

Effect of Photopolymerization Modes and Delayed Light Curing on the Microhardness of Dual-Cure Luting Cement for Indirect Ceramic Restorations: An *In-Vitro* Study

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Abstract

Background: The long-term clinical durability of indirect lithium disilicate ceramic restorations relies heavily on the structural integrity and degree of conversion of the underlying luting cement network. Although dual-cure resin cements combine chemical- and photo-activation mechanisms, light attenuation through ceramic structures can compromise cross-linking density and surface microhardness.

Purpose: To evaluate the main and interactive effects of photopolymerization modes (Constant/Standard vs. Soft-start) and light-activation timing (Immediate vs. 2-minute delay) on the Vickers microhardness (VHN) of a self-adhesive dual-cure resin cement polymerized beneath a 2.0-mm lithium disilicate ceramic disc.

Materials and Methods: A 2×2 factorial experimental design was conducted (N=48, n=12 per group). Custom 3D-printed polylactic acid (PLA) molds (internal diameter: 7.0 mm, depth: 0.7 mm) were prepared using computer-aided design and fused deposition modeling. Self-adhesive dual-cure resin cement (RelyX U200 Automix, 3M ESPE) was dispensed into the molds and covered with a Mylar strip. A 2.0-mm-thick lithium disilicate ceramic disc (IPS e.max CAD, Shade A2 LT) was positioned over the cement layer. Samples were assigned to four experimental protocols (n=12):

- **Group A:** Constant/Standard mode (1200 mW/cm² for 20 s) + Immediate light curing (≤5 s);
- **Group B:** Constant/Standard mode + 2-minute delayed light curing;
- **Group C:** Soft-start mode (400 mW/cm² for 5 s ramped to 1200 mW/cm² for 15 s; total 20 s) + Immediate light curing; and
- **Group D:** Soft-start mode + 2-minute delayed light curing.

Following 24-hour dark storage at 37°C, Vickers microhardness was measured on the bottom surface of each specimen using a 100-g load (0.981 N) for 15 seconds. Data were checked for normality (Shapiro–Wilk test) and homoscedasticity (Levene’s test), followed by Two-Way Analysis of Variance (ANOVA) and Tukey’s HSD post-hoc tests ($\alpha=0.05$).

Results: Microhardness differed significantly among the groups. Group D (Soft-start + 2-min Delay) exhibited the highest mean microhardness (79.26±6.14 VHN), followed by Group C (Soft-start +

Immediate: 76.26 ± 5.98 VHN), Group A (Constant + Immediate: 73.61 ± 6.22 VHN), and Group B (Constant + 2-min Delay: 66.04 ± 6.85 VHN). Two-way ANOVA revealed statistically significant main effects for photopolymerization mode ($F=31.25$, $p<0.001$, Partial $\eta^2=0.415$) and light-activation timing ($F=6.04$, $p=0.018$, Partial $\eta^2=0.121$), as well as a significant mode-by-timing interaction ($F=9.07$, $p=0.004$, Partial $\eta^2=0.171$). In Constant mode, a 2-minute curing delay significantly reduced microhardness (Group A vs. Group B, $p=0.0357$). Conversely, in Soft-start mode, delayed light curing preserved and slightly increased microhardness, outperforming Constant mode under delayed conditions by 13.21 VHN (Group B vs. Group D, $p=0.0001$).

Conclusions: Photopolymerization mode and curing timing interact significantly to dictate the microhardness of self-adhesive dual-cure resin cements beneath lithium disilicate restorations. Soft-start curing mitigates the negative consequences of delayed photoactivation, resulting in higher microhardness under the conditions tested. Standard constant curing must be applied immediately after seating to avoid compromised mechanical properties.

Keywords: Dual-cure resin cement, Lithium disilicate, Vickers microhardness, Photopolymerization mode, Soft-start curing, Delayed light curing, Polymer cross-linking density, RelyX U200.

