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An Investigation into the Role of Core Porcelain Thickness and Lamination in Determining the Flexural Strength of In-Ceram Dental Materials

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Abstract

Purpose: A biaxial flexure test was conducted to evaluate the effect of reducing the thickness of In-Ceram core material and veneering with Vitadur α dentine porcelain on its flexural strength.

Materials and Methods: Four groups of 10 discs were tested; group I discs were In-Ceram discs with mean thickness of 1.58 ± 0.08 mm, group II discs were In-Ceram discs with mean thickness of 1.0 ± 0.11 mm, group III discs were laminated In-Ceram core porcelain/Vitadur α discs with a mean total thickness of 2.06 ± 0.15 mm and core porcelain thickness of 1.0 ± 0.11 mm; group IV discs were Vitadur α discs with a mean thickness of 2.08 ± 0.16 mm.

Results: Mean flexural strength values decreased between groups: 436 ± 38 MPa for group I, 352 ± 30 MPa for group II, 237 ± 24 MPa for group III, and 77 ± 14 MPa for group IV. The result of ANOVA and Tukey tests indicated that the mean flexural strength of group II was significantly less than group I, indicating that thickness of the In-Ceram core provides critical flexural strength to the final product. The addition of $\approx$ 1 mm of Vitadur α veneering porcelain to In-Ceram core significantly ($p = 0.05$) reduced the flexural strength as compared to the nonveneered In-Ceram core specimens (group II). The Vitadur α specimens (group IV) were significantly weaker than all the other groups.

Conclusion: This study indicates that lamination should be avoided in areas where maximum strength is required for In-Ceram all-ceramic crowns and bridges.

Dental materials should fulfill four main criteria: strength, biocompatibility, esthetics, and fit. Currently available systems have been shown by many investigators to have a clinically acceptable marginal fit.[1–4] The unsurpassed esthetics and biocompatibility of ceramics are recognized as superior to metal ceramic restorations; however, a major drawback of some ceramics has been their high clinical failure rate in posterior sites.[5–8] The demand for improved clinical performance has led to the development and introduction of several new ceramic restorative materials and techniques. One of the primary focuses of dental ceramic developers and engineers has been improving the strength characteristics of ceramics. While it is clear that the long-term clinical performance of ceramic restorations depends on a number of factors, the ability of ceramic materials to withstand fracture is of significant interest. Until recently, success in improving the strength of ceramics was rather limited; however, in the last 30 years research in dental ceramics has accelerated and outpaced anything done in the earlier part of the 20th century, and the application of certain industrial ceramics and processing techniques has facilitated the introduction of a wide range of new dental restorative products. The first to have a major impact in dentistry, In-Ceram by Vita Zahnfabrik (Bad Sackingen, Germany), was comprised of a partially sintered alumina core infiltrated with glass at high temperature. This core was then veneered with porcelain adjusted to have the correct coefficient of thermal expansion. The resulting restoration has been used extensively for a number of years with excellent short-term success rates,[9] while failure rates for molar crowns are reported as 1 to 2% per year over 5 years.[10] As far as three-unit fixed partial dentures (FPDs) are concerned, the few clinical studies done to date indicate that In-Ceram can be reliably used for short-span anterior FPDs, provided that a suitable design of connectors can be applied.[11,12] A similar evaluation was made by Vult von Steyern et al,[13] who reported a survival rate of 90% for 20 FPDs after 5 years. They recommended that clinicians coat the framework with glaze only and refrain from use of veneering of the basal FPD pontic area to avoid critical strain.

It is known that relatively stiff coping plays a significant role in bearing the restoration load.[14,15] However, in dental applications, ceramic copings are usually covered with weaker

Table 1 Dimensions of biaxial test specimens

				D (mm)		*T* (mm)		T_1 (mm)		T_2 (mm)	
Group	Code	Material	No. of specimens	ξ	SD	ξ	SD	ξ	SD	ξ	SD
I	INC_1	In-Ceram core*	10	16	-	1.58	±0.08	-	-	-	-
II	INC_2	In-Ceram core*	10	16	-	1.0	±0.11	-	-	-	-
III	INC/VDα	In-Ceram core /Vitadur α	10	16	-	2.06	±0.15	1.0	±0.11	1.06	±0.18
IV	VDα	Vitadur α	10	16	-	2.08	±0.16	-	-	-	-

*Group I and Group II differ only in disc thickness.

