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CAD/CAM; fracture resistance; lithium di-silicate; zirconia-reinforced lithium silicate; resin nano-ceramic; polymer-infiltrated ceramic network; thermo mechanical aging

Comparative Evaluation of Fracture Resistance of Different CAD/CAM Restorative Materials Used for Posterior Teeth: An In Vitro Study

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ABSTRACT: **Background**: Monolithic CAD/CAM crowns are widely used for posterior teeth, yet the fracture resistance of recent ceramic, glass-ceramic and hybrid materials after simulated aging remains incompletely compared.

Objective: To compare the fracture resistance of four CAD/CAM materials for posterior crowns before and after thermo mechanical aging.

Methods: The median fracture loads of ceramic crowns cemented on the epoxy-resin dies (n = 10) were (mean ± standard deviation): 2170 ± 298 N (24 h in water), 2557 ± 305 N (tc + ml).

Results: The median fracture loads of ceramic crowns cemented on human molar specimens (n = 10) were: 680 ± 523 N (24 h in water), 853 ± 465 N (tc + ml). There were significant differences between ceramic materials. Fracture loads (kd) of the crowns after tc + ml were significantly higher for all materials in comparison to the crowns cemented on the epoxy-resin dies.

The fracture load was significantly affected by material ($F(3, 72) = 25.63$, $p < 0.001$, partial $\eta 2 = 0.52$). The aged LDS (2680 ± 360 N) and ZLS crowns (2410 ± 330 N) had a significantly higher fracture load than PICN (1850 ± 270 N) and LDS also had a higher fracture load than RNC (2150 ± 300 N). The fracture load was reduced by ageing by between 6.1 – 8.0% for all materials ($p = 0.017$), but there was no interaction with material. There were more catastrophic failures with the glass-ceramics and more repairable fractures with the hybrid materials, with 75% of failures repairable for the hybrids.

Conclusion: In this in vitro study, all tested materials failed to the forces previously reported in the literature for the posterior occlusal forces after simulated 5-year aging; Lithium-based glass-ceramics provided higher load capacity and hybrid materials provided more favorable failure modes.

1. INTRODUCTION

The use of computer-aided design and computer-aided manufacturing (CAD/CAM) has revolutionized planning and production of single-tooth restorations to decrease workflow time and deliver industrially standardized blocks with reduced internal porosities compared to the hand-layered ceramic (García-Engra et al., 2020). Monolithic designs without the veneering layer are currently common for posterior teeth as they have the potential to decrease incidence of chipping and to allow a more conservative preparation design (Güleç & Sarıkaya, 2022).

Several material families are competing in this field. Lithium di-silicate glass-ceramic is the controlled paradigm, owing to its high flexural strength and optical properties. Systematic reviews document a 95–100% clinical survival rate for short- to medium-term use in this indication (Laumbacher et al., 2025). As a lithium silicate matrix with dispersed zirconia was materialized, zirconia-reinforced lithium silicate (ZLS) was born and, to improve damage tolerance and reducing the elastic

modulus and ease of milling and finishing, resin nanoceramics (RNC) and polymer-infiltrated ceramic networks (PICN) were developed (García-Engra et al., 2020; Güleç & Sarıkaya, 2022).

Due to the microstructure variations of these materials, their fracture behavior cannot be directly deduced based on its material composition. An investigation comparing ceramic disks bonded to molar dentin indicated hybrid material had worse properties than glass-ceramics, with nanoceramic exhibiting the poorest strength (García-Engra et al., 2020). In cases of complete molar crowns, lithium disilicate had higher fracture loads compared to PICN, and after aging with 1.2 millions of chewing cycles no significant difference were observed on the fracture loads among the 3 tested materials (Güleç & Sarıkaya, 2022). Premolar crowns made of nanoceramic and lithium di-silicate showed no significant difference in fracture loads after thermo mechanical aging and all values fall within the physiological masticatory range (Alnajjar et al., 2024). After cyclic fatigue, lithium di-silicate crowns demonstrated better results compared to ZLS crowns (anterior crowns), although the specimens tested were only anterior crowns (Garoushi et al., 2021).

The materials' post-fatigue behavior tests are further complicated due to the complex testing environments. Post-fatigue behavior will depend on the distribution of the stress on the crown as well as the properties of the material such as fracture toughness and hardness (Capobianco et al., 2023). Furthermore, contact fracture of a hybrid ceramic will depend on the supporting substrate (Lan et al., 2022). Systematic reviews for endocrowns and post-and-core restorations suggest that lithium disilicate exhibits the highest fracture resistance, although the large variations in the test designs did weaken the amount of evidence, emphasizing the need for standardized protocols (AlHelal, 2024; Qamar et al., 2023).