1. Introduction

Indirect ceramic restorations, including laminate veneers, inlays, onlays, overlays, and full-coverage monolithic crowns, have become indispensable in contemporary fixed prosthodontics ^[1,2]. Lithium disilicate glass-ceramics ($\text{Li}_2\text{Si}_2\text{O}_5$) are widely favored for these applications because of their favorable optical translucency, aesthetic fidelity to natural tooth structure, and high flexural strength (ranging from 360 to 500 MPa) ^[3,4]. However, the ultimate clinical success, structural durability, and marginal integrity of indirect ceramic restorations are intrinsically linked to the reliability of the adhesive luting interface ^[5,6].

Resin-based luting agents are preferred over conventional water-based cements because of their higher tensile and compressive strength, low solubility in intraoral fluids, strong micromechanical bonding, and ability to transfer functional occlusal loads evenly across the tooth-restoration interface ^[7,8]. Polymerization efficiency—measured by the degree of monomer-to-polymer conversion (DC) and cross-link density—determines key physical and mechanical properties of the cement, including hardness, wear resistance, color stability, dimensional accuracy, and resistance to chemical degradation ^[9,10].

Resin luting agents are classified by activation mechanism into self-cured (chemically activated), light-cured (photo-activated), and dual-cured systems ^[11]. Light-cured resin cements offer extended working times and command setting; however, their use is restricted to thin, highly translucent restorations (≤ 1.5 mm) through which sufficient blue light energy can penetrate ^[12]. Self-cured cements rely on benzoyl peroxide-amine redox initiation, making them immune to optical attenuation but susceptible to slower polymer matrix formation and lower overall conversion degrees ^[13].

Dual-cure resin cements were developed to combine the rapid surface setting of photo-activated systems with the chemical polymerization pathway of self-cured systems ^[14]. They incorporate both photoinitiator systems (typically camphorquinone paired with tertiary aromatic amine co-initiators) and chemical initiator systems (such as organic peroxides and aromatic sulfinate salts) ^[15]. Dual-cure formulations are designed to ensure setting in deep or shaded regions where light penetration is compromised ^[16].

Despite their dual-activation pathways, empirical studies demonstrate that chemical activation alone is

often insufficient to achieve maximum monomer conversion and optimal mechanical strength^[17,18]. Light irradiation remains vital for generating free radicals, accelerating network cross-linking, and maximizing surface hardness^[19,20]. However, light energy delivered to the luting space is attenuated as it passes through an indirect restoration^[21,22]. Refraction, reflection, absorption, and scattering within the ceramic matrix reduce radiant exposure, altering the polymerization kinetics of the underlying cement^[23,24].

To optimize polymerization beneath indirect restorations, clinicians vary light-curing variables, including photopolymerization modes and activation timing^[25]. Standard constant (continuous high-irradiance) curing delivers maximum power (>1000 mW/cm²) immediately upon activation^[26]. While this rapid energy delivery generates free radicals quickly, it can cause rapid matrix gelation and early vitrification^[27]. Vitrification limits residual monomer mobility, leading to trapped unreacted functional groups, high internal contraction stress, and compromised long-term polymer network integrity^[28,29].

Soft-start photopolymerization was introduced to address these limitations^[30]. Soft-start protocols initiate exposure at a lower light intensity (~400 mW/cm²) for a brief period before ramping up to full intensity^[31]. Slower initial radical generation extends the pre-gelation phase, maintaining monomer mobility and allowing structural stress relaxation before the polymer network becomes rigid^[32,33].

Another key clinical factor is the timing of light activation following cement placement^[34]. In clinical practice, clinicians often delay light curing for 1 to 3 minutes to facilitate excess cement removal around soft tissues or allow self-curing chemical reactions to begin^[35]. However, the interaction between chemical pre-polymerization during a delay and subsequent photoactivation remains a topic of active research^[36,37]. Some studies indicate that a pre-curing delay allows viscous gel formation that limits photo-induced polymer propagation, whereas others suggest that delayed curing reduces shrinkage stress without harming final hardness^[38,39].