D: disc diameter; T: total thickness of the disc; T_1: thickness of core disc; T_2: thickness of Vitadur α veneer; ξ: mean; SD: standard deviation.

porcelain. Such a combination forms a layered structure with different elastic moduli and thermal expansion coefficients. These structures may also contain residual stresses in the different layers, influencing crack propagation and even the mechanical properties of the restoration.

The purpose of this study was to investigate the possible influence of specimen thickness and lamination on the flexural strength of In-Ceram core material.

Materials and methods

Four groups of 10 ceramic discs were prepared. These groups were:

Group I: In-Ceram core discs with mean thickness of 1.6 ± 0.08 mm and 16 mm diameter.

Group II: In-Ceram core discs with mean thickness of 1.0 ± 0.11 mm and 16 mm diameter.

Group III: Bilayered ceramic discs with 1.0 ± 0.11 mm thick In-Ceram core material laminated with 1.06 ± 0.18 mm thick Vitadur α (Vita Zahnfabrik) feldspathic porcelain (16-mm diameter).

Group IV: Vitadur α discs with mean thickness of 2.08 ± 0.16 mm and 16 mm diameter.

Table 1 represents the nature of each group, means (ξ), and standard deviation (SD) of their dimensions.

Construction of the silicon mold

Plastic discs (16-mm diameter) were punched from Vacupress sheets (Dentsply International, York, PA). The discs were layered to form 3-mm-thick discs. The layered plastic discs were then glued to the inside of a rectangular acrylic tray, and silicon impression material (Rema-Sil duplicating silicone, Dentaurum, Ispringen, Germany) was poured in the tray. After complete setting of the silicon impression material, it was removed to form a mold for the construction of the core material discs.

Core material preparation (groups I, II, and core material layer of group III)

The special silicon mold was used to make 30 Vita In-Ceram core material discs. One sachet of Vita In-Ceram special plaster material was mixed with 4.6 ml distilled water under vacuum for 20 seconds according to the manufacturer instructions, and the mix was poured into the mold using a standard smidgen 1/32 teaspoon (equivalent to 0.15 ml) measure for each disc on a vibrator. The alumina slip was prepared by mixing 38 g of Vita In-Ceram alumina powder with one ampoule of Vita In-Ceram alumina fluid and one drop of Vita In-Ceram alumina additive into a glass beaker on a vibrator. The mix was further vibrated in the ice-chilled Vitasonic unit (Vita Zahnfabrik) for 7 minutes and for an additional minute under vacuum to attain a smooth, creamy consistency. The alumina slip suspension was poured over the dry gypsum material inside the mold to fill the remaining space of the disc impression and allowed to dry completely before the bilayered discs were removed.

