Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Load-bearing capacity of pressable lithium disilicates applied as ultra-thin occlusal veneers on molars

Katrin Zumstein [a,1], Lorenzo Fiscalini [a,1], Nadin Al-Haj Husain [a,b], Erkan Evci [a], Mutlu Özcan [a], Alexis Ioannidis [a,*]

[a] University of Zurich, Center of Dental Medicine, Clinic of Reconstructive Dentistry, Zurich, Switzerland
[b] University of Bern, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, Bern, Switzerland

ARTICLE INFO

Keywords:
Ceramics
Computer-aided design
Computer-aided manufacturing
Dental materials
Dental porcelain
Fatigue
Lithium-disilicate ceramic
Occlusal dental veneers
Prosthetic dentistry

ABSTRACT

Purpose: The aim was to investigate the load bearing capacity of different pressable lithium disilicates cemented as occlusal veneers on molars.

Materials and methods: One control group and six test groups were formed consisting of 20 specimens each ($n = 20$). The six test groups differed in the utilizing pressable lithium disilicate to fabricate occlusal veneers. As a control group, "group Lis", the lithium disilicate with the highest reported flexural strength was used (initial LiSi Press, GC Europe; Leuven, Belgium / flexural strength: 508 MPa). The test groups consisted of other pressable lithium disilicates with lower flexural strength values: "Ema" (IPS e.max press), "Vit" (VITA Ambria), "Liv" (Livento Press), "Amb" (Amber Press), "Mas" (Amber Press Master) and "Ros" (Rosetta SP)". After the preparation of 140 extracted human molars, which included the removal of the central enamel, the specimens were scanned using a desktop scanner. With the aid of a design software, the occlusal veneers were designed in a standardized thickness of 0.5 mm. To fabricate the restorations, all tested materials were processed using heat-pressing technique. All restorations were adhesively cemented. Afterwards, the specimens underwent cyclic fatigue during an aging procedure in a chewing simulator (1'200'000 chewing-cycles, 49 N force, 5–55°C temperature changes). Subsequently, the specimens were statically loaded and the load which was necessary to fracture the specimen (F_{max}) were measured. Differences between the groups were compared applying the Kruskal-Wallis (KW) test and the Wilcoxon-Mann-Whitney-Test (WMW: $p < 0.05$). The two-parameter Weibull distribution values were calculated.

Results: The fatigue resistance was 100% for the groups Lis, Vit, Liv, Amb, Mas and Ros, whereas the group Ema showed a fatigue resistance of 95%. The control group Lis showed median F_{max} values of 2'328 N. The median F_{max} values for the test groups ranged between 1'753 N (Vit) and 2'490 N (Ros). Statistically significant difference was observed among the groups Lis (control) and Vit (KW: $p < 0.001$). Weibull distribution presented the highest shape values for the group Ros (12.83) and the lowest values for the group Ema (4.71).

Conclusion: Regarding their load-bearing capacity different pressable lithium disilicates can be recommended to fabricate ultra-thin occlusal veneers on molars when restoring occlusal tooth wear.

1. Introduction

Erosive tooth wear can result in a detrimental loss of tooth substance and lead to the exposure of dentin (Peutzfeldt et al., 2014). To reduce the associated symptoms, e.g. hypersensitivity, it may be clinically necessary for patients to have the worn dentition restored (Loomans et al., 2017). To compensate for the lost tooth substance by indirect means, defect-oriented minimally invasive treatment concepts have been developed (Donovan et al., 2021; Loomans et al., 2017). In the posterior region, the applied restorations in this indication are often fabricated out of heat-pressed lithium disilicate (Alkadi and Ruse, 2016; Guess et al., 2013; Ioannidis et al., 2019; Maeder et al., 2019). A systematic review including in vitro studies on occlusal veneers, suggested that lithium disilicate can withstand maximum bite forces in the posterior

---

* Corresponding author. Clinic of Reconstructive Dentistry, Center of Dental Medicine, University of Zurich, Plattenstrasse 11, CH-8032 Zurich, Switzerland.
E-mail address: alexis.ioannidis@zzm.uzh.ch (A. Ioannidis).

