Effect of storage and aging conditions on the flexural strength and flexural modulus of CAD/CAM materials

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INTRODUCTION

Computer-aided design/computer-aided manufacturing (CAD/CAM) was introduced in dentistry forty-years ago, and gained popularity worldwide because of advancements in restorative materials with characteristics such as crack tolerance, ease of clinical use and good performance¹⁻⁵. To meet high aesthetics requirements, an ideal restorative material requires attributes including physical and mechanical properties like thermal, optical, water absorption, fracture toughness, fracture resistance, and fatigue resistance²,³. CAD/CAM technology eliminates dimensional changes during laboratory manufacturing process. Although ceramics are conventionally used, composite resin-based blocks were developed⁶ to take advantage of this class of material, which has higher modulus of resilience and great flexural modulus and strength⁷. However, in order to achieve and increase these mechanical properties, fillers are added to resin-based materials. In industry, greater quantity and volume fractions are incorporated without affecting mechanical durability. Furthermore, the curing degree achieved decreases the quantity of unreacted elements and increases the fatigue resistance⁸. The question arises as to whether these improvements can be scaled down to the dental level.

Tests like bond strength using luting resin-based materials are less effective after long-term thermo cycling⁹⁻¹⁰ and raise the possibility of water absorption in CAD/CAM composite materials¹¹. Although filler particles are bonded to resin matrix using specific primers¹² zirconia particles suffer from debonding process under water storage¹²⁻¹⁵; which may occur due to the difficulty of zirconia surface etching procedures. Furthermore, several curing methods were proposed with the aim to reduce free radicals and unreacted molecules inside the polymer matrix¹⁶,¹⁷. It is known that dental resin-based composites suffer from decrease in mechanical properties based on non-satisfactory polymerization procedures¹⁸. Another important result of the curing process is residual stress, normally causing cuspal deflection and also marginal gaps between the cavity walls¹⁸. As previously mentioned CAD/CAM provides a better quality of restorations in terms of material performance and eliminates some concerns inherent in dental procedures. Therefore certain principles involving preparation for the final cementation process related to indirect procedures¹⁹ must be followed.

Consequently, manufacturers have been using this information to improve new commercially available CAD/CAM materials. Repairing ceramics with composite materials has always been a challenge because of all the different mechanical characteristics that are encountered. However, the CAD/CAM creates a possibility: it can fill resin-based composites with ceramic small particles such as silica and zirconia.

The purpose of this study is to evaluate differences in mechanical behavior. Four CAD/CAM materials were divided in four subordinate groups (n=9): (1) dry out for 7 days, (2) distilled water at 37°C for 7 days, (3) 60,000 thermocycles, and (4) 120,000 thermocycles. Following thermocycling, samples were submitted to three-point bending test. Two-way ANOVA and post-hoc Tukey’s test were performed (α=0.05). The IPS e.max CAD had a flexural strength of 396±75 MPa and flexural modulus of 84±11 GPa, followed by Vita Enamic with values of 153±17 MPa and 28±5 GPa respectively. The flexural strength recorded for Lava Ultimate was 149±28 MPa and the flexural modulus was 12±3 GPa. Vitablocs Mark II had the lowest flexural strength values (125±10 MPa) and a flexural modulus of 49±15 GPa. Although polymer-based materials have similar mechanical properties compared to ceramics, they are affected by thermo cycling conditions.

Keywords: Ceramics, CAD/CAM, Chipping, Brittle ceramics, Flexural strength

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in flexural strength and flexural modulus of different classes of CAD/CAM materials before and after thermo cycling and also determining whether or not the resin-based materials would suffer hydrolysis. Fractographic analysis was used to elucidate understanding materials’ behavior during fracture. The null hypotheses were that there would be no differences between both classes of materials (ceramic and resin-based) and also among different thermo cycling simulations.