The discs were sintered in a Vita Inceramat furnace (Vita Zahnfabrik) with the firing cycle set for a 6-hour climb to 120°C, a 2-hour climb to 1,120°C, and hold for 2 hours. The gypsum material was removed, and sintered discs were lightly ground manually on both surfaces with ultra-fine (600 grit) silicon carbide paper (Ace Hardware Corporation, Oak Brook, IL) to achieve a thickness of approximately 1.6 mm for group I ceramic discs and 1 mm for groups II and III. The thickness of each disc was measured using a micrometer (Mitutoyo Corp., Tokyo, Japan) accurate to 0.001 mm. The blue testing die liquid supplied by the manufacturer was used to evaluate discs for possible microcracks. Specimens with microcracks were discarded. Next the specimens were placed on a 0.1-mm-thick platinum-gold foil sheet and infiltrated with Vita In-Ceram Alumina glass (lanthanum aluminosilicate glass, batch no. 2990) in a Vita Inceramat furnace. The firing cycle was set for a 30-minute climb to 1,100°C, held for 6 hours. Excess glass was grossly removed with a coarse-grit diamond instrument. Care was taken not to scratch the infiltrated alumina substructure, as it was noticed that diamond instruments cause scratches difficult to remove during polishing. After microblasting with 50-μm aluminum oxide powder (Dentsply International) at 40 psi, the discs were fired a second time in a Vita Vacumat 30 porcelain furnace (Vita Zahnfabrik) at a 5-minute climb to 1,000°C and held for 10 minutes. Excess glass was again removed by microblasting, and the discs were ground on both surfaces with 220-grit silicon carbide abrasive paper on a metallurgical polishing wheel (Model 461512 Buehler Ltd. Lake Bluff, IL) with ample water coolant, to ensure complete removal of excess infiltration glass.

Application of Vitadur veneer (group III)

In-Ceram core discs to be veneered (Group III) were air abraded at one surface and cleaned with distilled water. Each disc was placed in an extrusion brass mold (16.5-mm diameter, 3-mm depth). Porcelain slurry (Vitadur α) was then vibrated on the microabraded surface of the discs and fired according to the

manufacturer's instructions. The firing took place in a Vita Vacumat 30 porcelain furnace. The first dentine firing was pre-dried for 6 minutes at 600°C, and then had a 6-minute climb to 960°C under vacuum with a 1-minute hold after vacuum release. In the first and second correction, firing discs were pre-dried for 6 minutes at 600°C, and then had a 6-minute climb to 950°C under vacuum and a 1-minute hold following the vacuum release. The veneer surface was then ground with 220-grit silicon carbide abrasive paper on a metallurgical polishing wheel (Buehler Ltd.) with ample water coolant. The final dimensions for each disc were measured using a micrometer (Mitutoyo Corp.).

Preparation of Vitadur porcelain discs (group IV)

Specimens of Vitadur α body porcelain (Group IV) were prepared by vibrating 1.5 g of Vitadur α body porcelain powder mixed with 0.5 cm^3 of distilled water. The porcelain slurry was vibrated and condensed in an extrusion brass mold (19-mm diameter, 3-mm deep). Excess moisture was removed with an absorbent tissue and then positioned in a ceramic tray containing particles of ground hydroxyapatite. These particles supported and allowed unobstructed shrinkage of discs during firing. The specimens were permitted to air dry for at least 2 hours before firing. The specimens were pre-dried for 6 minutes at 600°C in a Vita Vacumat 30 porcelain furnace and then had a 6-minute climb to 960°C under vacuum with a 1-minute hold after vacuum release. The discs were then ground at both surfaces on 220-grit silicon carbide abrasive paper on a metallurgical polishing wheel (Buehler Ltd.) with ample water coolant.

Final disc preparation

The specimens in groups III and IV were refired to achieve a natural glaze of the feldspathic porcelain. All the discs received additional polishing at one surface through a sequence of steps ranging from 220 to 600 grit silicon carbide abrasive papers on a metallurgical polishing wheel (Buehler Ltd.) under running water. The veneered discs (group III) had the core material surface as the finely polished one. The final thickness and diameter of each disc were measured with a micrometer (Mitutoyo Corp.).

Biaxial flexure testing

Test specimens were fractured biaxially with a piston on three ball technique as described by Wachtman et al.[16] Discs were concentrically supported on three 2.355-mm diameter steel spheres equally spaced around a 5.125-mm radius support circle. Specimens were loaded to failure by a compressive load applied through a 0.9-mm radius circular cylinder applied perpendicularly. A 0.2 mm/min crosshead speed and a 5 KN load cell were applied with a universal testing machine (Model 8500, Instron Corp, Canton, MA.) All specimens were tested so the polished surfaces were the tensile surfaces during fracture. Failure stress, δ, at the center of the lower surface was calculated by the equations:

