failures. With the fully anatomical design, crowns revealed a thickness of 2 mm in the occlusal area where the load was applied. The load to cause bulk fracture from radial cracks in ceramics increases as the square of the thickness increases.[15] Hence, the load to cause bulk fracture in the CAD/CAM lithium disilicate can be expected to diminish rapidly as the thickness is lowered. Clinical trials are needed in the future to determine the effect of restoration thickness on monolithic lithium disilicate and bilayer zirconia restorations. The results can be used to further determine appropriate material choice in clinical situations with different available occlusal restorative space.

The present study has several limitations, making it difficult to compare results directly with clinical situations. First, many more factors are involved in the attainment of a successful dental restoration, including the effects of moisture, restoration configuration and cementation, and fatigue, which have not been addressed by the scope of this study. Secondly, only one ceramic core/veneering porcelain thickness ratio was tested in this study. The 0.8 mm ceramic core thickness chosen in this current study was higher than the thickness used in some clinical situations, and the possible adverse effect for decreasing core thickness on each specific core material was not investigated. Additional study is needed to determine the critical core/veneer thickness ratio below which strength and structural reliability become significantly reduced. This information will improve our ability to design ceramic-based prostheses with a sufficiently high margin of safety. Third, only five ceramic core

materials with a sample size of ten were included in current study. The rationale to choose a sample size of 10 was to follow designs of previous studies,[26,27] and other all-ceramic materials with larger sample sizes should be investigated in the future. In addition, the thermocycling process can be considered if a universal standard can be applied. Lastly, based on the results of the current study, randomized clinical trials to compare zirconia restorations fabricated with powder/liquid veneering technique and heat-pressed veneering technique can provide more definitive information on their performance. Furthermore, the leucite-reinforced and lithium-disilicate glass-ceramic restorations made with different fabrication techniques (heat-pressed or CAD/CAM) can be considered for clinical trials to compare and confirm the effect of fabrication process on ceramics with similar composition; however, this study has provided further information on the in vitro strength of dental ceramics that will add to existing knowledge, and future studies that reflect clinical conditions are necessary for better characterization of new dental ceramics.

Conclusions

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Within the monolithic ceramic groups (0.8 mm and 1.5 mm cores) all five core materials exhibited similar flexural strengths.
2. The bilayer core/veneer groups had lower mean flexural strength and Weibull modulus than the monolithic core groups, indicating that veneering porcelain onto the tested ceramic core materials diminishes the strength and the reliability of the bilayer specimens.
3. Different fabrication techniques (heat-pressed and CAD/CAM) have no effect on the biaxial flexural strength and the Weibull modulus of the tested core materials; the only exception was the lithium-disilicate glass-ceramics fabricated with heat-press technique, which showed increased reliability with a higher Weibull modulus.
4. Compared with the powder/liquid veneering technique, the heat-pressed veneering technique provided higher flexural strength for the zirconia bilayer specimens; however, the heat-pressed veneering technique showed lower reliability with a lower Weibull modulus.
5. Both veneered zirconia-ceramic groups exhibited greater flexural strength than all monolithic leucite-reinforced and lithium-disilicate groups, regardless of the core thickness and fabrication techniques.

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