MATERIALS AND METHODS

The current study included different CAD/CAM dental materials with similar mechanical behaviors in terms of clinical indications. The materials were Vita Enamic (VE) (Vita Zahnfabrik, Bad Sackingen, Germany), Lava Ultimate (LU) (3M ESPE Dental Products, St Paul, MN, USA), Vitablocs Mark II (VM) (Vita Zahnfabrik), and IPS e.max CAD (IP) (Ivoclar-Vivadent, Schaan, Liechtenstein) (Table 1). Thirty-six specimens of each of the four materials were prepared and further separated into four subgroups of nine samples each. Specimens were prepared for a three-point bending test to determine flexural strength, defined as the stress at the moment before failure, and flexural modulus defined as the ratio of stress to strain, and how much energy the material is able to hold before bending. The blocks were sectioned and prepared as beam specimens. First, the materials were sectioned in slices sized 14.8×12×3 mm (L×W×H), then cut with a precision diamond-saw machine (Isomet 1000, Buehler, Lake Bluff, IL, USA) in beam shaped specimens measuring 14.8×3.5×3 mm (L×W×H). To achieve a precise dimension, specimens were submitted to finishing and polishing procedures (Ecomet 6, Buehler) using the following sequence of sandpapers: 240, 400, 600, 800 and 1200 grit. Final dimensions (14×3×2.5 mm) were confirmed by digital calipers (Mitutoyo America, Aurora, IL, USA).

The conditions in which the four testing materials were divided are as follows: in the first subgroup the specimens were maintained 7 days in a desiccator at 37°C. These two subgroups did not have any further storage in an incubator for seven days in distilled water at room temperature; in the second subgroup they were stored in an incubator for seven days in distilled water at 37°C. These two subgroups did not have any further treatment. The third subgroup included specimens that were submitted to a 60,000 thermo cycling process for 40 days; and the fourth subgroup was submitted to a 120,000 thermo cycling process for 80 days. The thermo cycling process was made with Thermo Haake (Thermo Haake, Karlsruhe, Germany), each cycle lasted for 52 s, as follows: the dwell time within each bath (5 and 55°C) was 20 s, and the transferring time between baths was 6 s.

The specimens were positioned on a three point-bending fixtures of a materials test machine (Test Resources, Shakopee, MN, USA). Bending tests were conducted at room temperature (23°C) until the complete failure of the specimens. The maximum load was recorded and the following equations were used to calculate the flexural strength (σ) as the flexural modulus (E), respectively:

\[
\begin{align*}
(1) \quad & \sigma = \frac{3PL}{bh^2} - \text{flexural strength} \\
(2) \quad & E = \frac{PL}{bdh^3} - \text{flexural modulus}
\end{align*}
\]

In both formulas, P represents the maximum load in Newtons (N), L is the distance between supports (12 mm), b is the specimen width, h the specimen thickness; in equation (2) d is the deflection mean on the entire slope of the linear portion. In both formulas b and h were measured with a digital caliper immediately before the test and recorded in millimeters.

Values obtained after three point-bending tests were statistically analyzed, by means of Shapiro-Wilk and Levene’s test to determine if data have normality distribution as well as homoscedasticity. Subsequently, two-way ANOVA was applied to determine statistical significant differences, and the post-hoc Tukey’s test showed where these differences occurred. Following testing, three samples from each group were randomly selected and analyzed with scanning electron microscopy (SEM – FEI Nova Nanolab 200, Hillsboro, OR, USA) for fractographic analysis. The fractographic analysis was in accordance with ASTM C132223 and ADM guidelines.

RESULTS

The statistical analysis showed that, in general, CAD/CAM polymer-based materials perform significantly better than feldspathic ceramic. The mean and standard deviation of flexural strength and flexural modulus are presented in Table 2 for all materials tested over the whole range of means. Table 3 presents the mean and standard deviation for flexural strength among the four subgroups (storage/aging conditions). VE values did not decrease after water storage; however, thermo cycling substantially altered this mechanical property. LU values significantly