$$\delta = AP/t^2$$

and

$$A = (3/4\pi)[\ 2(1+\nu)1n\ (a/r_o^*) + (1-\nu)\ (2a^2 - {r_o}^{*2})/2b^2 + (1+\nu)$$

where P is the applied load at failure; ν is Poisson's ratio (assumed to be 0.25); a is the radius of the support circle; b is the radius of the disk specimen; r is the equivalent radius given in $r_{o*} = (1.6\ r_{02} + t^2)^{\frac{1}{2}} - 0.657t$; t is the thickness of the disk specimen; and r_o is the radius of the piston at the surface of contact.

Statistical analysis

Mean flexural strength values were calculated for each experimental group, and differences between and within the groups were tested using ANOVA and Tukey's multiple comparisons test to evaluate the effect of both thickness reduction and veneering with feldspathic porcelain on the flexural strength of In-Ceram core porcelain. Level of significance for all statistical analyses was set at 0.05.

The Weibull moduli were calculated for the biaxial flexural strength data by plotting lnln(1/1 - f) versus ln(δ), where F = (i-0.5)/n; i = rank of specimen in terms of strength (i = 1 for the lowest strength specimen); n = total number of specimens; and δ = strength of specimen i. The best fit line for each plot was determined by linear regression. The slope of the line was calculated as Weibull modulus.[17]

Results

Mean flexural strength values were found to be: 436 ± 38 MPa for group I, 352 ± 30 MPa for group II, 237 ± 24 MPa for group III, and 77 ± 14 MPa for group IV. The results of the biaxial strength testing are summarized in Table 2. Mean load to failure was 760 ± 84 N for group I, 260 ± 79 N for group II, 763 ± 117 N for group III, and 242 ± 47 N for group IV. Delamination was not evident for any of the fractured specimens in Group III. ANOVA and Tukey tests indicated that the mean flexural strength of the 1.6 ± 0.08 mm mean thickness In-Ceram core porcelain specimens (group I) were significantly higher than those of the 1.0 ± 0.1 mm mean thickness specimens (group II). The addition of 1 mm veneering feldspathic porcelain to a fixed thickness of 1 mm In-Ceram core porcelain (group III) significantly ($p = 0.05$) reduced its flexural strength as compared to the nonveneered specimens in group II. The 2.0 ± 0.1 mm feldspathic Vitadur α specimens (group IV) were significantly weaker than veneered or nonveneered In-Ceram core porcelain specimens (groups I, II, III). A standard Weibull plot of the specimens is shown in Figure 1. Results of Weibull analysis are summarized in Table 3. Table 3 shows that groups I and II have the same Weibull moduli, and that group IV has the lowest Weibull modulus. Similarly, discs in group I exhibited the highest characteristic strength, followed by Groups II, III, and IV, in that order.

Discussion

Performance of brittle materials, including ceramics, composites, amalgams, and cements, is of particular importance, as

Table 2 Load to fracture (N) and biaxial strength (MPa) (n = 10)

	Material	Max	Min	Mean	Variance	S.D.	Cof. Var.
Load (P) (in N)	INC_1 (group I)	917	630	760	7,131	84	11
	INC_2 (group II)	405	174	260	6,230	79	30
	INC/VDα (group III)	987	618	763	13,750	117	15
	VDα (group IV)	337	172	242	26,479	47	20
Failure stress (δ)	INC_1 (group I)	476	354	436*	1,431	38	9
	INC_2 (group II)	400	306	352*	884	30	8
	INC/VDα (group III)	277	191	237*	584	24	10
	VDα (group IV)	102	55	77*	208	14	19

INC_1: In-Ceram discs with mean thickness of 1.58 ± 0.08 mm; INC_2: In-Ceram discs with mean thickness of 1.0 ± 0.11 mm; INC/VDα: In-Ceram core laminated with Vitadur α porcelain; VDα: Vitadur Alpha feldspathic porcelain.