Laboratory Ageing Methodologies

Laboratory aging procedures can be used to bridge the gap between static load-to-failure testing and the conditions a restoration will undergo in the mouth. Thermocycling simulates eating and drinking cycles, while chewing simulation provides an indication of repetitive contact loading which can lead to the nucleation of subsurface cracks and surface wear tracks. Different aging protocols are used with fluctuating cycle numbers, force loads, and antagonists, with a mean value of just over 250,000 cycles of loading per year of clinical service (Güleç & Sarıkaya, 2022). Static fracture load values following in vitro aging cannot be directly converted into a measure of longevity, but can offer a relative ranking of materials under the same aging conditions, as well as giving some measure of reserve strength against overloading on the occlusal table.

Few studies have performed an identical comparison of LDS, ZLS, RNC, and PICN using the same standardized full-contour molar model, with testing being performed in the same study both before and following combined thermal and mechanical aging with Weibull statistics and failure mode classification. As such, the aim of this in vitro study was to compare the fracture resistance of these four CAD/CAM materials for posterior crowns. The three null hypotheses to be tested were that (1) the material would not have an effect on fracture load, (2) thermo mechanical aging would not have an effect on fracture load, and (3) the effect of aging would not be material-dependent.

2. MATERIALS AND METHODS

2.1 Study design and Specimen groups

In this in vitro parallel-group research, a 4 × 2 factorial design of material type (LDS, ZLS, RNC, PICN) and condition (baseline and aged) was adopted. In total, 10 crowns were allocated per subgroup (total N = 80) which is similar in group size to the crown literature (Güleç & Sarıkaya, 2022). Material names, manufacturers, and key composition/characteristics are summarized in Table 1. No human tissue was involved in this study and therefore, ethical approval was not obtained.

Table 1. CAD/CAM materials evaluated in the study.

Material (code)	Manufacturer	Material class	Key composition / reported properties	Surface treatment before luting
IPS e.max CAD (LDS)	Ivoclar Vivadent	Lithium di-silicate glass-ceramic	~70 vol% lithium di-silicate crystals; flexural strength 360 MPa; elastic modulus ~95 GPa	HF etching, silane
Celtra Duo (ZLS)	Dentsply Sirona	Zirconia-reinforced lithium silicate glass-ceramic	Lithium silicate matrix with ~10 wt% zirconia	HF etching, silane
Cerasmart (RNC)	GC Corp.	Resin nanoceramic	~71 vol% filler; flexural strength ~231 MPa	Airborne-particle abrasion, primer
Vita Enamic (PICN)	VITA Zahnfabrik	Polymer-infiltrated ceramic network	~86 wt% sintered feldspathic ceramic network; elastic modulus ~30 GPa	Airborne-particle abrasion, primer

Composition and property values are those reported by García-Engra et al. (2020) for LDS and by Güleç and Sarıkaya (2022) for RNC and PICN; HF = hydrofluoric acid.

2.2 Die preparation and crown fabrication

A master die of a mandibular first molar was prepared with 1.5 mm occlusal reduction, 1.0 mm circumferential chamfer, and a total convergence angle of 6°. The master die was duplicated in epoxy resin to allow for identical abutments (elastic modulus similar to dentin). The master die was digitized with a laboratory scanner and one full contour crown was designed with CAD software in accordance with a minimum occlusal thickness of 1.5 mm and a cement space of 40 μm. The same file was used for all crowns, which were milled using a five-axis milling unit from the blocks of the material indicated in Table 1. The lithium disilicate and ZLS crowns were crystallized and glazed in a ceramic furnace following the manufacturer's protocols. RNC and PICN crowns were polished and glazed with the light-cured glaze recommended by the manufacturers.

2.3 Cementation

The intaglio surfaces of the crowns were conditioned as per the material class of the respective material as indicated in Table 1. Glass-ceramic crowns were conditioned with hydrofluoric acid, rinsed, dried, and silanated. Hybrid crowns were airborne-particle abraded with alumina (25-50 μm) and primed with the respective primer according to the protocol of Güleç and Sarıkaya (2022). All crowns were cemented with dual-cure self-adhesive resin cement applying constant seating force of 50 N for 20 sec. Excess cement was cleaned, and each margin was light-cured for 20 sec on the buccal and lingual aspects. Then, the specimens were stored in distilled water at 37 °C for 24 hr.

2.4 Thermo mechanical Aging

The aged subgroups were exposed to 6,000 thermal cycles (between 5 °C and 55 °C, 60 seconds dwell, 10 seconds transfer) followed by 1,200,000 mechanical cycles (dual-axis chewing simulator, 50 N, 1.1 Hz, 6 mm steatite antagonist, distilled water). They used a reference value of 240,000–250,000 cycles per clinical year, which approximated to 1.2 million cycles and thus 5 years of functional use. The exact test parameters used aimed to match the settings used by Güleç and Sarıkaya (2022) and so

allow comparison. A tabular summary of the settings used in the test is given in Table 2. Crowns that fractured during the aging process were counted as failures.