[1] equally contributing authors.

https://doi.org/10.1016/j.jmbbm.2022.105520
Received 30 June 2022; Received in revised form 4 October 2022; Accepted 7 October 2022

region (Albelasy et al., 2020).

For the fabrication of lithium disilicate occlusal veneers, today different methods are available (Anadioti et al., 2015). Among other methods, lithium disilicate restorations can be manufactured by the heat-pressing technique (Gakis et al., 2022). This technique uses ad wax-template which is fixated and vested into a mold. The vested templates are heated in an oven and the pressable lithium disilicate ingots are then heat-pressed into the resulting void in a heat-pressing sintering-oven.

Recently, different pressable lithium disilicates ingots are introduced. Lithium disilicate ingots usually contain SiO_2 (57–80 wt%), Li_2O (11–19 wt%), K_2O (0–13 wt%), P_2O_5 (0–11 wt%), ZrO_2 (0–8 wt%), ZnO (0–8 wt%) and other oxides and ceramic pigments (0–10 wt%) (information provided by the manufacturers). The exact composition in wt% varies among the different available materials.

The flexural strengths provided by the manufacturers for pressable lithium disilicate materials range between 396 and 508 MPa. These values are derived from standardized biaxial flexural tests and are a measure of the mechanical performance of a material (De Angelis et al., 2021; Lin et al., 2012). When applied as occlusal veneer, lithium disilicate is adhesively bonded to the underlying tooth. Evidence suggests that the adhesive bond is crucial for occlusal veneers to be able to withstand high loads (Ioannidis et al., 2019; Morikofer et al., 2021). In this context, one can anticipate that the adhesion between the tooth substance and the cementation surface of the used materials can render individual minor differences in the mechanical performance in this application irrelevant.

Yet, no study exists which compares currently marketed pressable lithium disilicates applied as occlusal veneers. Thus, the aim of this study was to investigate the load bearing capacity of six different pressable lithium disilicates as occlusal veneers on molars. The null hypothesis was that load-bearing capacity (F_{max}) among the tested groups would not show significant difference.

2. Material and methods

2.1. Sample size calculation and group formation

One control group and six test groups were formed which consisted of 20 specimens each (n = 20) (Table 1). The calculation of the sample size (G*Power 3.1; Heinrich Heine University, Dusseldorf, Germany) was based on mean F_{max} values and determined by using data from a former publication (Maeder et al., 2019). To reach a power of 95% in a two-tailed *t*-test (group 1: 1’415 ± 569 MPa; group 2: 845 ± 320 MPa, $\alpha = 0.05$), a specimen number of 19 per group was suggested. In this experiment, n = 20 was used.

The seven groups differed in the utilized pressable lithium disilicate to fabricate the occlusal veneers. As a control group, “group Lis”, the lithium disilicate with the highest reported flexural strength was used (initial LiSi Press, GC Europe; Leuven, Belgium / flexural strength: 508 MPa). The test groups consisted of pressable lithium disilicates with lower flexural strength values: “Ema” (IPS e.max press; Ivoclar Vivadent, Schaan, Liechtenstein / flexural strength: 470 MPa), “Vit” (VITA Ambria; VITA Zahnfabrik, Bad Säckingen, Germany / flexural strength 396 MPa), “Liv” (Livento Press; Centres+Metaux SA, Biel, Switzerland / flexural strength: 400MPA), “Amb” (Amber Press; HASS Corporation, Gwahakdanjiro Gangneung-si, Korea / flexural strength: 450 MPa), “Mas” (Amber Press Master; HASS Corporation, Gwahakdanjiro Gangneung-si, Korea / flexural strength: 450 MPa) and “Ros” (Rosetta SP; HASS Corporation, Gwahakdanjiro Gangneung-si, Korea / flexural strength: 460 MPa). To fabricate the restorations, all the tested materials were processed with the heat-pressing technique.

