

Er, Cr:YSGG and Nd:YAG Laser Surface Treatment of Lithium Disilicate Ceramics: SEM, EDX Analysis and Composite Bond Strength Evaluation

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Abstract

This study is an evaluation of the impact of pre-treatment regimes – Hydrofluoric Acid (HFA), Neodymium-doped Yttrium-Aluminum Garnet (Nd:YAG), and Erbium, Chromium: Yttrium-Scandium-Gallium-Garnet (Er,Cr:YSGG) laser – on the surface roughness (Ra), topography, and repair bond strength (RBS) of lithium disilicate ceramics (LDC) with micro-hybrid composite (MHC), having high-viscosity, and an injectable composite (IC) with low-viscosity. Ninety LDC disks were fabricated. The discs were divided into three groups according to surface pretreatment ($n = 30$ each). Group 1: HFA, Group 2: ErCr:YSGG, Group 3: Nd:YAG laser. To assess the Ra , five samples from each cohort were examined under a profilometer. Five samples from each surface treatment group were subjected to topographical evaluation by means of SEM. Twenty samples from each group were allocated into two groups determined by the viscosity of the resin composite. Low-viscosity IC(A) and high-viscosity MHC(B). A universal testing machine and a stereomicroscope were used to assess the RBS and failure modes. Statistical analysis was performed using ANOVA followed by post hoc Tukey, ($p < 0.05$). HFA-pretreated samples achieved the maximum Ra scores. Nd:YAG laser-treated LDC discs exhibited the minimum Ra scores. The highest bond strength was observed in Group 1A samples. Nd:YAG laser + MHC discs demonstrated the lowest RBS. HFA, as a surface conditioning regime, and a low-viscosity IC, as a repair material, displayed better performance in terms of improving surface characteristics and bond strength with LDC.

Keywords: Hydrofluoric acid, micro-hybrid composite, injectable composite, lithium disilicate ceramics, surface topography

I. Introduction

All-ceramic restorations have recently gained significant attention in modern dentistry due to the growing demand for esthetic dental materials¹. All-ceramic materials, when compared with metal-based options, offer several benefits, including translucency, fluorescence, and biocompatibility². Dentists now have multiple choices when selecting materials for fabricating single-unit crowns³. Among these, lithium disilicate ceramics (LDC) composed of lithium oxide (Li_2O) dispersed within a silicate-based glass matrix are extensively used for anterior crowns because of their favorable aesthetics⁴. However, LDC demonstrates inferior strength relative to that of highly translucent zirconia⁵. When LDC fractures inside the mouth, complete replacement of the restoration is often required, which can compromise the remaining healthy tooth structure by necessitating additional preparation and a larger restoration⁶. Intraoral ceramic fractures occur in 2–5 % of LDC restorations within 5 years, with complete replacement increasing treatment costs by 300–500 % and requiring additional tooth reduction of 0.5–1.0 mm⁷, thereby compromising long-term tooth

prognosis and patient satisfaction. The FDI endorses repairing compromised restorations instead of complete removal and substitution⁸. Consequently, direct repair with composite resin is regarded as the best clinical approach for managing ceramic fractures when structurally feasible.

To ensure a durable and effective repair, adequate adhesion between the ceramic and the composite material is essential⁹. Various protocols are employed to repair the ceramic by enhancing the surface roughness (Ra), which eventually augments the repair bond strength (RBS) with the composite¹⁰. Hydrofluoric acid (HFA) etching and subsequent application of silane establishes a dependable and durable bond, representing the gold standard for surface modification of LDC restorations, which enhances the surface topography by increasing Ra , thereby generating microporosities and micro-undercuts that facilitate improved micromechanical interlocking^{11,12}. However, HFA can cause harm and can be particularly aggressive to oral tissues. Therefore, it should be imperative to find better alternatives¹³.