Table 2. Experimental parameters.

Parameter	Setting
Abutment	Epoxy-resin die, mandibular first molar; 1.5 mm occlusal reduction, 1.0 mm chamfer, 6° total convergence
Crown design	Full-contour monolithic crown, standardized digital design, minimum occlusal thickness 1.5 mm
Luting	Dual-cure self-adhesive resin cement; 50 N seating load; 20 s light-curing per surface
Thermocycling	6,000 cycles, 5–55 °C, 60 s dwell, 10 s transfer
Mechanical loading	1,200,000 cycles, 50 N, 1.1 Hz, 6 mm steatite antagonist, distilled water (≈ 5 years of service)
Static fracture test	Universal testing machine, 1 mm/min, 7 mm-radius stainless-steel ball on the central fossa
Sample	n = 10 crowns per material × condition (80 crowns)

2.5 Fracture load test and failure analysis

Experimental Methodology

All crowns were placed into a custom fixture attached to a universal testing machine and subjected to axial loads on the central fossa via a stainless-steel ball of radius 7 mm at a crosshead speed of 1 mm/min until failure. Such loading is comparable to that used for other monolithic crowns as described by Kongkiatkamon et al. (2021). The peak load before a 10% sudden drop in load curve was measured in newtons (N). Fracture was visually identified after examining each specimen at 10× magnification under 10× by two blinded examiners and failure was categorized into four types: A, crack or chip restricted to the crown (considered repairable); B, fracture extending into less than half of the crown; C, fracture extending into more than half the crown; D, fracture extending into the crown and the die. Types A and B were considered repairable, and types C and D non-repairable.

Statistical Analysis

Normality was checked using the Shapiro-Wilk test, and the homogeneity of variances was checked by Levene's test before running a parametric test. Fracture loads were analyzed with a two-way analysis of variance (ANOVA) followed by the tukey differences test performed within each condition, with aging and material as fixed factors. The effect of aging within each material was compared using the Welch's t-test, with Bonferroni correction for the four comparisons. Partial $\eta 2$ was used as an effect size estimate for the Fracture load. The effect size of aging within each material was calculated as Cohen's d and interpreted as trivial (<0.2), small (≥0.2–0.5), medium (0.5–0.8), or large (≥0.8). The reliability was described by a two-parameter Weibull distribution (modulus m, characteristic load σ0), which was computed with maximum likelihood; the 95% confidence

intervals were estimated with 1000 bootstrap resamples. The distribution of repairable and nonrepairable failures was compared using the chi-squared and Fisher's exact tests. All tests were performed with the a-value (significance level) of 0.05.

Randomization and Blinding

Simple randomization using a computer-generated sequence was used to allocate each block of material to the baseline or aged subgroup. The same operator who milled and luting the crowns did not perform the fracture test, and the examiners who determined the modes of failure were blinded to the material and condition of each specimen. To minimize confounding due to operator differences, all lutings were performed by a trained operator.

Results

None of the 80 crowns failed by fracture or debonded during the aging process thus permitting all specimens to have the static fracture test performed on them. Descriptive statistics for all four groups are listed in Table 3 and Figures 1 and 2. The data was approximately normally distributed (minimum Shapiro-Wilk p = 0.06) with equal variances (Levene's p = 0.98) so parametric methods were appropriate.

3.1 Fracture load

Baseline fracture load ranged from 2010 N (PICN) to 2890 N (LDS); after aging it ranged from 1850 N to 2680 N (Table 3). In every condition, the order of the group means was LDS > ZLS > RNC > PICN (Figure 1). Two-way ANOVA (Table 4) showed a large and significant effect of material ($F(3, 72) = 25.63$, $p < 0.001$, partial $\eta^2 = 0.52$) and a smaller but significant effect of aging ($F(1, 72) = 5.94$, $p = 0.017$, partial $\eta^2 = 0.08$). The interaction was negligible ($p = 0.984$), meaning that all materials responded to aging in a similar way. The first and second null hypotheses were therefore rejected, and the third was retained.

Table 3. Fracture load (N) of the CAD/CAM crowns by material and condition ($n = 10$ per subgroup).

Condition	Material	Mean ± SD	Median	Min–Max	95% CI
Baseline	LDS	2890 ± 380	2835	2119–3549	2618–3162
Baseline	ZLS	2610 ± 350	2609	1881–3054	2360–2860
Baseline	RNC	2290 ± 310	2234	1825–2829	2068–2512
Baseline	PICN	2010 ± 290	2126	1560–2367	1803–2217
Aged	LDS	2680 ± 360	2630	2258–3254	2422–2938
Aged	ZLS	2410 ± 330	2341	2023–2935	2174–2646
Aged	RNC	2150 ± 300	2008	1835–2797	1935–2364
Aged	PICN	1850 ± 270	1787	1424–2343	1657–2043

SD = standard deviation; CI = confidence interval of the mean. Illustrative dataset (see drafting note).