2.2. Specimen preparation

The apical part of 140 intact extracted human molars was embedded in an acrylic hollow cylinder made of 3D printed resin (Med 610; Stratasys, Rechovot, Israel) with the aid of self-curing resin (Technovit 4071; Kulzer, Wasserburg, Germany). In order to imitate a substance deficiency derived from erosions or attritions of the teeth, the occlusal enamel of the molars was removed to expose an inner part of dentin, edged by a border of enamel (WS Flex 18 C P80 to P2500; Hermes Schleifwerkzeuge, Hamburg, Germany / LaboPol-21; Struers, Ballerup, Denmark). Thereafter, the teeth were additionally prepared with diamond burs, including the removal of the remaining sharp edges and a slight opening of the fissures (FG D18 GB, FG250A GB, FG 405L GB, FG201 GB, FG D3 GB; Intensiv SA, Montagnola, Switzerland). The specimens were allocated randomly to one of the experimental groups and stored in 0.5% Chloramin T throughout the whole duration of the study.

Table 1
Restorative materials and respective compositions for the control and the test groups provided by the manufacturer.

Group	Restorative material	Chemical composition	Flexural Strength (MPa)
Lis	Lithium disilicate ceramic (Initial LiSi Press; GC Europe, Leuven, Belgium)	SiO2 (57–80), Li2O (11–19), K2O (0–13), P2O5 (0–11), ZrO2 (0-8), ZnO (0–8), other oxides and ceramic pigments (0–10)	508
Ema	Lithium disilicate ceramic (IPS e.max Press; Ivoclar Vivadent, Schaan, Liechtenstein)	SiO2 (71.9), Al2O3 (5.4), Li2O (13), K2O (2), Na2O (1.4), P2O5 (2.6), B2O3 (0.007), ZrO2 (1.7), CeO2 (1.2), V2O5 (0.15), Tb203 (0.35), Er2O3 (0.4), HfO2 (0.03)	470
Vit	Lithium disilicate ceramic (VITA Ambria; Vita Zahnfabrik, Bad Säckingen, Germany)	SiO2 (58–66), ZrO2 (8–12), Li2O (12–16), Pigments (<10), various (>10)	396
Liv	Lithium disilicate ceramic (Livento Press; Centres+Metaux SA, Biel, Switzerland)	SiO2 (65–80), Al2O3 (0–11), Li2O (11–19), K2O (0–7), Na2O (0-5), CaO (0–10), P2O5 (1.5–7), ZnO (0–7), others (0–15)	400
Amb	Lithium disilicate ceramic (Amber Press; HASS Corporation, Gwahakdanjiro Gangneung-si, Korea)	SiO2 (68–86), Li2O (10–15), P2O5 (2–5), K2O (0–2), Na2O (0–2), others (2–8)	450
Mas	Lithium disilicate ceramic (Amber Press Master; HASS Corporation, Gwahakdanjiro Gangneung-si, Korea)	SiO2 (70–85), Li2O (10–15), Al2O3 (1–8), others (2–15)	450
Ros	Lithium disilicate ceramic (Rosetta SP; HASS Corporation, Gwahakdanjiro Gangneung-si, Korea)	SiO2 (60–80), Li2O (10–15), Al2O3 (1–8), others (2–20)	460

2.3. Scanning procedures and digital design of the restorations

With the aid of a desktop scanner (Imetric 4D; Courgenay, Switzerland), an digital impression of the prepared tooth was taken. After transferring the impression data to a design software (3 Shape software; Copenhagen, Denmark), the occlusal veneers were designed with a standardized to a thickness of 0.5 mm (Fig. 1).

2.4. Fabrication of the restorations

To produce the heat-pressed restorations according to the digital design, multiple steps were pursued. First, a PMMA-template was milled

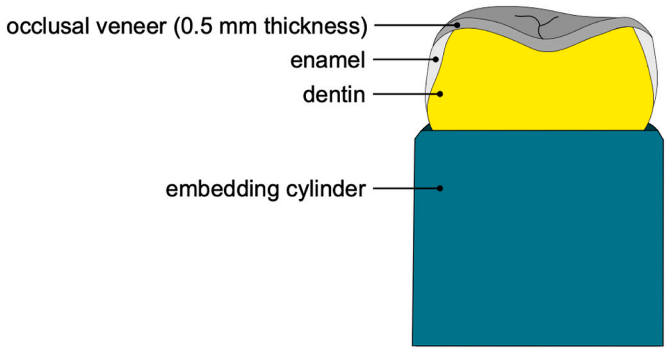

Fig. 1. Schematic sketch of cross-section of cemented overlay on molar.