Recent advancements in dental technology have significantly expanded the application of lasers in both hard and

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soft tissue procedures. Among the available laser systems, the erbium, chromium:yttrium-scandium-gallium-garnet (Er, Cr:YSGG) laser, emitting a wavelength of 2780 nm, has gained significant attention in dentistry^{14,15}. Classified under the erbium laser subgroup, it is uniquely absorbed by water molecules and hydroxyl groups in hydroxyapatite crystals¹⁶. Previous studies have shown that applying Er, Cr:YSGG laser irradiation operating at 4–6 W/20 Hz produces marked changes in the LDC, causing significant *Ra* alterations, which in turn enhanced the bond strength of the resin cement^{17,18}. However, data is still dubious regarding its efficacy on the RBS of LDC to composite and hence needs inquiry.

Whereas the neodymium-doped yttrium aluminum garnet (Nd:YAG) laser emits a wavelength of 1064 nm that is preferentially absorbed by water and pigmented tissues¹⁹. Due to its absorption properties, the Nd:YAG laser is widely applied in dental applications^{20,21}. Studies demonstrate that Nd:YAG irradiation improves *Ra* via induction of melting followed by irregular recrystallization, thereby improving *Ra* and bond strength^{22,23}. Conversely, some research findings indicate that Nd:YAG laser treatment does not significantly alter the micromorphology of LDC compared to untreated ceramics^{24,25}. Given these conflicting findings, further research is necessary to clarify its effects.

Apart from the conditioning methods implemented, the viscosity of the repair material is of considerable importance²⁶. Composites with differing viscosities are currently utilized for the repair of fractures in indirect restorations. Low-viscosity composites are often preferred by dental practitioners because of their superior ability to penetrate and adapt to the surface irregularities²⁷. Composite viscosity is affected by both the chemical makeup of the matrix and the quantity of fillers²⁸. Aali *et al.* reported that the RBS of resin matrix ceramics was higher with injectable composites (IC) having low viscosity than high-viscosity microhybrid composite (MHC)²⁹. Based on the current available evidence, the literature is scarce regarding the impact of viscosity on RBS to LDC, and hence need for future exploration.

The objective of existing research is to systematically evaluate how different pre-treatment methods influence the *Ra* and RBS of LDC when bonded to composite material of varying viscosity. Therefore, it was hypothesized that the topography and *Ra* of LDC discs irradiated with Er, Cr:YSGG, and Nd:YAG lasers would not differ significantly from those conditioned with HFA. Furthermore, the RBS of LDC discs luted with resin composites of varying viscosities was expected to remain comparable across each pre-treatment group.

II. Material and Methods

(1) Specimen preparation

The present study was approved by the ethical committee of King Abdulaziz University and followed the checklist for reporting *in vitro* study (CRIS) guidelines. A total of ninety LDC discs (Celtra Duo, Dentsply Sirona, Charlotte, USA), dimensioned 6 mm × 2 mm

(diameter × thickness), were prepared via a CAD-CAM system. Sample size calculation (G*Power 3.1.9.7) determined $n = 10$ per subgroup to detect a 20-% difference in RBS with 80 % power at $\alpha = 0.05$ (effect size $d = 1$, based on previous studies. The specimens were ultrasonically cleansed in distilled water for 10 min. Each specimen was embedded in clear orthodontic acrylic resin (Ortho-Jet, Lang Dental, Illinois), filled inside a polyvinyl chloride (PVC) pipe, exposing the flat intaglio surface for treatment. Polishing and finishing were carried out using 1000-grit silicon carbide paper^{27,30}. The total number of discs was equally allocated into three groups ($n = 30$) depending on the conditioning protocol applied.

Group 1: HFA

The ceramic surface received 10% HFA treatment (IPS Ceramic Etching Gel, Ivoclar Vivadent, Schaan, Liechtenstein) by means of disposable microbrush application. HFA-ceramic contact time was maintained at 60 seconds under ambient conditions ($23\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$)³¹. Subsequently, specimens underwent 30-second distilled water irrigation to eliminate residual HFA, and then dried using oil-free compressed air for 10 seconds.