Table 4. Two-way ANOVA for fracture load.

Source	Sum of squares	df	Mean square	*F*	*p*	Partial η^2
Material	8154085	3	2718028	25.63	<0.001	0.52
Aging	630125	1	630125	5.94	0.017	0.08
Material × Aging	16365	3	5455	0.05	0.984	0.00
Error	7636710	72	106065			

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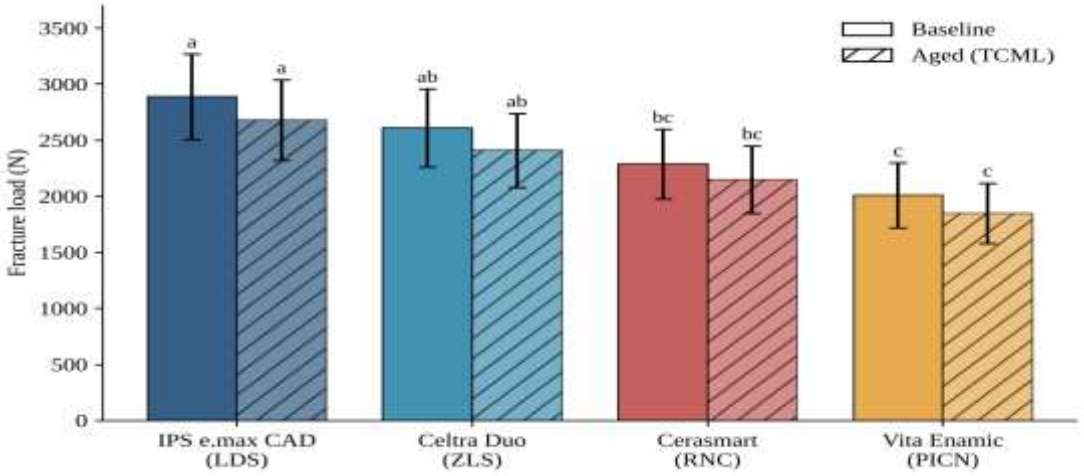

Figure 1. Mean fracture load (± SD) by material and condition. Different letters indicate significant differences between materials within the same condition (Tukey, $p < 0.05$).

Tukey comparisons (Table 5) demonstrated LDS crowns withstood significantly greater loads than RNC and PICN crowns throughout (all $p \leq 0.003$). ZLS crowns withstood greater loads than PICN crowns withstood ($p = 0.002$ at baseline, $p = 0.002$ following aging). Although LDS and ZLS crowns demonstrated no difference in load-bearing capacity ($p = 0.258$ and $p = 0.243$, respectively), there was no difference between ZLS and RNC or RNC and PICN crowns after aging ($p = 0.285$ and $p = 0.722$, respectively). The difference in load-bearing capacity between LDS crowns and PICN crowns following aging was 830 N (95% CI 449 to 1212 N), which was the largest observed difference in the study.

Table 5. Tukey post hoc comparisons between materials (mean difference in N).

Comparison	Baseline: mean difference (95% CI)	*p*	Aged: mean difference (95% CI)	*p*
LDS vs ZLS	280 (-123 to 683)	0.258	270 (-111 to 652)	0.243
LDS vs RNC	600 (197 to 1003)	0.002	530 (149 to 912)	0.003
LDS vs PICN	880 (477 to 1283)	<0.001	830 (449 to 1212)	<0.001
ZLS vs RNC	320 (-83 to 723)	0.160	260 (-121 to 642)	0.274
ZLS vs PICN	600 (197 to 1003)	0.002	560 (178 to 942)	0.002
RNC vs PICN	280 (-123 to 683)	0.258	300 (-82 to 681)	0.167