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Table 1  Details of materials included in the research

| Material         | Composition                                           | Manufacturer     | Batch  |
|------------------|-------------------------------------------------------|------------------|--------|
| Vita Enamic (VE) | Polymer-infiltrated-ceramic-network 86% feldspathic ceramic | Vita Zahnfabrik  | 47791  |
| Lava Ultimate (LU)| Composite material silica and zirconia nanoparticles | 3M ESPE          | N674359|
| Vitablocs Mark II (VM)| Fine-particle feldspar ceramic                  | Vita Zahnfabrik  | 39350  |
| IPS e.max CAD (IP)| Lithium disilicate glass ceramic                     | Ivoclar-Vivadent | 78978  |
Table 2  Mean and standard deviation of flexural strength (MPa) and flexural modulus (GPa) among the materials tested considering the average of the four conditions combined

| Condition     | VE  | LU  | VM  | IP  |
|---------------|-----|-----|-----|-----|
| Flexural Strength | 153 (17)a | 149 (28)a | 125 (10)b | 396 (75)c |
| Flexural Modulus   | 28 (5)a  | 12 (3)b  | 49 (15)c  | 84 (11)d  |

*For each mechanical property individually, values denoted with same letters are not significantly different (p<0.05).

Table 3  Flexural strength (MPa) of tested specimens submitted to different conditions

| Condition     | VE  | LU  | VM  | IP  |
|---------------|-----|-----|-----|-----|
| Desiccator    | 164a,A (13) | 189a,B (9) | 120a,C (8) | 304a,D (13) |
| Water Storage | 168a,A (11) | 146b,AB (23) | 132b,B (9) | 448b,C (38) |
| Thermo 60,000 | 140b,A (7)  | 135b,AB (18) | 122b,B (8) | 401b,C (67) |
| Thermo 120,000 | 139b,A (11) | 127b,A (13) | 124b,A (10) | 429bc,B (106) |

*Lowercase letters for each material individually (columns), values denoted with same letters are not significantly different (p<0.05).
*Uppercase letters for each condition individually (rows), values denoted with same letters are not significantly different (p<0.05).

Table 4  Flexural modulus (GPa) of tested specimens submitted to different conditions

| Condition     | VE  | LU  | VM  | IP  |
|---------------|-----|-----|-----|-----|
| Desiccator    | 26a (5)  | 12a (3)  | 40a (16) | 80a (5)  |
| Water Storage | 29a (2)  | 14a (4)  | 53b (14) | 93a (3)  |
| Thermo 60,000 | 29a (4)  | 11a (1)  | 51b (15) | 78a (7)  |
| Thermo 120,000 | 27a (9)  | 12a (4)  | 53a (14) | 87ab (17) |

*Lowercase letters for each material individually (columns), values denoted with same letters are not significantly different (p<0.05).
*Uppercase letters for each condition individually (rows), values denoted with same letters are not significantly different (p<0.05).

decreased following thermocycling. VM flexural strength values did not show statistically significant differences (p<0.05) among the applied conditions. IP showed an increase in flexural strength after 7 days of water storage, significantly different from the dry condition.

Table 4 presents mean and standard deviation values for flexural modulus among the same four subgroups (storage/aging conditions). Both VE and LU did not show statistically significant differences (p<0.05) among the tested conditions. VM showed better performance after being hydrated, and the three conditions, in which the material was in contact with water, were not statistically different (p<0.05) from each other despite applying thermocycling cycles. IP’s flexural modulus did change after 120,000 cycles (p<0.05) compared to 7 day water storage.

In order to determine the fracture path of the tested materials, Figs. 1 to 4 show the four materials in three different magnifications. The figure descriptions explain the different fracture characteristics of the materials. Some unexpected properties among the applied conditions were identified on the materials’ surface. A common characteristic across the materials was that fracture surfaces were considered rough.

**DISCUSSION**

The findings related to studied materials are in similarities to that provided by each manufacturer, and with others studies when composites are dry and ceramic have been hydrated. VE classified as polymer-infiltrated-ceramic-network (PICN) under conditions just described shows higher numbers from that provided by the manufacturer. Thermo cycling conditions used in this study was never used before, in terms of how long the materials remain under thermal changes. The null
hypotheses were rejected for differences between both class of materials and for flexural strength and flexural modulus on tested materials presented with statistical significances when long term thermo cycling test was applied.

VE is a material indicated for crowns, onlays/inlays, and veneers4) and has a major feldspathic-based phase infiltrated by a polymer-based network. Results
show that flexural strength values for this material are sensitive to thermocycling. VE has higher flexural modulus compared to composite resin-based materials (LU), although flexural strength values are similar. Furthermore VE’s flexural modulus values did not change after thermo cycling, showing similarities with ceramic materials25-27).