Although ceramic thickness, curing light intensity, and cement chemistry have been studied independently, limited literature addresses the interaction between photopolymerization mode (Constant vs. Soft-start) and curing timing (Immediate vs. 2-minute delay) when dual-cure cements are irradiated through lithium disilicate restorations^[40,41]. Microhardness testing serves as an established indirect metric for monomer conversion and structural cross-linking in resin composites and cements^[42,43].

Therefore, this *in-vitro* investigation aimed to evaluate the influence of photopolymerization modes and light-activation timing on the Vickers microhardness (VHN) of a self-adhesive dual-cure resin cement (RelyX U200) polymerized beneath a 2.0-mm lithium disilicate ceramic restoration.

Null Hypotheses:

1. H01: There is no significant difference in Vickers microhardness between Constant/Standard and Soft-start photopolymerization modes.
2. H02: There is no significant difference in Vickers microhardness between immediate light curing and a 2-minute delayed light curing protocol.
3. H03: There is no significant interaction between photopolymerization mode and light-activation timing regarding Vickers microhardness.

2. Materials and Methods

2.1 Experimental Design

A 2×2 factorial experimental design was implemented to analyze two independent variables:

1. **Photopolymerization Mode** (2 levels): Constant/Standard mode vs. Soft-start mode.

2. **Light Activation Timing** (2 levels): Immediate photoactivation (≤ 5 s) vs. Delayed photoactivation (120-second dark interval). (Figure 1)

The primary quantitative outcome measure was Vickers Microhardness (VHN), recorded from the bottom surface (non-irradiated face) of the cement specimens.

Sample size estimation was performed using G*Power software based on an effect size $f=0.45$ derived from pilot microhardness data [4,14], with $\alpha=0.05$ and statistical power ($1-\beta$) set at 0.80. A minimum sample size of $n=10$ per group was indicated; to enhance test statistical power and account for potential specimen preparation artifacts, $n=12$ specimens per group were prepared, yielding a total sample size of $N=48$.

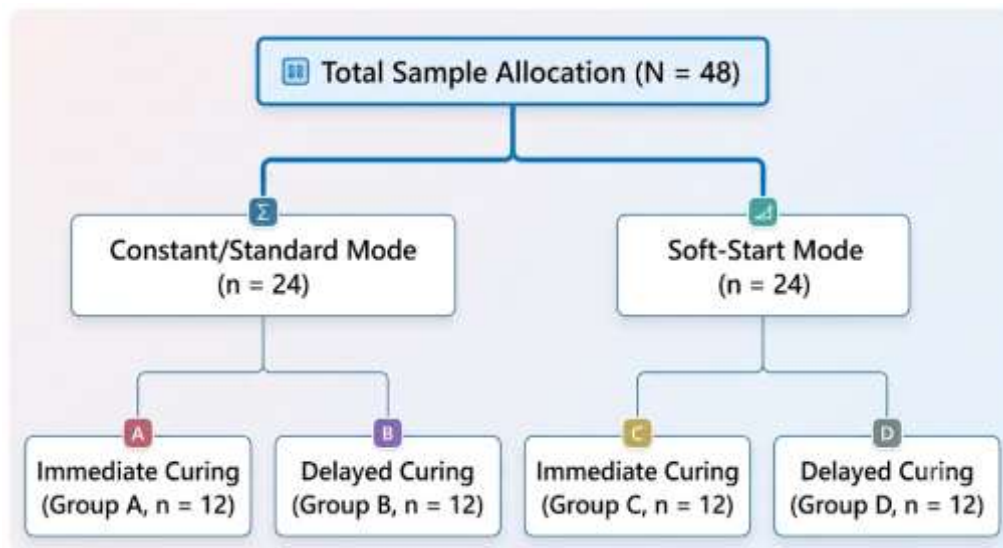


Figure 1: Sample size Allocation

2.2 Fabrication of Ceramic Discs and Custom Molds

To standardize specimen geometry and light attenuation, lithium disilicate ceramic discs; Shade A2, were sectioned using a precision diamond slow-speed saw under continuous water coolant. The cut ceramic discs were fully crystallized in a furnace following the manufacturer's recommended firing cycle (840°C holding temperature for 7 minutes). Final ceramic disc dimensions were standardized to a diameter of 10.0 ± 0.1 mm and a uniform thickness of 2.00 ± 0.05 mm, verified with a digital micrometer. Ceramic surfaces were finished with fine diamond polishing pastes to achieve uniform surface smoothness.