out of a prefabricated disc (VITA CAD-Waxx; VITA Zahnfabrik) with the aid of a 5-axis milling machine (Programill PM7; Ivoclar Vivadent). In a second step, the milled templates were fixated by a wax sprue (Renfert GmbH, Hilzingen, Germany) and vested (IPS PressVEST Premium; Ivoclar Vivadent) into a mold. To completely dissolve the vested templates, they were heated in an oven (KaVo EWL 5645; KaVo; Kloten, Switzerland) at rate of 5°C min^{-1} from room temperature to 850°C (holding time 60 min).

The pressable lithium disilicate ingots (Lis: Initial LiSi Press; Ema: IPS e.max press; Vit, VITA Ambria; Liv: Livento Press; Amb: Amber Press; Mas: Amber Press Master; Ros: Rosetta Press) were then heat-pressed into the resulted void in a heat-pressing sintering-oven (Programat EP 5010; Ivoclar Vivadent): rate 60°Cmin^{-1} from 700°C to 898°C (holding time: 25 min). After the careful removal of the vest from the cooled restoration, a cleaning with air abrasion at a pressure of 2 bar (50 μm Al_2O_3; Cobra, Renfert GmbH) to remove the remaining vesting material was performed. Once the restorations were completely cleaned, the surface was polished.

2.5. *Cementation of the restorations*

The cementation procedure, including the conditioning steps, were the same for all the ceramic restorations of the study groups. In order to condition the inner surface of the occlusal veneers, 5% hydrofluoric acid (IPS ceramic etching gel; Ivoclar Vivadent) was applied for 20 s followed by water-rinsing and air-drying. A silane (Monobond Plus; Ivoclar Vivadent) was then applied on all the reconstructions and air-dried after 60 s. The conditioning of both, enamel and dentin, was performed by using 37% phosphoric acid during 30 s (Total Etch; Ivoclar Vivadent) followed by 30 s water-spraying of the etched surface and air-drying. Further, the dentinal parts were conditioned (Syntac Primer/ Syntac Adhesive; Ivoclar Vivadent). The prepared teeth were then bonded (Heliobond; Ivoclar Vivadent) and after 20 s carefully air-blown before light-curing (20 s, 1’200 mW/cm^2) (Bluephase PowerCure; Ivoclar Vivadent). The cementation occurred with a flowable light-curing resin cement (Variolink Esthetic LC; Ivoclar Vivadent). After the correct positioning of the restorations onto the prepared teeth and the careful removal of excess cement, the specimens were photo-polymerized (6 × 40 s 1’200 mW/cm^2) (Bluephase PowerCure; Ivoclar Vivadent).

2.6. *Aging of the specimens*

The aging procedure of the specimens occurred with the aid of a chewing simulator, applying 1’200’000 chewing-cycles of 49 N force at a 1.67 Hz loading frequency (Custom-made chewing simulator, Zurich, Switzerland). The applied forces to the specimens very applied in a perpendicular direction to the occlusal plane using an indenter (stainless-steel, tip of ∅ 8 mm). Furthermore, thermo-cycling was performed simultaneously using distilled water surrounding the specimens. The water temperature altered every 120 s between 5 and 55 °C. After the aging procedure, the specimens were inspected with a 1.25× magnification stereomicroscope to check for the integrity of the restorations.

2.7. *Static loading of the specimens*

With the objective to measure the needed load to entirely fracture the reconstruction (F_{max}), a universal testing machine (Zwick / Roell Z010; Zwick, Ulm, Germany) was used. The testing machine continuously applied a force in the axial direction (1 mm/min) perpendicular to the occlusal plane. The specification of the failure types were classified in the 10x magnification stereomicroscope (Leica DFC300 FX; Wetzlar, Germany) and on digital photographs. In total, 4 failure scores were categorized: (1) score 0: no visible fracture, (2) score 1: cohesive fracture within the restoration, (3) score 2: cohesive fracture of the restoration and the cement layer, (4) score 3: fracture of the restoration-cement-tooth complex.