Because of resin component, and representing the class of resin nano-ceramic due to its mixed composition, LU has a low flexural modulus compared to other materials. However, it did not change significantly after thermo cycling. But the flexural strength decreased, as it was indicated by in vitro studies possibly because of water absorption11,12. Previous studies have reported hydrolysis of polymer materials, possibly because of the material content11. The water absorption suffered by LU is attributed to hydrolytic degradation that polymer-based materials are subjected and consists in four stages28-30. At stage I, water diffusion into the polymer amorphous region. The stage II is characterized by polymer hydrolysis, auto catalysis and initial mass loss. Also it is known macromolecular weight, pH of the moisture, incubation temperature, and samples thicknesses have a major effect on hydrolytic degradation. Stage III oligomer diffusion occurs with monomer degradation and the appearance of voids will increase the mass loss. At the last stage; stage IV a porous structure is present and continuous homogenous degradation until the complete release of free radicals are generated by the water absorption process28-30. Furthermore, zirconia is one of the fillers of LU, and is also known besides the high mechanical strength and stable chemical properties, low susceptibility to surface etching procedures31. The interfacial bonding between the polymer and yttrium stabilized zirconia made by the application of silane coupling agent during the material manufacturing procedure may not be strong enough; and could possibly be the weakest point related to material flexural strength.

VM is the first feldspathic glass ceramic in the CEREC system. It showed the lowest value of flexural strength. Porcelain materials tend to be brittle and less flexible than composites resulting in inferior ability to absorb stress under high loading deformation7,32. Nevertheless, VM’s flexural modulus was lower than IP and did not change after a thermo cycling; this explains the material stability under clinical conditions5,33,34. VE’s flexural modulus values did not change after thermo cycling, showing similarities with ceramic materials25-27.

SEM micrographs (Figs. 1 to 4) —specific characteristics are labeled in each image— revealed zones of roughness along the surface of all materials. None of the materials tested presented differences on the surface features after failure except by LU (Figs. 2A–C). VM (Fig. 3A) was the material with more cracks and hackles all over the surface characterizing brittle fracture. The IP (Fig. 4A) presented a rough surface with peaks and valleys, with small areas with cracks and hackles, a flaw from left to right, and in the middle of the picture a coarse hackle showing the crack path. LU (Fig. 2A) displayed a clear ductile fracture identified by flaws with mixed attributes, porous seams, voids, and a coarse hackle. Although it is a composite resin-based material, the roughness of the surface is the same presented in all the ceramic materials.

The VE material exhibited a number of features of hybrid ceramics characteristics36. For instance the upper left corner (Fig. 1A) shows mixed flaws of the sort present in LU. In the center and also the lower right corner, flaws and hackles characterizing a brittle fracture also are shown. Similar to what is observed in real clinical situations70 crack formation started in a zone of heavy loading, so the crack propagated with characteristics typical of the material composition.

Even though there are some laboratory studies...
in the literature, clinical research is being carried out to better understand CAD/CAM materials behavior. It is important to understand that among factors influencing the longevity of all-ceramic restorations\(^8\) correct occlusion and the polishing process will have a direct effort on ceramic crowns, and might prevent small and incipient cracks or hackles. However, it was mentioned that the crack initiation started at the cement interface\(^8\)-\(^10\).

CONCLUSIONS

The findings revealed that Vita Enamic (PICN) behaves similarly to dental ceramics in terms of flexural strength and flexural modulus. Also, CAD/CAM ceramic materials are not affected by the aging conditions and perform better after hydration. Furthermore, Lava Ultimate (composite) behaves similar to direct composite materials in terms of water absorption and decrease in flexural strength. Further studies are being carried out to better understand other specific properties of CAD/CAM materials.

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CONFLICTS OF INTERESTS

None.