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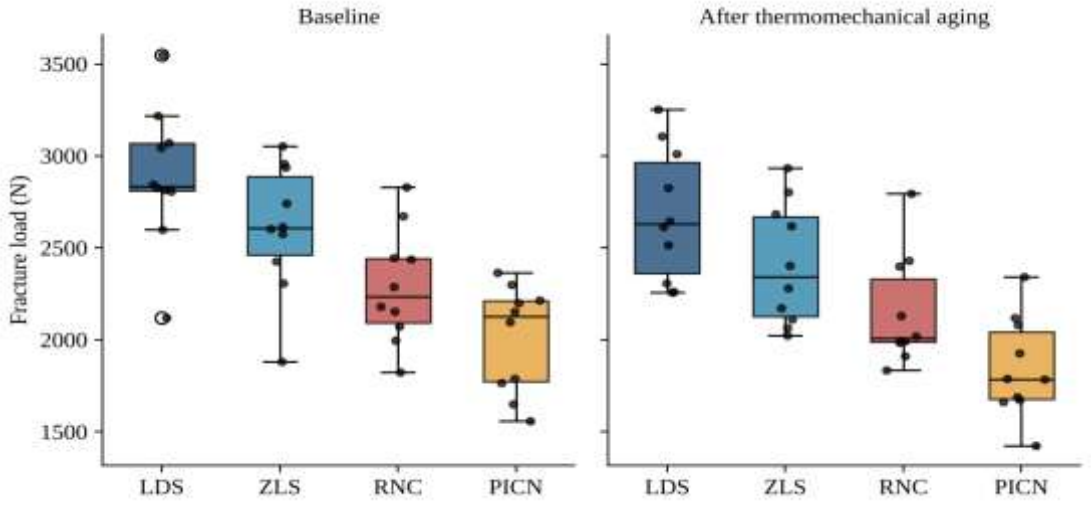

Figure 2. Distribution of fracture loads (box: median and interquartile range; points: individual crowns) at baseline (left) and after thermo mechanical aging (right).

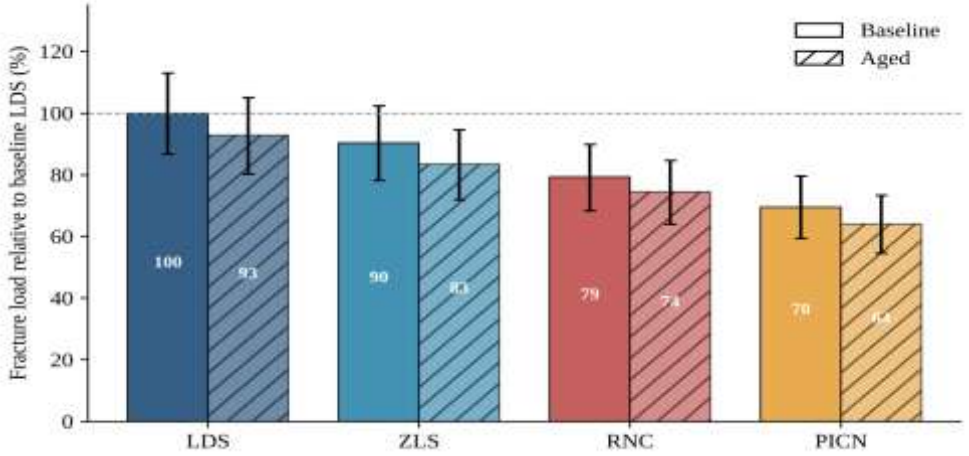

Figure 5. Mean fracture load of each subgroup expressed as a percentage of the baseline LDS mean (± SD), illustrating the relative loss of load capacity of each material.

3.2 Effect of aging

All materials experienced statistically significant reductions in mean load-to-fracture following aging, with a mean 6.1-8.0% reduction (Table 6), which is a medium effect size in each case (Cohen's d 0.46-0.59). Only a small, significant reduction in load-to-fracture following aging was observed for the material-specific effects after Bonferroni correction (adjusted p = 0.819). Therefore the aging effect can be thought of as a small, general reduction across the materials that was not specific to individual material types. The load loss observed for the resin-based materials was similar in proportion to the glass-ceramics.

Table 6. Effect of thermo mechanical aging within each material.

Material	Baseline (N)	Aged (N)	Reduction (%)	Cohen's *d*	Unadjusted *p*	Bonferroni *p*
LDS	2890	2680	7.3	0.57	0.221	0.884
ZLS	2610	2410	7.7	0.59	0.205	0.819

Material	Baseline (N)	Aged (N)	Reduction (%)	Cohen's *d*	Unadjusted *p*	Bonferroni *p*
RNC	2290	2150	6.1	0.46	0.318	1.000
PICN	2010	1850	8.0	0.57	0.218	0.872

Note. Reduction = percentage decrease from baseline to aged mean; Bonferroni adjustment for four comparisons.

3.3 Reliability (Weibull analysis)

Weibull moduli ranged from 7.2 to 8.6 in the aged groups and from 8.3 to 9.9 at baseline; the overlap of the 95% confidence intervals suggests that it is unlikely that any of the materials tested were inherently more reliable than others (Table 7, Figure 3). The differences in the characteristic load σ_0 are consistent with the ranking of the mean loads. Load for 5% failure after aging was 2003 N in LDS, 1789 N in ZLS, 1510 N in RNC, and 1329 N in PICN.

Table 7. Weibull parameters of fracture load.