Group 2: Er, Cr:YSGG laser

A pulsed Er, Cr:YSGG laser (Biolase Waterlase iPlus, California, USA) was employed to treat the specimens at a wavelength of 2780 nm with a pulse duration of 60 microseconds and a repetition rate of 10 Hz. The laser operated at a power output of 3 W, delivered through a 600- μm -diameter glass fiber tip (MZ6, 9 mm length) attached to the Waterlase iPlus/MD Gold handpiece. Based on the fiber tip diameter, the cross-sectional area was calculated as 0.000283 cm^2 , yielding an irradiance of approximately 10600 W/cm^2 and a fluence of 106 J/cm^2 (irradiance × exposure time). The laser tip was positioned perpendicular to the specimen surface at a working distance of approximately 10 mm and applied in hard tissue mode with continuous air/water coolant spray (65 % air, 55 % water) for 60 seconds per specimen³².

Group 3: Nd:YAG laser

The LDC discs in this group were pretreated with an Nd:YAG laser ($\lambda = 1064\text{ nm}$, Fidelis Plus III, Fotona, Ljubljana, Slovenia) operated at 3 W average power output, 300 μs pulse duration, 100 mJ pulse energy, and 20 Hz repetition rate. A 300- μm -diameter optical fiber was employed for beam transmission with a calculated cross-sectional area of 0.000071 cm^2 , yielding an irradiance of approximately 42300 W/cm^2 . The fiber tip was positioned manually approximately 2 mm above the disc surface in a perpendicular orientation and scanned horizontally across the entire surface at a rate of 2 mm/s for 60 seconds, delivering a total fluence of approximately 2538 J/cm^2 . No water spray or air cooling was applied to induce controlled surface melting and recrystallization¹⁹.

All laser treatments were performed by a single calibrated independent operator (initials) with 5+ years of dental laser experience. Post-treatment, samples from all the groups were thoroughly cleansed using distilled water to clear any remaining residues and air-dried.

(2) *Ra assessment*

From each group, five specimens were randomly chosen for *Ra* evaluation using a profilometer (KLA Tencor P-7, KLA Corporation, California, USA) ($n = 5$). The probe was positioned at the center of each surface, and measurements were recorded at three separate points with a traverse length of 0.8 mm and a constant rate of 0.5 mm/s, followed by calculation of the mean *Ra* value³³.

(3) *Topographic surface analysis*

Five specimens from each surface conditioning group were selected for surface morphology evaluation ($n = 5$), with representative images presented from each group. Before analysis, all the samples underwent a thin gold layer coating process using a gold sputter coating device (BAL-TEC SCD 005) to enhance conductivity. Following preparation, the specimens were analyzed by means of scanning electron microscopy (SEM) (Merlin Compact, Zeiss, Jena, Germany) at different magnifications³⁴.

(4) *Resin composite repair*

Following surface treatment, 20 LDC discs per group were coated with a one-step self-etch adhesive, AdheSE One (Ivoclar Vivadent, Schaan, Liechtenstein), using an applicator, air-dried, and polymerized for 10 seconds by means of an LED curing unit (1 200 mW/cm², Radii Cal, SDI, Australia). 20 discs from each group were allocated into two subgroups determined by the viscosity of the resin composites utilized ($n = 10$). Low-viscosity injectable composite (IC) (G-aenial Universal Injectable, GC Corp) (A) and Microhybrid composite (MHC) (Filtek Z250 XT, 3M ESPE) possessing high viscosity (B). They were both built on the respective discs at a thickness of 2 mm with a Teflon mold and light-cured for 20 seconds. Following bonding, immersion of the samples in distilled water was performed and incubated at 37 °C using a Memmert incubator (Waltham, MA, USA) for 24 hours before RBS evaluation.

(5) *Simulated ageing*

Thermocycling (Nova Ética, São Paulo, Brazil) was conducted to simulate the ageing of samples over a total of 10 000 cycles. Each cycle comprises a sequential immersion in water baths maintained at temperatures of 5 °C and 55 °C, with each immersion lasting 30 seconds and a transitional period of 2 seconds between the respective immersions³⁵.