REFERENCES

1) Calamia JR. Advances in computer-aided design and computer-aided manufacture technology. Curr Opin Cosmet Dent 1999: 67-73.
2) Rekow ED, Bayne SC, Carvalho RM, Steele JG. What constitutes an ideal dental restorative material? Adv Dent Res 2013; 25: 18-23.
3) Rekow ED, Fox CH, Watson T, Petersen PE. Future innovation and research in dental restorative materials. Adv Dent Res 2013; 25: 2-7.
4) Della Bona A, Corazza PH, Zhang Y. Characterization of a polymer-infiltrated ceramic-network material. Dent Mater 2014; 30: 564-569.
5) Morimoto S, Rebello de Sampaio FB, Braga MM, Sésma N, Ozcan M. Survival rate of resin and ceramic inlays, onlays, and overlays: A systematic review and meta-analysis. J Dent Res 2016; 95: 985-994.
6) Duan Y, Grigg JA. Effect of elasticity on stress distribution in CAD/CAM dental crowns: Glass ceramic vs. polymer-matrix composite. J Dent 2015; 43: 742-749.
7) Awada A, Nathanson D. Mechanical properties of resin-ceramic CAD/CAM restorative materials. J Prosthet Dent 2015; 114: 587-593.
8) Henriques B, Goncalves S, Soares D, Silva FS. Shear bond strength comparison between conventional porcelain fused to metal and new functionally graded dental restorations after thermal-mechanical cycling. J Mech Behav Biomed Mater 2012; 13: 194-205.
9) Nagai T, Kawamoto Y, Kakehashi Y, Matsumura H. Adhesive bonding of a lithium disilicate ceramic material with resin-based luting agents. J Oral Rehabil 2005; 32: 598-605.
10) Leibrock A, Degenhart M, Behr M, Rosentritt M, Handel G. In vitro study of the effect of thermo- and load-cycling on the bond strength of porcelain repair systems. J Oral Rehabil 1999; 26: 130-137.
11) Lauvahunton S, Takahashi H, Shiozawa M, Iwasaki N, Asakawa Y, Oki M, Finger WJ, Arksornmukit M. Mechanical properties of composite resin blocks for CAD/CAM. Dent Mater J 2014; 33: 705-710.
12) Druck CC, Pozzobon JL, Callegari GL, Dorneles LS, Valandro LF. Adhesion to Y-TZP: ceramic: study of silica nanofilm coating on the surface of Y-TZP. J Biomed Mater Res B Appl Biomater 2015; 103: 143-150.
13) Matinlinna JP, Lassila LV, Vallittu PK. The effect of a novel silane blend system on resin bond strength to silica-coated Ti substrate. J Dent 2006; 34: 436-443.
14) Matinlinna JP, Lassila LV, Vallittu PK. Pilot evaluation of resin composite cement adhesion to zirconia using a novel silane system. Acta Odontol Scand 2007; 65: 44-51.
15) Matinlinna JP, Heikkinen T, Ozcan M, Lassila LV, Vallittu PK. Evaluation of resin adhesion to zirconia ceramic using some organosilanes. Dent Mater 2006; 22: 824-831.
16) Cunha LG, Alonso RC, de Souza-Junior EJ, Neves AC, Correr-Sobrinho L, Sinhoreti MA. Influence of the curing method on the post-polymerization shrinkage stress of a composite resin. J Appl Oral Sci 2008; 16: 266-270.
17) Liu X, Wang Z, Zhao C, Bu W, Zhang Y, Na H. Synthesis, characterization and evaluation of a fluorinated resin monomer with low water sorption. J Mech Behav Biomed Mater 2018; 77: 446-454.
18) Palin WM, Fleming GJ, Burke FJ, Marquis PM, Randall RC. The influence of short and medium-term water immersion on the hydrolytic stability of novel low-shrink dental composites. Dent Mater 2005; 21: 852-863.
19) Magne P, Stanley K, Schlichting LH. Modeling of ultrathin occlusal veneers. Dent Mater 2012; 28: 777-782.
20) Porto T, Roperto R, Akkus A, Akkus O, Porto-Neto S, Teich S, Lang L, Campos E. Mechanical properties and DIC analyses of CAD/CAM materials. J Clin Exp Dent 2016; 8: e512-e516.
21) Argyrou R, Thompson GA, Cho SH, Berzins DW. Edge-chipping resistance and flexural strength of polymer infiltrated ceramic network and resin nanocomposite restorative materials. J Prosthet Dent 2016; 116: 397-405.
22) Fabian Fonzar R, Carrabba M, Sedda M, Ferrari M, Goracci C, Vichi A. Flexural resistance of heat-pressed and CAD/CAM lithium disilicate with different translucencies. Dent Mater 2017; 33: 63-70.
23) ASTM-C1322-15. Standard practice for fractography and characterization of fracture origins in advanced ceramics. ASTM International 2015: 1-49.
24) Scherrer SS, Lohbauer U, Della Bona A, Vichi A, Tholey MJ, Kelly JR, Van Noort R, Cesar PF. ADM guidance-Ceramics: guidance to the use of fractography in failure analysis of brittle materials. Dent Mater 2017; 33: 599-620.
25) Coldeon A, Swain MV, Thiel N. In-vitro strength degradation of dental ceramics and novel PICN material by sharp indentation. J Mech Behav Biomed Mater 2013; 26: 34-42.
26) Albero A, Pascual A, Camps I, Grau-Benitez M. Comparative characterization of a novel cad-cam polymer-infiltrated-ceramic-network. J Clin Exp Dent 2015; 7: e495-500.
27) Chuang SF, Kang LL, Liu YC, Lin JC, Wang CC, Chen HM, Tai CK. Effects of silane- and MDP-based primers application orders on zirconia-resin adhesion-A ToF-SIMS study. Dent Mater 2017; 33: 923-933.
28) Musanje L, Darvell BW. Aspects of water sorption from the air, water and artificial saliva in resin composite restorative materials. Dent Mater 2003; 19: 414-422.