2.8. *Weibull analysis*

Maximum likelihood estimation without a correction factor was used for 2-parameter Weibull distribution, including the Weibull modulus, scale (m) and shape (0), to interpret catastrophic failure strength (F_{max}) of the occlusal veneers (Minitab Software V.16, State College, PA, USA).

2.9. *Statistical analysis*

The metric variable (F_{max}) was described with mean, median, standard deviations, quartiles, minimum and maximum. They were compared using a non-parametric Kruskal-Wallis test (KW). The exact p-values were calculated for the pair-wise comparisons between the groups using the Wilcoxon-Mann-Whitney-Test (WMW), applying the Bonferroni correction for the multiple testing.

The categorical variables (failure scores) were summarized by counts and proportions of the categories and compared applying the Chi-squares test with exact determination of the p-value.

3. Results

3.1. *Fatigue resistance*

One of all tested specimens did not survive the thermo-mechanical aging procedures. The specimen belonged to the group Ema and showed a debonding of the restoration during the chewing simulation. This results in a fatigue resistance of 100% for the groups Lis, Vit, Liv, Amb, Mas and Ros, whereas the group Ema showed a fatigue resistance of 95%.

3.2. *Load-bearing capacity*

The control group Lis showed median F_{max} values of 2’328 (Table 2, Fig. 2). The median F_{max} values for the test groups ranged between 1’753 N and 2’490 N (group Ros). A statistically significant difference was found among the groups Lis (control) and Vit (WMW: $p < 0.001$).

Table 2
Load bearing-capacities F_{max} for the test- and control groups.

Group	n	F max		
		Mean ± SD	Median	Range min to max
Lis	20	2183 ± 351	2328	1307 to 2495
Ema	19	1922 ± 497	2034	1039 to 2492
Vit	20	1753 ± 265	1753	1080 to 2177
Liv	20	1949 ± 452	1933	1061 to 2494
Amb	20	2047 ± 356	2029	1419 to 2506
Mas	20	2239 ± 295	2332	1406 to 2495
Ros	20	2304 ± 290	2490	1629 to 2496

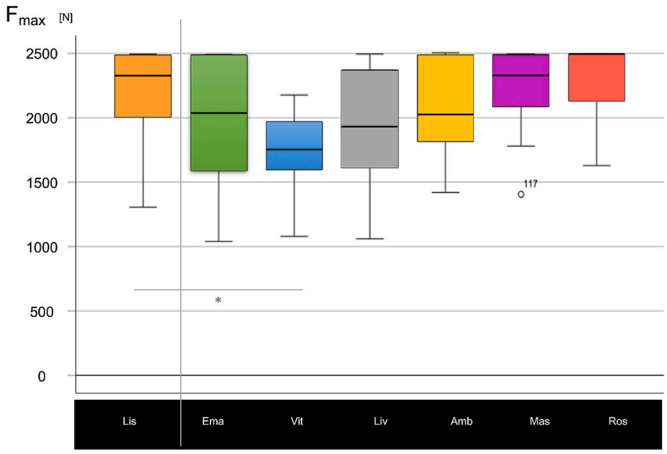

Fig. 2. Box-plots for the F_{max} values of the test- and control. Significant difference between the control group and the test groups are marked with an asterisk. All comparisons were made to the control group.

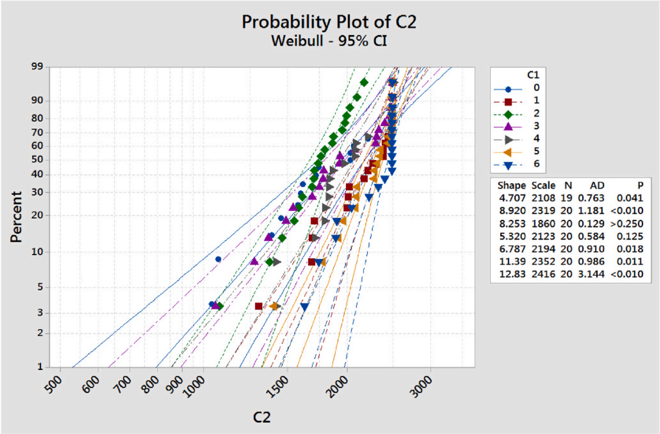

Fig. 3. Two-parameter Weibull modulus distribution based on shape and scale values for all groups (N: number of specimens) tested using AD: Anderson-Darling statistics and the corresponding P: P-value (Groups tested: 0: Lis; 1: Ema; 2: Vit; 3: Liv; 4: Amb; 5: Mas; 6: Ros).