* Means are statistically different from each other at ($p = 0.05$).

these materials are substantially weakened by flaws in the presence of tensile stress.[18] Strength is affected by the flaw distribution within the structure, the stress field associated with these flaws, the rate of loading, and environmental factors. The effect of specimen thickness is one of the most important factors in the determination of biaxial flexure strength, as the calculated stress is inversely proportional to the second power of its thickness, as derived in equation 1.

In this study, reducing the thickness of In-Ceram core porcelain discs from 1.6 mm to 1.0 mm led to a 15% reduction in the flexural strength. Jones[19] suggested that a high modulus of rupture core material would be beneficial only if it is present in sufficient thickness. This has been verified experimentally for relative strengths of laminated discs by Southan.[20] Thickness dependence of aluminous core porcelain was also demonstrated by several investigators. Piddock et al[21] and Hopkins[14] reported a decrease in shell strength with increasing thickness of disk specimens. On the other hand, Thompson et al,[22] in a fractographic study of clinically failed crowns, concluded that fracture initiation sites of dental ceramics are controlled primarily by the location and size of the critical flaw and not by specimen thickness.

The strength of ceramic materials depends on their ability to inhibit the initiation and growth of cracks. Crack initiation is controlled by the surface condition of the material, while resistance to crack growth is determined by the internal structure. The difference in the behavior of the two porcelains could be attributed to the difference in their microstructure. Vitadur N core porcelain (Vita Zahnfabrik) has a high level of interfacial and internal porosity when the surface roughness and porosity is reduced by good adaptation of the porcelain to platinum foil. This makes the material less sensitive to crack initiation from the surface and more sensitive to bulk porosity. Therefore, an increase in the thickness could mean an increased probability of having a critical crack-initiating flaw in the zone of maximum tensile stress during bending. Comparatively, porosity is substantially decreased with In-Ceram core material through the use of very precise mixing and forming techniques to ensure a high density of the core porcelain before firing. Total porosity is also decreased after sintering of the core material by glass infusion. The microstructure of In-Ceram core porcelain is also improved due to its relatively smaller grain size (1 to 5 μm). The probability of defects occurring decreases with grain size, and the conditions for crack formation become less favorable. The smaller grain size is maintained, and inhibition of secondary crystallization and grain growth is achieved through the use of a very low sintering temperature. This method has the disadvantage of long overall firing time.[23]

Since flaw distribution varies considerably from object to object and even within the same object when processed under different conditions, it is virtually impossible to match in vitro with in vivo conditions. For bonded or laminar materials, the situation is even more complex, since in vitro testing involves two dissimilar materials jointed at an interface region. Many times, prostheses and restorations are fabricated using multiple materials often having different elastic properties. Such construction implies that internal interfaces exist between material layers. Elastic property differences across interfaces can lead to high interfacial stress as well as significantly altered stress distributions elsewhere in the structure. Third phases may also exist at

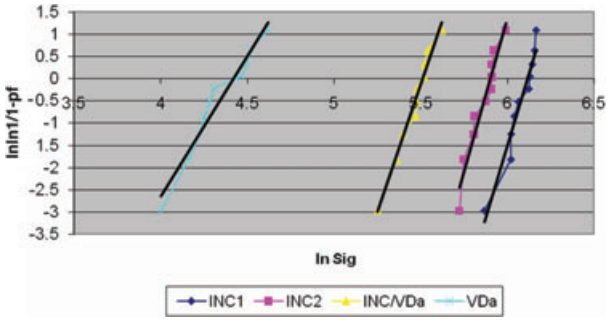

Figure 1 Weibull plots for all test specimens.