(6) *RBS analysis*

All specimens were subjected to RBS testing utilizing a universal testing apparatus (Instron 5965 Material Testing System). Each sample was firmly affixed to a metallic jig to guarantee that the interface between the composite material and the ceramic substrate was positioned at an angle of 90° in relation to the horizontal plane. Using a 100 kgF load cell, load was applied via a 0.35-mm-diameter steel wire employed at a crosshead speed of 1.0 mm/min until the bonded interface failed. Bond strength was computed according to the equation $B = F/A$ and expressed in Megapascals (MPa)²⁶

where B = bond strength (MPa), F = force (N), and A = interfacial area (mm²).

(7) *Failure analysis*

An optical stereomicroscope (Olympus SZX16, Olympus Corporation) was employed to inspect the debonded specimens, capturing qualitative images of the failure patterns at 40 × magnification. The failures were categorized as adhesive, cohesive, or admixed.

(8) *Statistical assessment*

Statistical analysis was conducted using SPSS version 28.0 (IBM Corp., Armonk, NY, USA). Data normality was assessed using the Shapiro-Wilk test, and homogeneity of variances was evaluated using Levene's test. One-way analysis of variance (ANOVA) was performed to compare surface roughness and repair bond strength values across the three surface conditioning protocols. When ANOVA revealed significant differences ($p < 0.05$), Tukey's honestly significant difference (HSD) *post hoc* test was applied for pairwise comparisons between groups. Results are presented as mean ± standard deviation, with statistical significance set at $\alpha = 0.05$.

III. Results

(1) *EDX of LDC disc*

SEM visualization of a Lithium Disilicate Ceramics Disc is shown in Fig. 1A. EDX spectrum depicting the elemental composition of the lithium disilicate ceramic (LDC) examined in this study. Prominent peaks for aluminum (Al), oxygen (O), silicon (Si), and other elements verify the material's composition. The presence of trace elements such as Na, Mg, P, Cl, K, and Ca indicates their role as minor constituents Fig. 1B.

(2) *Surface topography of LDC following different surface treatment regimes*

SEM micrograph of LDC subjected to hydrofluoric acid treatment. This image illustrates the significant dissolution of the glassy matrix, revealing lithium disilicate crystallites and forming a highly irregular, retentive microstructure. The acid-etching process selectively removes the glassy phase while maintaining the crystalline structure, resulting in a honeycomb-like or microporous surface with notable roughness, observed in Fig. 2A. SEM micrograph of LDC treated with an Er, Cr:YSGG laser. This micrograph shows a markedly different topography from that of HFA etching, characterized by laser-induced microexplosions and photothermal ablation effects. The surface reveals exposed lithium disilicate crystallites with distinct geometric facets and sharp edges, appearing as smooth, polygonal glass structures (bright regions) surrounded by a microrough fused matrix without dissolution, as seen in Fig. 2B. LDC treated with Nd:YAG laser, shows a micrograph indicating significant thermal modification, marked by melting and resolidification phenomena. The surface displays a highly heterogeneous topography with prominent microcracks (dark linear features), resolidified melt zones (smooth bright areas), and thermally altered