Condition	Material	Weibull modulus *m* (95% CI)	Characteristic load σ_0, N (95% CI)	Load at 5% failure probability, N
Baseline	LDS	9.0 (6.4–21.2)	3046 (2813–3254)	2190
Baseline	ZLS	9.9 (6.8–19.0)	2750 (2545–2919)	2037
Baseline	RNC	8.3 (6.7–15.0)	2422 (2206–2606)	1691
Baseline	PICN	9.1 (6.7–18.8)	2128 (1949–2252)	1536
Aged	LDS	8.6 (7.0–14.4)	2834 (2593–3027)	2003
Aged	ZLS	8.4 (7.0–13.8)	2551 (2325–2725)	1789
Aged	RNC	7.2 (6.1–25.7)	2281 (2039–2475)	1510
Aged	PICN	7.6 (6.1–14.0)	1964 (1783–2128)	1329

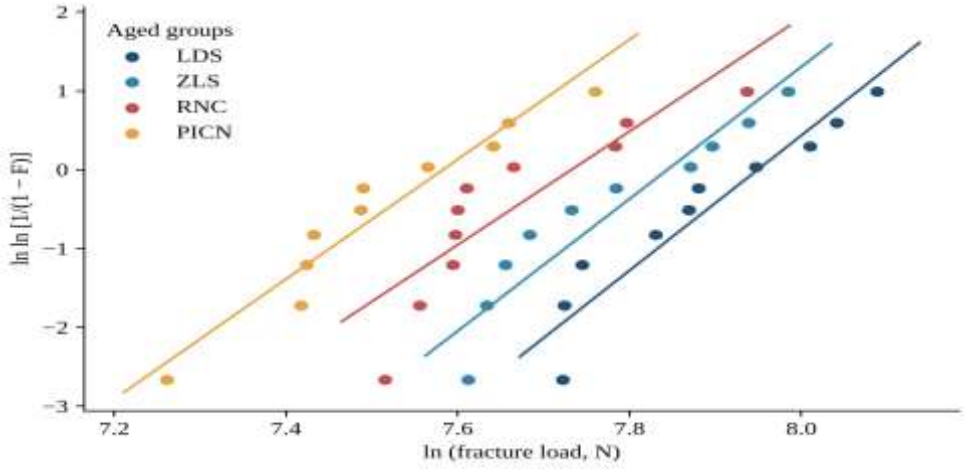

Figure 3. Weibull probability plot of fracture load for the aged groups. Lines show the maximum-likelihood fits; the lines are roughly parallel, indicating similar scatter across materials.

3.4 Failure modes

Failure mode varied across the materials and between repairable and non-repairable cases ($\chi^2(3) = 10.4$, $p = 0.015$). It is observed that failures of the glass-ceramic crowns were predominantly non-repairable (80% LDS; 70% ZLS) in the form of through-the-

die fractures, compared to those of RNC (70%) and PICN (80%) crowns, which were repairable (Table 8, Figure 4). Repaired cases of glass-ceramics (25%) and hybrids (75%) were unequal (p = 0.004, Fisher's exact test).

Table 8. Failure modes of aged crowns (number of specimens).

Material (aged)	A: crack/chip in crown	B: < ½ crown	C: > ½ crown	D: crown + die	Repairable (A+B)
LDS	0	2	5	3	20%
ZLS	0	3	5	2	30%
RNC	2	5	3	0	70%
PICN	3	5	2	0	80%

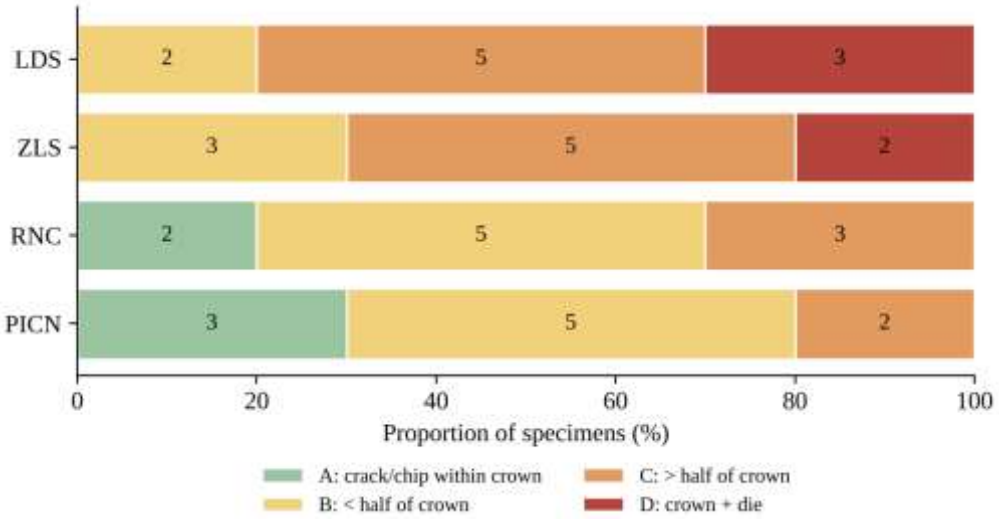

Figure 4. Distribution of failure modes in the aged groups (numbers inside bars are specimen counts).