3.3. *Failure types*

For all ceramic types tested failure type 2 was the most commonly observed ranging between 65 and 100% (Table 3). This was followed by failure type score 3 indicating the fracture of the restoration-cement-tooth complex In group VIT exclusively score 2 failure type were observed referring to cohesive fracture of the ceramic material.

3.4. *Weibull analysis*

The Weibull distribution presented the highest scale values for the group Ros (2.42) compared with those of milled specimens of group Vit (1.86) (Fig. 3). A high Weibull scale value suggests a higher 63.2 percentile in the distribution and therefore more reliable results.

4. Discussion

The present investigation showed no significant difference in load-bearing capacities when comparing the median F_{max} values of the control-to the test groups with one exception. The null hypothesis that load-bearing capacity (F_{max}) among the tested groups does not differ has therefore been rejected. Only one restoration showed debonding during the aging phase. All other restorations of all investigated materials withstood the thermo-mechanical aging simulating dynamic loading forces under clinical conditions.

That the aging procedures of the specimen in almost all of the cases did not lead to any failure of the restorations seems to be promising for the long-term stability of the occlusal veneers. Teeth and restored teeth must withstand cyclic loads and temperature changes in the wet oral cavity. The dynamic fatigue and the temperature alterations were simulated with a chewing simulator under wet conditions in order to simulate physiological conditions for clinical service of the restored tooth over 5 years (Bates et al., 1975; DeLong and Douglas, 1991; Steiner et al., 2009). Static loading of the specimens led to all type of failures from no visible damage of the restoration to complete fracture of the restoration-cement-tooth complex. Most of the specimens showed a cohesive fracture of the restoration and of the cement layer (score 2) which was also found to be the predominant failure mode in comparable studies(Gierthmuehlen et al., 2022; Ioannidis et al., 2020). In the present investigation, static loading forces went up to 2’500 N. Clinically, maximum masticatory forces in the posterior region range from 200 to 540 N and reach up to 800 N in patients suffering from bruxism (Bates et al., 1975).

Table 3
Fracture scores of the test- and control groups.

Group	n	Score 0 [%]	Score 1 [%]	Score 2 [%]	Score 3 [%]
Lis	20	0	0	80	20
Ema	19	5	0	75	10
Vit	20	0	0	100	0
Liv	20	0	10	75	15
Amb	20	5	0	65	30
Mas	20	0	5	60	35
Ros	20	0	0	60	40

In one recently published study with similar experimental conditions a high load-bearing capacity was demonstrated for heat pressed lithium-disilicate (Ioannidis et al., 2020). The median F_{max} values amounted to 1’555 N. In the described study the material used was IPS e.max Press which was also investigated in this study.

Fracture strength and fracture toughness values provided by the manufacturer derive from standardized mechanical material tests and cannot be compared to load-bearing capacities found in the present investigation. In this study, the entire tooth-cement-restoration complex was tested and not the restorative material itself how it is done in standardized material testing. Proper adhesion of the restoration to the dentinal substrate is crucial and dictates on the longevity of adhesion and thus the load-bearing capacity since crack formation usually starts from the zone of cementation (Zhang et al., 2009).