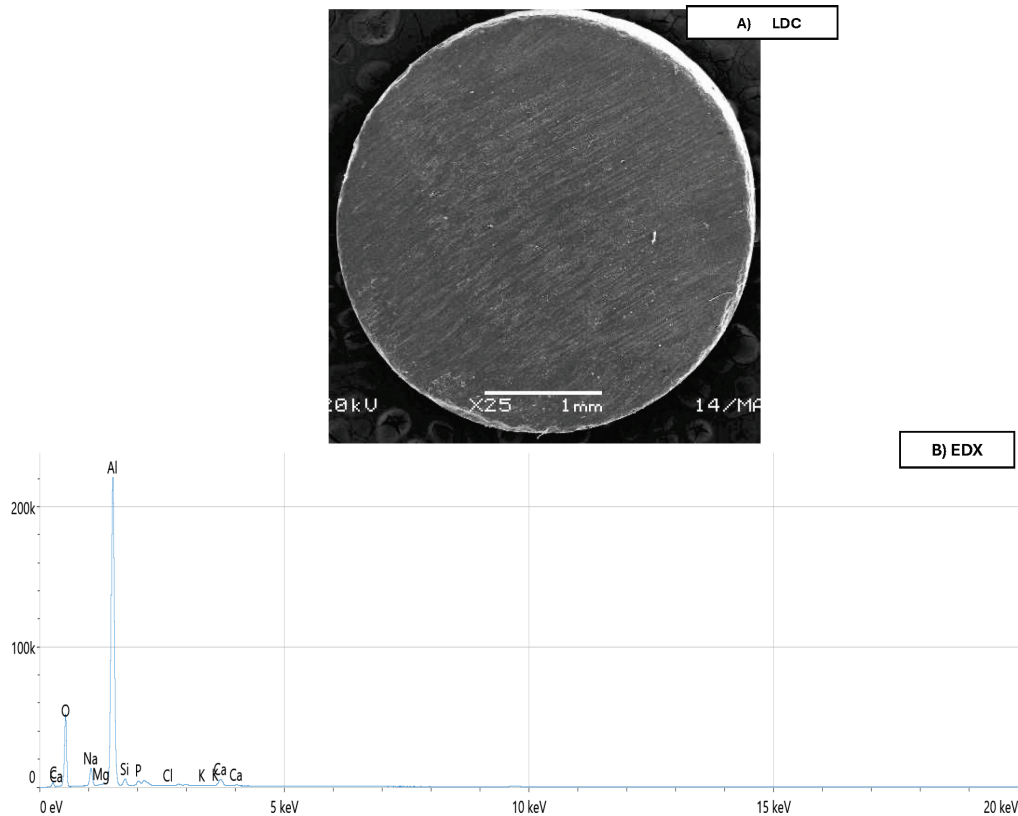


Fig. 1: **A:** Lithium Disilicate Ceramics Disc observed under SEM; **B:** EDX spectrum showing the characteristic elemental composition of lithium disilicate ceramic (LDC) used in this study. Prominent peaks corresponding to aluminum (Al), oxygen (O), silicon (Si), and other constituent elements confirm the material composition. The presence of trace elements (Na, Mg, P, Cl, K, Ca) represents minor constituents.