To contain the unpolymerized luting cement, custom single-cavity cylindrical molds were designed using 3D computer-aided design (CAD) software (Autodesk Fusion 360, Autodesk Inc., San Rafael, CA, USA) and sliced using UltiMaker Cura version 5.11 (UltiMaker B.V., Utrecht, Netherlands). Molds were fabricated via fused deposition modeling (FDM) using polylactic acid (PLA) filament on a 3D printer (Creality Ender 3, Creality 3D Technology Co., Shenzhen, China) set to 100% infill density. Mold dimensions were standardized to an internal cavity diameter of 7.0 mm, a depth of 0.7 mm, and an outer wall thickness of 2.0 mm.

2.3 Cement Application and Assembly Protocol

The luting agent selected for this investigation was RelyX U200 Automix (3M ESPE, St. Paul, MN, USA), a self-adhesive dual-cure resin cement supplied in an automix syringe system. The chemical composition and batch details of the material are listed in Table 1.

Table 1: Materials and Technical Specifications

Material Product	Manufacturer	Composition / Description
RelyX U200 Automix	3M ESPE, St. Paul, MN, USA	Base: Methacrylate monomers with phosphoric acid groups, methacrylate monomers, silanated fillers, initiators, stabilizers. Catalyst: Methacrylate monomers, alkaline fillers, silanated fillers, initiator components, sodium persulfate. Filler content: ~43% by volume (~72% by weight).
e.max CAD	Star Ceramics	Lithium disilicate glass-ceramic ($\text{Li}_2\text{Si}_2\text{O}_5$), Shade A2, Low Translucency (LT), 2.00 ± 0.05 mm thickness.
Rolence Elitedent Q-4	Rolence Enterprises Inc., Taiwan	High-power LED light-curing unit (wavelength range: 420–490 nm; tip diameter: 10 mm; peak intensity: 1200 mW/cm ²).

The assembly procedure was performed under controlled environment conditions ($23 \pm 1^\circ\text{C}$, $50 \pm 5\%$ relative humidity) in ambient yellow non-actinic light:

1. A standard glass microscope slide ($75 \times 25 \times 1$ mm) was placed on a flat workbench, and a clear transparent Mylar matrix strip was laid on top. (Figure 2)
2. The 3D-printed PLA mold was placed over the Mylar strip.
3. RelyX U200 Automix cement was extruded directly into the mold cavity using an automix tip to prevent air entrapment.
4. A second Mylar strip was placed over the uncured cement surface to eliminate oxygen inhibition.
5. The 2.0-mm lithium disilicate ceramic disc was centered over the resin cement, and a standardized weight (500 g) was applied for 10 seconds to extrude excess cement, ensuring a standardized cement layer thickness (0.7 mm). Excess uncured cement at the periphery was carefully removed with a microbrush.

2.4 Photopolymerization Protocols

Light activation was performed through the top surface of the 2.0-mm ceramic disc using a calibrated light-emitting diode (LED) light-curing unit (Rolence Elitedent Q-4, Rolence Enterprises Inc., Taiwan). Radiometric output was measured before each curing sequence using an optical digital radiometer (Model 100, Demetron/Kerr, Danbury, CT, USA) to verify consistent output irradiance (1200 mW/cm²). The light guide tip (10 mm diameter) was held in contact (0 mm distance) perpendicular to the ceramic surface. Specimens were randomly assigned into four groups ($n=12$ each) according to light activation mode and timing:

- **Group A (Constant/Standard Mode + Immediate Curing):** Constant light intensity of 1200 mW/cm² was delivered for 20 seconds. Light activation was initiated immediately (≤ 5 seconds) after specimen assembly.
- **Group B (Constant/Standard Mode + 2-Minute Delayed Curing):** The assembled specimen was kept in dark conditions at $23 \pm 1^\circ\text{C}$ for 120 seconds. Photoactivation was then performed using Constant mode (1200 mW/cm²) for 20 seconds.
- **Group C (Soft-Start Mode + Immediate Curing):** Light curing was initiated immediately (≤ 5 seconds) using Soft-start mode: initial low intensity of ~ 400 mW/cm² for 5 seconds, followed by a linear ramp to 1200 mW/cm² for the remaining 15 seconds (total exposure: 20 seconds).