Table 3 Weibull analysis (n = 10)

Material	Weibull modulus (m)	Characteristic strength(δ_0) (MPa)
INC_1 (I)	13	453
INC_2 (II)	13	365
INC/VDα (III)	11	248
VDα (IV)	6	83

INC_1: In-Ceram discs with mean thickness of 1.58 ± 0.08 mm; INC_2: In-Ceram discs with mean thickness of 1.0 ± 0.11 mm; INC/VDα: In-Ceram core discs laminated with Vitadur α; VDα: Vitadur Alpha feldspathic porcelain discs.

interfaces, as may structural defects.[18] The strength of material failing from an interface may demonstrate different flaws (with different distributions) from face-surface failing materials. Therefore, an understanding of actual clinical failure modes is absolutely necessary before results of in vitro strength testing can be considered to have clinical validity; however, some explanation regarding differences in the variability of strengths across the different groups can be made through the results of Weibull plotting. Weibull plots exhibit how consistent the experienced strengths of each material are. As outcomes deviate farther from the best fit line, the more variable the strength of the material is considered to be. To create a quantitative value for this variability, the Weibull moduli of each plot was computed. The Weibull moduli assigns a numeric, interval-scale value that indicates how variable the strength of each material is when placed under similar conditions as compared to other materials. Higher moduli, such as those found in groups INC_1 and INC_2, show that these materials have more consistent outcomes when their strengths are tested, which means that their respective average measures of strength are more representative of the actual observed strength of the material than the other materials with lower Weibull moduli. Based on these results, it can be inferred that the characteristic strengths of 453 MPa and 365 MPa possessed by INC_1 and INC_2, respectively, are more representative of the two materials' strengths than the characteristic strengths of 248 MPa and 83 MPa possessed by INC/VDα and VDα, respectively. Since the characteristic strength of INC_1 is higher than INC_2, it can be further inferred that $INC_1$is superior to INC_2.

The effect of porcelain veneering of ceramic cores on the overall strength of different systems has been questioned. Several investigators measured the flexural strength of different ceramic materials with and without veneers. A general tendency of veneered specimens to have lower strength value than their nonveneered counterparts has been reported.[24] In this study, the addition of 1.0 mm feldspathic porcelain to a fixed 1.0 mm thickness of In-Ceram core porcelain significantly reduced the flexural strength, by approximately 34%. The results of this study are in agreement with several previous studies.[20,25-27]

The fracture resistance of any laminate composite depends to a great extent on the interfacial bond between the individual laminates. A strong interface should provide sufficient stress transfer between the individual laminates to allow the applied load to be transferred and accommodated. Conversely, a weak interface will frequently result in failure by a process of delamination under an applied load, possibly arising from crack initiation and propagation within and along the laminate interface.[25,26,28,29]

Delamination of In-Ceram alumina core/Vitadur α specimens has been observed by many investigators.[24,28,30,31] However, in this study, delamination was not encountered. Failure always left a residual layer of feldspathic porcelain on the core, suggesting that the bond between the core porcelain and the veneering porcelain is stronger than the cohesive strength of Vitadur α porcelain. This is consistent with the findings of Thompson et al[22] and Guazzato et al,[27] who related their findings to the type of test method used and to the relative layer heights. This could also be attributed to the way the specimens were prepared before testing, as both surfaces of the core material were finely ground and polished, possibly removing surface flaws before lamination with the feldspathic porcelain. Irrespective of where failure is likely to initiate, it should be noted that masticatory forces can be effectively transferred through the restoration to the underlying tooth and jaw. The mechanical properties of the luting cement and the natural tooth substance together with the fit of the restorations will affect load transference and therefore influence the ability of the crown to survive large biting forces. Nevertheless, as far as possible, core thickness should not be sacrificed for dentine. Obviously, esthetics are of prime concern in the labial and interproximal areas; however, on the palatal surface it would be better to leave the whole thickness (commonly about 1.0 mm) of core.

Conclusions

Within the limitations of this study, the following conclusions can be drawn:

(1) Reducing the thickness of In-Ceram core porcelain leads to a significant reduction in its flexural strength.
(2) Veneering In-Ceram core porcelain with Vitadur α feldspathic porcelain overwhelmingly reduces its flexural strength.
(3) While accepting the constraints imposed by good esthetics, where possible, the thickness of dentine should be reduced and that of the core maximized.

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