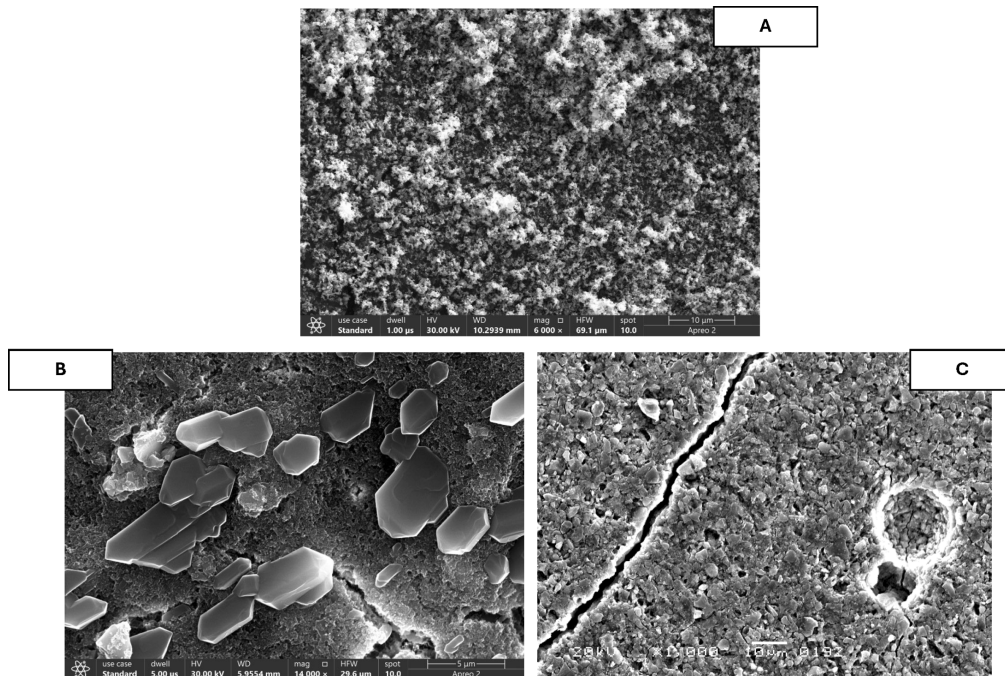


Fig. 2: **A:** SEM micrograph showing LDC treated with hydrofluoric acid. The micrograph demonstrates extensive dissolution of the glassy matrix with exposure of lithium disilicate crystallites, creating a highly irregular, retentive microstructure. The acid etching selectively removes the glassy phase while preserving the crystalline framework, resulting in a honeycomb-like or microporous topography with pronounced surface roughness; **B:** SEM micrograph showing LDC treated with Er, Cr:YSGG laser. The micrograph reveals a distinctly different topography compared to HFA etching, characterized by laser-induced micro explosions and photothermal ablation effects. The surface exhibits exposed lithium disilicate crystallites with well-defined geometric facets and sharp edges, appearing as smooth, polygonal glass structures (bright regions) surrounded by a microrough fused matrix with no dissolution; **C:** SEM micrograph showing LDC treated with Nd:YAG laser, the micrograph reveals significant thermal modification characterized by melting and re-solidification phenomena. The surface exhibits a highly heterogeneous topography with prominent microcracks (dark linear features), resolidified melt zones (smooth bright areas), and thermally altered regions showing a granular, frosted appearance. The conspicuous crack networks indicate substantial thermal stress from rapid heating and cooling cycles.

regions with a granular, frosted look. The noticeable crack networks suggest substantial thermal stress due to rapid heating and cooling cycles Fig. 2C.

(3) *Ra* assessment

Table 1 shows the *Ra* of LDC after using different surface conditioners. Group 1 (HFA) ($1245.76 \pm 0.079 \mu\text{m}$) pretreated samples displayed maximum scores of *Ra*. Whereas, Group 3 (Nd:YAG laser) ($859.12 \pm 0.056 \mu\text{m}$) exhibited minimum roughness scores. Inter-group comparative analysis discovered that Group 2 (Er, Cr:YSGG laser) ($934.86 \pm 0.074 \mu\text{m}$) and Group 3 displayed comparable *Ra* outcomes ($p > 0.05$)

Table 1: *Ra* evaluation of LDC following application of different laser types and HFA.

Tested groups	Mean $\pm$ SD <i>Ra</i> (μm)	<i>p</i> -value!
Group 1: HFA	1245.76 ± 0.079^a	< 0.05
Group 2: Er, Cr:YSGG laser	934.86 ± 0.074^b	
Group 3: Nd:YAG laser	859.12 ± 0.056^b	

!ANOVA

Hydrofluoric acid (HFA), Erbium, Chromium-doped Yttrium-Scandium-Gallium-Garnet (Er, Cr:YSGG) laser (Neodymium-doped yttrium aluminum garnet (Nd:YAG) laser

The different superscript denotes a statistically significant difference, Post Hoc Tukey ($p < 0.05$)

(4) *RBS* evaluation

Table 2 presents the RBS of LDC to a composite of different viscosities after using different surface conditioners. The highest bond strength ($11.21 \pm 0.54 \text{ MPa}$) was discovered in Group 1A (HFA + IC) samples. While Group 3B (Nd:YAG laser + MHC) ($5.54 \pm 0.18 \text{ MPa}$) discs demonstrated the lowest RBS. Comparison among tested groups revealed that Group 2A (Er, Cr:YSGG laser + IC) ($7.56 \pm 0.11 \text{ MPa}$) and Group 3A (Nd:YAG laser + IC) ($7.34 \pm 0.19 \text{ MPa}$) did not exhibit significant variation in bond strength values ($p > 0.05$) Likewise, Group 2B (Er, Cr:YSGG laser + MHC) ($5.85 \pm 0.21 \text{ MPa}$) and Group 3B (Nd:YAG laser + MHC) also exhibited comparable scores of RBS. ($p > 0.05$) Whereas bond strength values differed significantly between Group 1A and Group 1B. (HFA + MHC) ($9.62 \pm 0.27 \text{ MPa}$). ($p < 0.05$).