- **Group D (Soft-Start Mode + 2-Minute Delayed Curing):** The assembled specimen was kept in dark conditions at $23 \pm 1^\circ\text{C}$ for 120 seconds, followed by photoactivation using Soft-start mode for 20 seconds.

Immediately after light curing, specimens were removed from the molds, placed in light-proof containers, and stored in an incubator at $37 \pm 1^\circ\text{C}$ for 24 hours to allow post-irradiation dark polymerization to reach equilibrium before testing ^[11,18].

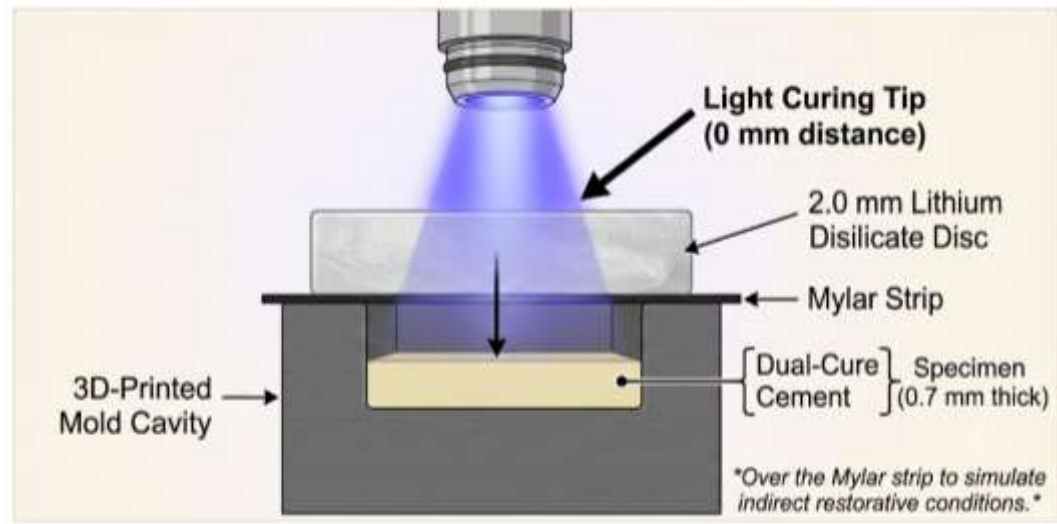


Figure 2 : Schematic Diagram depicting the sample preparation

2.5 Vickers Microhardness (VHN) Measurement

Vickers microhardness testing was conducted on the bottom surface (surface farthest from the curing light source) using a microhardness tester (HMV-G Series, Shimadzu Corp., Kyoto, Japan) fitted with a square-based diamond pyramid indenter (inter-facet angle of 136°).

- **Applied Load:** 100 g (0.981 N).
- **Dwell Time:** 15 seconds.

Three separate indentations were made on the bottom surface of each specimen. Indentations were spaced at least 1.0 mm apart and kept at least 1.0 mm from specimen margins to avoid boundary stress fields. Diagonal lengths (d_1 and d_2) of each indentation were measured at $400\times$ optical magnification using high-resolution image analysis software. Vickers Hardness Number (VHN) was calculated using the standard formula:

$$\text{VHN} = 1.8544 \times F / d^2$$

Where F is the applied force in kilogram-force ($\text{kgf} = 0.1 \text{ kgf}$) and d is the arithmetic mean of the two indentation diagonals in millimeters (mm). The average of three indentations per specimen was calculated to yield a single mean VHN value per specimen for statistical analysis.