The test group Vit showed as the only group a significant lower F_{max} compared to the control group Lis. Vit is the only tested material in the present study containing ZrO_2. The highest values are usually measured when ZrO_2 as a restorative material is tested (Denry and Kelly, 2008). It has been demonstrated that ZrO_2 reinforced lithium disilicate enhanced fracture toughness, flexural strength, elastic modulus and hardness compared with lithium disilicate glass ceramic (Elsaka and Elnaghy, 2016). On the other hand, it has been shown that ZrO_2 being content of a lithium-disilicate ingot did not improve mechanical properties in studies comparing different pressed lithium disilicates (Hallmann et al., 2019; Sieper et al., 2017). Flexion tests showed that the addition of more than 10% of ZrO_2 reduced the flexural strength (Corado et al., 2022). The heat treatment process improves and provides greater mechanical strength. It has been shown that the specimens with the lowest percentage of ZrO_2 exhibited greater crystallinity and corroborated the microstructural analysis (Corado et al., 2022). SEM analyses showed a greater amount of elongated crystals of lithium disilicate when comparing samples with higher percentage of ZrO_2. Therefore, specimens with lower zirconia showed greater flexural strength than samples with higher additions of ZrO_2 (Corado et al., 2022). One limitation of this study was the limited number of specimens, which could explain the fact that despite the choice of different material constituents and their varying effect on mechanical properties, differences among the groups were hardly significant. Future studies should involve higher number of specimens and test our conclusions in an in-vivo setting.

5. Conclusions

Regarding their load-bearing capacity all the tested pressable lithium disilicates can be recommended to fabricate ultra-thin occlusal veneers on molars in order to restore the occlusal tooth wear.

CRediT authorship contribution statement

Katrin Zumstein: Writing – original draft, Investigation. **Lorenzo Fiscalini:** Writing – review & editing, Investigation, Formal analysis. **Nadin Al-Haj Husain:** Writing – review & editing, Investigation. **Erkan Evci:** Writing – review & editing. **Mutlu Özcan:** Writing – review & editing, Investigation, Formal analysis. **Alexis Ioannidis:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no competing interest.

Data availability

Data will be made available on request.

Acknowledgements

This study was mainly financially supported by the Clinic of Reconstructive Dentistry, Center of Dental Medicine, University of Zurich, Switzerland. The Swiss Society for Reconstructive Dentistry (SSRD) supported this investigation in parts with a research grant. The authors express their special thanks to Michele Piccini for his valuable help during fabrication of the specimens.

References

Albelasy, E.H., Hamama, H.H., Tsoi, J.K.H., Mahmoud, S.H., 2020. Fracture resistance of cad/cam occlusal veneers: a systematic review of laboratory studies. J. Mech. Behav. Biomed. Mater. 110, 103948.

Alkadi, L., Ruse, N.D., 2016. Fracture toughness of two lithium disilicate dental glass ceramics. J. Prosthet. Dent 116 (4), 591–596.

Anadioti, E., Aquilino, S.A., Gratton, D.G., Holloway, J.A., Denry, I.L., Thomas, G.W., Qian, F., 2015. Internal fit of pressed and computer-aided design/computer-aided manufacturing ceramic crowns made from digital and conventional impressions. J. Prosthet. Dent 113 (4), 304–309.

Bates, J.F., Stafford, G.D., Harrison, A., 1975. Masticatory function–a review of the literature. 1. The form of the masticatory cycle. J. Oral Rehabil. 2 (3), 281–301.

Corado, H.P.R., da Silveira, P., Ortega, V.L., Ramos, G.G., Elias, C.N., 2022. Flexural strength of vitreous ceramics based on lithium disilicate and lithium silicate reinforced with zirconia for cad/cam. Int. J. Biomater. 2022, 5896511.

De Angelis, F., D`Arcangelo, C., Vadini, M., 2021. The effect of dentin bonding and material thickness on the flexural properties of a lithium-disilicate glass-ceramic. J. Adhesive Dent. 23 (4), 309–318.

DeLong, R., Douglas, W.H., 1991. An artificial oral environment for testing dental materials. IEEE Trans. Biomed. Eng. 38 (4), 339–345.

Denry, I., Kelly, J.R., 2008. State of the art of zirconia for dental applications. Dent. Mater. 24 (3), 299–307.

Donovan, T., Nguyen-Ngoc, C., Abd Alraheam, I., Irusa, K., 2021. Contemporary diagnosis and management of dental erosion. J. Esthetic Restor. Dent. 33 (1), 78–87.