(5) *Failure mode analysis*

Fracture distribution among the different tested groups is observed in Fig. 3. It was discovered that Groups 2A and 3A presented predominantly the admixed failures. Whereas Group 2B and 3B displayed adhesive failures the most. On the other hand, Groups 1A and 1B exhibited cohesive failures the most.

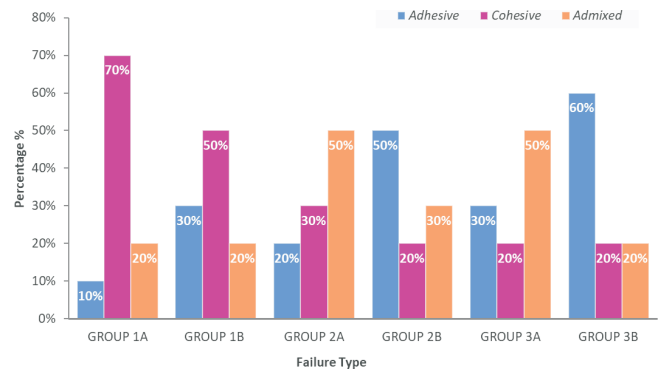


Fig. 3: Distribution of fracture types across the tested groups.

Table 2: RBS of lithium disilicate ceramic specimens restored with composites of variable viscosities after using different laser types and HFA.

Tested groups	RBS Mean $\pm$ SD (MPa)	<i>p</i> -value!
Group 1A: HFA + IC	11.21 ± 0.54^a	< 0.05
Group 1B: HFA + MHC	9.62 ± 0.27^b	
Group 2A: Er, Cr:YSGG laser + IC	7.56 ± 0.11^c	
Group 2B: Er, Cr:YSGG laser + MHC	5.85 ± 0.21^d	
Group 3A: Nd:YAG laser + IC	7.34 ± 0.19^c	
Group 3B: Nd:YAG laser + MHC	5.54 ± 0.18^d	

!ANOVA

Hydrofluoric acid (HFA), Erbium, Chromium-doped Yttrium-Scandium-Gallium-Garnet (Er, Cr:YSGG) laser (Neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, Microhybrid Composite (MHC), Injectable composite (IC)

The different superscript denotes a statistically significant difference, Post Hoc Tukey ($p < 0.05$)

IV. Discussion

This study was conducted under the assumption that treatment of LDC discs with Er, Cr:YSGG, and Nd:YAG lasers would not result in significant changes in *Ra* or surface topography when compared to HFA conditioning. Furthermore, the RBS of LDC discs luted with resin composites of varying viscosities was expected to remain comparable across each pre-treatment group. Based on the findings, both lasers (Er, Cr:YSGG, and Nd:YAG) produced significantly lower *Ra* and bond strength values compared to HFA. Moreover, low-viscosity IC displayed better performance than high-

viscosity MHC, thereby causing both null hypotheses to be rejected.

Among the tested groups, surfaces treated with 10% HFA demonstrated the highest SBS values. This result aligns with prior work by Lyann *et al.*, who have reported significantly better outcomes with HFA³⁶. Structurally, LDCs are composed of densely arranged, interwoven, needle-shaped lithium disilicate crystals along with smaller secondary lithium orthophosphate crystals. HFA acts by preferentially dissolving the silica-rich glassy framework, leaving behind a rough microstructure by creating microporosity and increasing the surface free energy^{37,38}. This increased surface area, which allows for stronger micromechanical interlocking, ultimately enhances bond strength between the ceramic and resin restoration^{4,36}.