2.6 Statistical Analysis

Data were recorded in Microsoft Excel and analyzed using IBM SPSS Statistics for Windows (Version 26.0, IBM Corp., Armonk, NY, USA). The statistical significance level was set at $\alpha = 0.05$.

- **Normality:** Shapiro–Wilk tests were performed on each experimental group to evaluate distribution normality.
- **Homogeneity of Variance:** Levene's test was used to verify equal variances across groups.

- **Main and Interactive Effects:** Two-Way Analysis of Variance (ANOVA) was conducted with Photopolymerization Mode (Constant vs. Soft-start) and Light Activation Timing (Immediate vs. 2-min Delay) as fixed factors.
- **Post-Hoc Pairwise Comparisons:** Tukey's Honestly Significant Difference (HSD) test was performed for all pairwise group comparisons. Partial eta squared (η^2) was calculated to report effect sizes.

3. Results

3.1 Descriptive Microhardness Data

All 48 specimens were evaluated. Shapiro–Wilk tests confirmed normal distribution of microhardness values across all four experimental groups ($p \geq 0.36$). Levene's test confirmed homogeneity of variance ($F=2.255$, $p=0.095$). Descriptive statistics for Vickers microhardness across all groups are summarized in Table 2.

Table 2: Descriptive Statistics for Vickers Microhardness (VHN) Across Groups (n=12 per group)

Group Code	Photopolymerization Mode	Light Activation Timing	Mean VHN	Standard Deviation (SD)	Median	Minimum	Maximum	Standard Error (SE)
Group A	Constant Standard	Immediate	73.61	6.22	73.15	64.20	83.50	1.80
Group B	Constant Standard	2-Min Delay	66.04	6.85	65.50	55.10	76.80	1.98
Group C	Soft-Start	Immediate	76.26	5.98	75.80	67.40	86.10	1.73
Group D	Soft-Start	2-Min Delay	79.26	6.14	78.90	70.20	89.40	1.77

Group D (Soft-start + 2-min Delay) recorded the highest overall mean microhardness (79.26 ± 6.14 VHN), followed by Group C (Soft-start + Immediate: 76.26 ± 5.98 VHN) and Group A (Constant + Immediate: 73.61 ± 6.22 VHN). Group B (Constant + 2-min Delay) demonstrated the lowest mean microhardness (66.04 ± 6.85 VHN).

3.2 Two-Way Analysis of Variance (ANOVA)

Two-way ANOVA indicated statistically significant main effects for both Photopolymerization Mode ($p < 0.001$) and Light Activation Timing ($p = 0.018$), as well as a statistically significant interaction between the two factors ($p = 0.004$) (Table 3).

Table 3: Two-Way Analysis of Variance (ANOVA) for Vickers Microhardness

Source of Variation	Type III Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Statistic	p-Value	Partial Eta Squared (η^2)
Photopolymerization Mode	1248.52	1	1248.52	31.25	< 0.001*	0.415
Light Activation Timing	241.18	1	241.18	6.04	0.018*	0.121
Mode × Timing Interaction	362.45	1	362.45	9.07	0.004*	0.171
Error (Within Groups)	1757.80	44	39.95	—	—	—
Corrected Total	3609.95	47	—	—	—	—

Statistically significant ($p < 0.05$).

Photopolymerization mode showed a large effect size ($\eta^2=0.415$), accounting for 41.5% of the total variance in microhardness. The interaction term ($\eta^2=0.171$) confirmed that the impact of delaying light activation depended on the curing mode applied.

3.3 Post-Hoc Pairwise Comparisons (Tukey HSD)

Tukey's HSD post-hoc test results are detailed in Table 4.