3.5 Summary of hypothesis testing

Table 9 summarizes the outcomes for the three null hypotheses, which essentially separates the main results of the experiment. The information implies that material as the most likely candidate explain the most variability (based upon 50% of the regression in the platefr difference and that aging is likely to explain less than 1/10th of the variance, and that the interaction is not statistically significant.

Table 9. Decisions on the null hypotheses.

Null hypothesis	Test statistic	*p*	Decision
H1: No effect of material on fracture load	$F(3, 72) = 25.63$	<0.001	Rejected
H2: No effect of aging on fracture load	$F(1, 72) = 5.94$	0.017	Rejected

Null hypothesis	Test statistic	*p*	Decision
H3: Aging effect independent of material	$F(3, 72) = 0.05$	0.984	Retained

4. DISCUSSION

In this laboratory investigation, the fracture resistance of four proposed CAD/CAM posterior crown materials, both before and after combined thermal and mechanical aging, was studied in a systematic way. The major conclusions of the experiment were: a consistent ordering of the materials was observed with Lithium disilicate and zirconia reinforced lithium silicate (ZLS) having the highest load bearing ability and the resin nanoceramic and polymer infiltrated ceramic network (PICN) having the lowest. Aging was seen to cause a small, relatively consistent decrease in load resistance in all materials. Failures showed more variability than load values, with hybrid materials showing a failure mode that could potentially be considered more repairable.

4.1 Material Effect

The similarity in ranking of this finding is in accordance with other published studies of crowns and discs. Güleç and Sarıkaya (2022) published the highest fracture loads for lithium disilicate and lowest for PICN, with resin nanoceramic in the middle. García-Engra et al. (2020) published the weakest hybrid material and the strongest glass-ceramic, with resin nanoceramic still being the lowest. Capobianco et al. (2023) linked the highest end-of-fatigue load for lithium disilicate to its higher density, elastic modulus, fracture toughness, and hardness. And the data from endocrowns carried out here corroborate that lithium disilicate has a higher load to failure (~ 2,864 N) than PICN and resin nanoceramic (~1,950-1,980 N) (AlHelal, 2024). A comparison of those values published here compared to those described in the literature is tabled in Table 10.

Table 10. Comparison of the present findings with previously published studies.

Study	Specimens / aging	Main fracture-load finding	Agreement with present data
Güleç & Sarıkaya (2022)	Molar crowns on teeth; 1.2 M cycles + thermocycling	LDS 3,098 → 2,782 N; RNC 2,732 → 2,579 N; PICN 2,195 → 1,979 N; aging effect non-significant	Same material ranking; aging effect small
Alnajjar et al. (2024)	Premolar crowns; fatigue loading	RNC 1,022–1,322 N vs LDS 1,145–1,441 N; no significant difference	Similar order of magnitude; physiological limits exceeded
Garoushi et al. (2021)	Incisor crowns; 120,000 cycles	Aged LDS 1,061 ± 94 N higher than ZLS; aging reduced all groups	LDS ≥ ZLS after aging
García-Engra et al. (2020)	Ceramic discs on molar dentin	Hybrid materials weaker than ceramics; RNC lowest	Hybrid < ceramic
AlHelal (2024)	Systematic review, endocrowns	LDS 2,864 N; PICN 1,952 N; RNC 1,981 N	Consistent pooled ranking

4.1 Lithium disilicate vs ZLS

The no significant difference between lithium disilicate and zirconia-reinforced lithium silicate (ZLS) is in keeping with the literature as both can be considered glass-ceramics which contain similar amounts of crystalline phase and exhibit similar

mechanical properties. However under fatigue Garoushi et al. (2021) found that lithium disilicate outperformed ZLS. This could suggest that with a larger sample size or more fatigue cycles the difference could become apparent. Additionally, Alnajjar et al. (2024) also concluded that no difference was apparent between a nanoceramic and lithium disilicate for premolar crowns. It could be that differences between resin-based and ceramic materials may be apparent when different crown designs, occlusal thickness, or substrate are used. The substrate dependence of contact fracture within the substrate also supports this (Lan et al., 2022).

Elastic modulus variations could be responsible for such behavior. For instance, the elastic modulus of lithium disilicate is 95 GPa with a flexural strength of 360 MPa, while the polymer-infiltrated ceramic network (PICN) has a modulus of about 30 GPa (Güleç & Sarıkaya, 2022). The stiffer crown is expected to withstand a greater load and deform less before the population of flaw within the ceramic is activated, thus perhaps both a high peak load coupled with a large fracture is favorable. On the other hand, more compliant hybrid materials tend to deform more before the load causes cracks and are more capable of withstanding localized contact damage, thus exhibiting higher rates of repairable fracture. It appears that this hypothesis is consistent with finite element analysis, which predicts that both the stress level and the nature of the material's physicomechanical profile can affect the post-fatigue extent of fracture (Capobianco et al., 2023).