In contrast, LDC discs pretreated with Er, Cr:YSGG, and Nd:YAG lasers showed significantly lower *Ra* and RBS values compared to those treated with HFA. Nevertheless, the effect of Er, Cr:YSGG laser irradiation on the RBS of LDC to the composite has yet to be definitively established. Some investigations have suggested that Er, Cr:YSGG laser enhances adhesion by creating microscopic pits and pores on the ceramic surface, thereby improving micromechanical retention^{39,40}. However, its effectiveness is strongly influenced by the laser's power settings. Based on preliminary testing and manufacturer recommendations, a 3W power setting with 55 % water cooling was employed for the Er, Cr:YSGG laser. However, post-hoc analysis suggests these parameters may have delivered excessive energy density (10 600 W/cm²), potentially causing surface melting rather than controlled ablation. Instead of generating a uniform micro-roughened surface suitable for micromechanical retention, excessive energy may result in surface melting, glazing, or the formation of micro-cracks^{41,42}. These changes hinder adhesive penetration and mechanical interlocking, ultimately weakening the resin-ceramic bond as reported by Ataol and Ergun⁴³. Similar results have also been observed by Akyil *et al.* and Chaharom *et al.*, supporting the view that higher energy outputs may negatively influence bonding effectiveness^{44,45}.

Similarly, treating LDC surfaces with the Nd:YAG laser resulted in lower *Ra* and bond strength values compared to the control group. This result contradicts previous studies, which have suggested that using the Nd:YAG laser before composite repair can improve bond strength relative to no treatment^{46,47}. Nonetheless, its overall effectiveness is still debated and is generally considered less reliable than traditional surface conditioning techniques. The limited effectiveness of the Nd:YAG laser on LDC is primarily due to the ceramic's high translucency and poor absorption of infrared radiation at 1 064 nm. This low absorption means that not enough energy reaches the ceramic surface to make effective modifications, thereby reducing bonding efficiency^{44,48}. Instead, the energy applied often leads to undesirable effects such as localized melting, surface cracking, and the resolidification of the glaze layer, which can further weaken the bond interface.

At present, a variety of composite materials differing in viscosity are routinely used for the repair of indirect dental restorations⁴⁹. Among these, low-viscosity composites are often favored by clinicians due to their superior ability to penetrate fracture interfaces. The present study demonstrated that low-viscosity-IC achieved significantly higher RBS compared to high-viscosity-MHC, irrespective of the surface pretreatment applied³⁴. These results are consistent with the findings of Kemaloğlu and coauthors⁵⁰. They reported similar outcomes in their laboratory investigations and attributed the superior performance of injectable composites to their reduced viscosity and enhanced wettability⁵⁰. Furthermore, the diminished polymerization shrinkage and contraction forces at the interface contribute significantly to the enhanced adaptation of IC to the conditioned ceramic surface²⁸. This combination of properties ultimately contributes to improved repair efficiency and stronger interfacial bonding.

Analyzing fracture modes is crucial in adhesion testing, as assessment of bond quality should not rely exclusively on bond strength data. Analysis of failure modes can offer valuable insights about possible clinical limitations⁵¹. It was discovered that Group 2A and 3A presented the admixed failures predominantly. Whereas Group 2B and 3B displayed adhesive failures the most. On the other hand, Groups 1A and 2B exhibited cohesive failures in abundance. Adhesive failure takes place at the junction between the restorative material and ceramic, primarily resulting from insufficient surface conditioning, stresses induced by polymerization shrinkage, and improper application of the adhesive^{14,52}. The type of failure modes further confirms the bond strength outcomes.

The present research analysis demonstrates certain limitations. Primarily, the study was conducted as a lab-based analysis; therefore, generalizations of these findings should be made with certain caution. Moreover, these findings are specific to the ceramic type, laser modality, and the laser parameters employed in the study. Future investigations should be aimed at surface topography analysis using atomic force microscopy.

V. Conclusions

Hydrofluoric acid etching combined with low-viscosity injectable composite demonstrated superior performance for lithium disilicate ceramic repair, achieving the highest surface roughness and bond strength. Both Er, Cr:YSGG and Nd:YAG laser treatments produced comparable but significantly lower outcomes, suggesting the need for parameter optimization before clinical recommendation. Injectable composites consistently outperformed microhybrid composites across all surface conditioning protocols, providing clear material selection guidance for ceramic repair procedures. While HFA remains the clinical gold standard, the tested laser parameters (3 W, 60 seconds) were suboptimal, warranting future dose-response studies to establish clinically effective protocols.

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