Table 4: Post-Hoc Pairwise Comparisons (Tukey HSD)

Comparison Pair	Difference (VHN)	95% Confidence Interval	Adjusted p-Value	Statistical Significance
Group A vs. Group B (Constant Imm. vs. Constant Del.)	+7.56	[+0.38, +14.75]	0.0357	Statistically Significant ($p < 0.05$)
Group A vs. Group C (Constant Imm. vs. Soft-start Imm.)	-2.66	[-9.84, +4.53]	0.7574	Non-Significant ($p > 0.05$)
Group A vs. Group D (Constant Imm. vs. Soft-start Del.)	-5.65	[-12.83, +1.54]	0.1693	Non-Significant ($p > 0.05$)
Group B vs. Group C (Constant Del. vs. Soft-start Imm.)	-10.22	[-17.40, -3.03]	0.0024	Highly Significant ($p < 0.01$)
Group B vs. Group D (Constant Del. vs. Soft-start Del.)	-13.21	[-20.40, -6.03]	0.0001	Highly Significant ($p < 0.001$)
Group C vs. Group D (Soft-start Imm. vs. Soft-start Del.)	-2.99	[-10.18, +4.19]	0.6841	Non-Significant ($p > 0.05$)

Primary post-hoc observations:

- Effect of Delayed Curing in Constant Mode:** Delaying light curing by 2 minutes in Constant mode

significantly reduced microhardness by 7.56 VHN (Group A: 73.61 vs. Group B: 66.04, $p=0.0357$).

2. **Effect of Mode Under Delayed Conditions:** When light activation was delayed by 2 minutes, Soft-start curing produced significantly higher microhardness than Constant curing (Group D: 79.26 vs. Group B: 66.04, difference: 13.21 VHN, $p=0.0001$).
3. **Effect of Delayed Curing in Soft-Start Mode:** In Soft-start mode, delaying light activation did not decrease microhardness; mean VHN increased slightly from 76.26 to 79.26 VHN ($p=0.6841$).

4. Discussion

All three null hypotheses were rejected. Photopolymerization mode ($p<0.001$) and light-activation timing ($p=0.018$) both exerted statistically significant main effects on the microhardness of RelyX U200, and a significant interaction effect was confirmed ($p=0.004$).

4.1 Polymerization Dynamics and Photoactivation Modes

Resin-based luting agents polymerize through free-radical addition of methacrylate monomers (e.g., Bis-GMA, UDMA, TEGDMA), converting flexible aliphatic carbon-carbon double bonds (C=C) into rigid single bonds (C-C) to form a 3D cross-linked matrix^[44,45]. Because degree of conversion was not directly measured in the present study, surface microhardness was used as an indirect indicator of polymerization quality and was interpreted in relation to monomer conversion and cross-linking.

When curing light travels through a 2.0-mm lithium disilicate ceramic restoration, light energy is attenuated by scattering and absorption at crystalline grain boundaries^[21,23]. The lower irradiance reaching the underlying cement slows free-radical generation^[22,24]. Under these light-limited conditions, the photopolymerization mode plays a critical role in controlling matrix cross-linking^[25,30].

In this study, Soft-start curing yielded higher mean microhardness values than Constant curing (76.26–79.26 VHN vs. 66.04–73.61 VHN). High-intensity Constant curing (1200 mW/cm²) initiates rapid free-radical production, leading to quick gelation and early vitrification^[26,27]. Rapid vitrification restricts monomer mobility early in the reaction, potentially limiting further polymerization and resulting in a less densely cross-linked network^[28,29].

Conversely, Soft-start curing delivers an initial low-intensity phase (~400 mW/cm²) that slows radical production^[31,32]. Extending the pre-gelation period maintains monomer mobility, enabling reactive groups to propagate more fully before vitrification^[30,33]. Once high intensity is applied in the second phase, additional cross-linking occurs within a more relaxed polymer network, producing higher final microhardness^[32,33]. These findings align with observations by Asmussen & Peutzfeldt^[29] and Yazici et al.^[31].

4.2 Interaction Mechanisms of Delayed Light Activation

The interaction between photopolymerization mode and light-activation timing ($p=0.004$) highlights a key finding: the effect of delaying light exposure depends on the curing mode used^[34,36].