Elsaka, S.E., Elnaghy, A.M., 2016. Mechanical properties of zirconia reinforced lithium silicate glass-ceramic. Dent. Mater. 32 (7), 908–914.

Gakis, P., Kontogiorgos, E., Zeller, S., Nagy, W.W., 2022. Effect of firing and fabrication technique on the marginal fit of heat-pressed lithium disilicate veneers. J. Prosthet. Dent 127 (1), 154–160.

Gierthmuehlen, P.C., Jerg, A., Fischer, J.B., Bonfante, E.A., Spitznagel, F.A., 2022. Posterior minimally invasive full-veneers: effect of ceramic thicknesses, bonding substrate, and preparation designs on failure-load and -mode after fatigue. J. Esthetic Restor. Dent. 34 (1), 145–153.

Guess, P.C., Selz, C.F., Steinhart, Y.N., Stampf, S., Strub, J.R., 2013. Prospective clinical split-mouth study of pressed and cad/cam all-ceramic partial-coverage restorations: 7-year results. Int. J. Prosthodont. (IJP) 26 (1), 21–25.

Hallmann, L., Ulmer, P., Gerngross, M.D., Jetter, J., Mintrone, M., Lehmann, F., Kern, M., 2019. Properties of hot-pressed lithium silicate glass-ceramics. Dent. Mater. 35 (5), 713–729.

Ioannidis, A., Bomze, D., Hammerle, C.H.F., Husler, J., Birrer, O., Muhlemann, S., 2020. Load-bearing capacity of cad/cam 3d-printed zirconia, cad/cam milled zirconia, and heat-pressed lithium disilicate ultra-thin occlusal veneers on molars. Dent. Mater. 36 (4), e109–e116.

Ioannidis, A., Muhlemann, S., Ozcan, M., Husler, J., Hammerle, C.H.F., Benic, G.I., 2019. Ultra-thin occlusal veneers bonded to enamel and made of ceramic or hybrid materials exhibit load-bearing capacities not different from conventional restorations. J. Mech. Behav. Biomed. Mater. 90, 433–440.

Lin, W.S., Ercoli, C., Feng, C., Morton, D., 2012. The effect of core material, veneering porcelain, and fabrication technique on the biaxial flexural strength and weibull analysis of selected dental ceramics. J. Prosthodont. 21 (5), 353–362.

Loomans, B., Opdam, N., Attin, T., Bartlett, D., Edelhoff, D., Frankenberger, R., Benic, G., Ramseyer, S., Wetselaar, P., Sterenborg, B., et al., 2017. Severe tooth wear: European consensus statement on management guidelines. J. Adhesive Dent. 19 (2), 111–119.

Maeder, M., Pasic, P., Ender, A., Özcan, M., Benic, G., Ioannidis, A., 2019. Load-bearing capacities of ultra-thin occlusal veneers bonded to dentin. J. Mech. Behav. Biomed. Mater. 95 (95), 165–171.

Morikofer, N., Benic, G.I., Park, J.M., Ozcan, M., Husler, J., Ioannidis, A., 2021. Relationship between internal accuracy and load-bearing capacity of minimally invasive lithium disilicate occlusal veneers. Int. J. Prosthodont. (IJP) 34 (4), 365–372.

Peutzfeldt, A., Jaeggi, T., Lussi, A., 2014. Restorative therapy of erosive lesions. Monogr. Oral Sci. 25, 253–261.

Sieper, K., Wille, S., Kern, M., 2017. Fracture strength of lithium disilicate crowns compared to polymer-infiltrated ceramic-network and zirconia reinforced lithium silicate crowns. J. Mech. Behav. Biomed. Mater. 74, 342–348.

Steiner, M., Mitsias, M.E., Ludwig, K., Kern, M., 2009. In vitro evaluation of a mechanical testing chewing simulator. Dent. Mater. 25 (4), 494–499.

Zhang, Y., Kim, J.W., Bhowmick, S., Thompson, V.P., Rekow, E.D., 2009. Competition of fracture mechanisms in monolithic dental ceramics: flat model systems. J. Biomed. Mater. Res. B Appl. Biomater. 88 (2), 402–411.