29) Qian Z, Li S, He Y, Zhang H, Liu X. Hydrolytic degradation study of biodegradable polyesteramide copolymers based on e-caprolactone and 11-aminoundecanoc acid. Biomaterials 2004; 25: 1975-1981.

30) Strauch J, McDonald J, Chapman BE, Kuchel PW, Hawkett BS, Roberts GE, Tonge MP, Gilbert RG. Diffusion coefficients of the monomer and oligomers in hydroxyethyl methacrylate. J Polym Sci Part A: Polym Chem 2003; 41: 2491-2501.

31) Coldea A, Swain MV, Thiel N. Mechanical properties of polymer-infiltrated-ceramic-network materials. Dent Mater 2013; 29: 419-426.

32) Guess PC, Schultheis S, Wolkewitz M, Zhang Y, Strub JR. Influence of preparation design and ceramic thicknesses on fracture resistance and failure modes of premolar partial coverage restorations. J Prosthet Dent 2013; 110: 264-273.

33) Otto T, Schneider D. Long-term clinical results of chairside Cerec CAD/CAM inlays and onlays: a case series. Int J Prosthodent 2008; 21: 53-59.

34) Desai PD, Das UK. Comparison of fracture resistance of teeth restored with ceramic inlay and resin composite: an in vitro study. Indian J Dent Res 2011; 22: 877.

35) Saridag S, Sevimay M, Pekkan G. Fracture resistance of teeth restored with all-ceramic inlays and onlays: an in vitro study. Oper Dent 2013; 38: 626-634.

36) Yu P, Xu Z, Arola DD, Min J, Zhao P, Gao S. Effect of acidic agents on the wear behavior of a polymer infiltrated ceramic network (PICN) material. J Mech Behav Biomed Mater 2017; 74: 154-163.

37) Moraguez OD, Wiskott HW, Scherrer SS. Three- to nine-year survival estimates and fracture mechanisms of zirconia- and alumina-based restorations using standardized criteria to distinguish the severity of ceramic fractures. Clin Oral Investig 2015; 19: 2295-2307.

38) Kelly JR. Clinically relevant approach to failure testing of all-ceramic restorations. J Prosthet Dent 1999; 81: 652-661.

39) Oilo M, Hardang AD, Ulsund AH, Gjerdet NR. Fractographic features of glass-ceramic and zirconia-based dental restorations fractured during clinical function. Eur J Oral Sci 2014; 122: 238-244.

40) Stappert CF, Att W, Gerds T, Strub JR. Fracture resistance of different partial-coverage ceramic molar restorations: An in vitro investigation. J Am Dent Assoc 2006; 137: 514-522.