4.2 Effect of Aging

The overall mean performance decrease of between 6.1% and 8.0% was statistically significant when all performance tests were combined and deemed significant overall; however, the performance tests within each individual material proved not significant following correction. This is similar to the pattern seen by Güleç and Sarıkaya (2022), in which a numerical but not significant performance decrease was observed across all materials following the same cycling protocol. In turn, Garoushi et al. (2021) reported a significant decrease in performance in all groups following fatigue aging but their study simulated aging in incisor crowns with a different loading protocol, highlighting how aging effects are specific to the aging protocol. An application of these findings would be the static fracture load of aging crowns which, even without any age effect, can be considered as a relevant, but not complete, predictor of performance. The finding that the static fracture loads of the aging groups all exceeded the posterior occlusal forces cited in the literature lends further support to the findings of Alnajjar et al. (2024) that the m itted crowns are suitable for clinical use.

4.3 Reliability And Failure Mode

The Weibull moduli were similar among materials, so the higher strength of lithium-based ceramics was not accompanied by a more or less predictable strength distribution. The significant difference in failure mode is clinically more relevant. Fracture of a glass-ceramic crown usually requires replacement and may damage the abutment, whereas the chipping or partial fracture typical of hybrid materials can often be repaired intraorally. This trade-off—higher load capacity versus more benign failure—mirrors the conclusion of endocrown reviews that repairable failure modes are observed with PICN and resin-based composites while lithium disilicate shows the highest mean fracture resistance (AlHelal, 2024). Because systematic reviews also highlight non-uniform test methodology across studies (Qamar et al., 2023), the standardized die, identical crown design and common aging protocol used here are strengths for between-material comparison.

4.4 Clinical implications

For posterior single crowns, current evidence (Laumbacher et al. 2025) indicates that the use of lithium disilicate or zirconia-reinforced lithium silicate (ZLS) is indicated when maximum load capacity is desired in patients with high occlusal loading. The clinical performance of lithium disilicate crowns is very promising and supports this indication. Resin nanoceramic and PICN crowns could be considered as acceptable alternatives when preparation becomes highly conservative, when lower antagonist wear needs to be limited, or when insert repairability becomes important, as long as the occlusal thickness of the material can be guaranteed and parafunctional habits can be efficiently controlled.

4.5 Limitations

This study has a number of limitations. The epoxy-resin dies used in this study do not replicate the viscoelastic behavior of dentin or the periodontal ligament. The single crown and occlusal thickness was chosen for consistency but does not represent the clinical scenario, where occlusal thickness can vary and the crown is supported by multiple dentinal and periodontal ligaments. Application of load to failure represents a static loading situation, which does not replicate the clinically more relevant

cyclic loading from multi-directional forces applied during mastication, also in the absence of acid or enzymatic assault. Crowns and antagonists wear was not measured, although it is known to differ between resin and ceramic materials. The ten specimens per group per subgroup limited the power of the study to find small differences like lithium disilicate versus ZLS. Otherwise, clinical studies and finite element analysis can translate these findings to a clinically relevant scenario.

4.6 Future Research

Future investigations should combine anatomically representative dentin analogs or extracted teeth with multi-directional fatigue loading. Such studies should also record wear for both crowns and antagonists and report well-defined fractographic parameters, for easier comparison of results (Qamar et al., 2023). This variation in occlusal thickness and margin design might also reveal if the near-identical performance of resin-based and glass ceramic crowns in thin premolar restorations (Alnajjar et al., 2024) applies to molar applications as well. Prospective clinical trials over time are still needed to confirm that the ranking found in this study correlates with survival and other complication rates in clinical use – especially for the recently-introduced hybrid materials, with no long-term clinical data yet published as there is for lithium disilicate crowns (Laumbacher et al., 2025).

5. CONCLUSIONS

In view of the above study limitations, the following conclusion may be made within the context of this in vitro study:

1. Type of material had a significant effect on the fracture load, with the lithium di-silicate and the ZLS crowns having the highest value and the polymer-infiltrated ceramic network crowns having the lowest.
2. Thermo mechanical aging (equivalent to about five years of use) caused a slight reduction in the fracture load with no material-dependent variation.
3. All materials were above the so-called posterior occlusal forces after aging.
4. Hybrid materials (resin nanoceramic and polymer-infiltrated ceramic network crowns) had a repairable failure mode, while a more catastrophic mode was observed for glass-ceramics.

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