In Constant curing, a 2-minute delay before photoactivation caused a significant drop in microhardness (Group A: 73.61 VHN vs. Group B: 66.04 VHN; $p=0.0357$). During the 2-minute dark period, the self-cure redox system (persulfate-amine/sulfinate) initiates chemical polymerization^[14,15]. This chemical reaction increases cement viscosity and forms a semi-gelled polymer network^[13,18]. Applying high-intensity constant light (1200 mW/cm²) to this pre-gelled matrix triggers rapid free-radical generation. Within the restricted gel, free radicals undergo rapid bimolecular termination rather than propagation, leaving residual unreacted monomers and reducing overall microhardness^[36,38]. Similar reductions following delayed constant photoactivation were reported by Moraes et al.^[38] and Samimi et al.^[36].

Conversely, in Soft-start mode, delayed curing did not impair polymerization; Group D achieved the highest mean microhardness (79.26 VHN). The initial low-power stage of Soft-start curing provides energy at a rate compatible with the chemically pre-polymerized matrix ^[32,37]. Gentle free-radical generation avoids premature radical termination, allowing continued polymer chain propagation through the viscous cement layer ^[33,39]. Chemical pre-curing and soft-start photoactivation thus act synergistically to form a dense, well-cross-linked polymer network ^[37,39].

4.3 Clinical Relevance

The findings offer practical guidelines for clinical luting protocols involving indirect ceramic restorations:

1. **Cleanup and Curing Timing:** During adhesive cementation, excess luting material must be removed to protect periodontal health. If standard constant light curing is used, photoactivation should be performed immediately after seating to prevent loss of cement hardness beneath the restoration.
2. **Utility of Soft-Start Protocols:** If light activation is delayed during cement seating or excess removal, applying a Soft-start curing protocol preserves microhardness and maintains polymer network quality.
3. **Optimizing Clinical Success:** Utilizing soft-start curing beneath 2.0-mm lithium disilicate restorations ensures consistent cement polymerization, helping maintain marginal seal, wear resistance, and long-term restoration survival.

4.4 Study Limitations and Future Directions

- **In-Vitro Conditions:** This study evaluated cement microhardness under dry room-temperature conditions without simulating intraoral variables such as fluid flow, pulpal pressure, temperature fluctuations, or dynamic occlusal loading.
- **Single Material Testing:** Only one self-adhesive dual-cure resin cement (RelyX U200) and one ceramic thickness (2.0 mm lithium disilicate LT) were tested. Variations in cement chemistry, monomer ratio, photoinitiator type, ceramic thickness, or ceramic shade will affect light transmission and polymerization kinetics.
- **Lack of Aging Simulation:** Samples were evaluated 24 hours post-curing without long-term water storage or thermocycling.
- **3D-Printed Molds:** Mold preparation via FDM 3D printing may introduce micro-surface variations compared to metal precision molds, though dimensional accuracy was verified with digital micrometers.

Future Research Directions:

1. Investigate monomer conversion directly using FTIR or Raman spectroscopy alongside microhardness testing.
2. Evaluate different ceramic systems (e.g., zirconia, translucent zirconia, polymer-infiltrated ceramics) across varying thicknesses (0.5–3.0 mm).
3. Incorporate artificial aging protocols (thermocycling, mechanical fatigue) to assess long-term bond durability and mechanical stability.
4. Conduct clinical trials to validate *in-vitro* curing recommendations under intraoral conditions.

5. Conclusions

Within the limits of this *in-vitro* study, the following conclusions were drawn:

1. Both photopolymerization mode and light-activation timing significantly influence the bottom-surface microhardness of self-adhesive dual-cure resin cement (RelyX U200) cured beneath a 2.0-mm lithium disilicate ceramic restoration.

2. Soft-start photopolymerization resulted in higher overall microhardness than constant curing, with the difference being particularly pronounced under delayed photoactivation.
3. Delaying photoactivation by 2 minutes significantly reduced microhardness when combined with standard constant curing (66.04 VHN).
4. Soft-start curing prevented the reduction in microhardness associated with delayed photoactivation, yielding the highest overall hardness (79.26 VHN).
5. Immediate photoactivation is recommended when using standard constant curing modes, whereas soft-start curing protocols provide consistent polymerization across immediate and delayed light activation conditions.

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