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Does the Thickness and Translucency of CAD/CAM Blocks Affect the Polymerization of Resin Cements with Different Structures?

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Abstract

This study evaluated the effects of CAD/CAM material thickness and translucency on the Vickers microhardness and bottom-to-top hardness ratio of adhesive and self-adhesive resin cements. Eighty specimens (n = 10 per group) were prepared using RelyX Ultimate and RelyX U200. Resin cements were light-activated through lithium disilicate-reinforced CAD/CAM blocks (Initial LiSi Block) with two thicknesses (2 and 4 mm) and two translucency levels (high translucency [HT] and low translucency [LT]). Vickers microhardness was measured on the top and bottom surfaces after 24 h, and the bottom-to-top hardness ratio was calculated as a relative hardness-based indicator of polymerization-related mechanical performance. Increasing block thickness from 2 to 4 mm significantly reduced the bottom-to-top hardness ratio for both resin cements under both translucency conditions ($p \leq 0.008$). High-translucency blocks produced significantly higher microhardness values than low-translucency blocks for both cements at both thicknesses ($p = 0.001$). The effect of thickness on microhardness varied according to cement type and translucency. For RelyX Ultimate, the bottom-to-top hardness ratio was significantly higher under 2 mm HT than 2 mm LT conditions ($p = 0.006$). Within the limitations of this study, greater CAD/CAM thickness and lower translucency were associated with less favorable polymerization-related mechanical performance.

Keywords: adhesive resin cement; microhardness; self-adhesive resin cement; translucency

1. Introduction

With the increasing use of computer-aided design and computer-aided manufacturing (CAD/CAM) technology in dentistry, the production of indirect restorations has become increasingly standardized and predictable [1–4]. Initially introduced for the fabrication and same-day delivery of inlay restorations [1], CAD/CAM technology has subsequently expanded to a wide range of indirect restorative applications [2–4]. The clinical success of indirect restorations depends on several factors, including cavity preparation, the properties of the restorative material, the cementation protocol, and the type of luting cement used [5].

Cementation is a critical step in the clinical prognosis of indirect restorations because the luting material contributes to retention, marginal sealing, stress distribution, and the overall integrity of the tooth–restoration complex [6]. The performance of a resin cement is influenced by several factors, including cement composition, the characteristics of the bonded surfaces, application conditions, and the extent of polymerization [7–9]. There-

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fore, adequate polymerization of the resin cement is particularly important for achieving favorable mechanical and clinical performance.

Resin cements are widely used for the luting of indirect restorations because of their low solubility, favorable esthetic properties, and ability to provide adhesion to both tooth structures and restorative materials [10]. According to their activation mechanisms, resin cements may be classified as chemically activated, light-cured, or dual-cured materials [11]. Because light transmission through an indirect restoration may be attenuated depending on the material and its thickness, previous studies have recommended the use of dual-cure or chemically activated resin cements when restorations are relatively thick or have limited light transmission [12–14].

The optical characteristics and thickness of CAD/CAM restorative materials are therefore important factors that may influence the polymerization of resin cements. Previous investigations have demonstrated that restoration thickness, shade, translucency, and ceramic type can affect the amount of light reaching the underlying resin cement and consequently influence polymerization-related mechanical properties [15–17]. However, these studies have used different restorative materials, cement formulations, thicknesses, optical classifications, and experimental protocols, making direct comparisons between their findings difficult.

Among CAD/CAM restorative materials, lithium disilicate-reinforced glass ceramics are widely used for indirect restorations because of their favorable mechanical and optical properties and their availability in different translucency levels. Initial LiSi Block (GC) was selected in the present study as a clinically relevant CAD/CAM restorative material that is available in high- and low-translucency variants. The availability of different translucency levels within the same ceramic system allowed the effects of translucency and thickness to be investigated while minimizing differences in chemical composition and microstructure between restorative materials. Therefore, the use of a single CAD/CAM ceramic system provided a standardized experimental model for specifically evaluating how material thickness and translucency influence the polymerization-related mechanical performance of resin cements.

Resin cement formulation may also contribute to differences in polymerization-related mechanical properties. Adhesive resin cements generally require multiple clinical application steps, which may increase technique sensitivity [18,19]. In contrast, self-adhesive resin cements simplify the cementation procedure by reducing or eliminating separate pretreatment steps [20]. Differences in monomer composition, filler characteristics, polymerization mechanism, and cross-linking behavior may consequently influence the hardness of the resulting polymer network. In addition, rheological characteristics such as viscosity and flowability may influence the distribution and thickness of the cement layer and may therefore represent additional material-dependent factors affecting polymerization-related mechanical performance.

Importantly, although Vickers microhardness is commonly used as an indirect indicator of polymerization-related mechanical performance, hardness is not determined solely by monomer conversion. Resin matrix composition, filler content and characteristics, filler distribution, cross-link density, and other material-dependent factors may also influence the measured hardness. Therefore, Vickers microhardness should not be considered a direct quantitative measurement of the degree of conversion. Direct analytical techniques such as Fourier-transform infrared spectroscopy (FTIR) can provide a more direct assessment of monomer conversion by evaluating changes in the carbon–carbon double-bond signal before and after polymerization. In contrast, Vickers microhardness reflects the mechanical properties of the resulting polymerized material and cannot distinguish the contribution of monomer conversion from that of other material-dependent factors. Accordingly, the

bottom-to-top hardness ratio used in the present study should be interpreted as a relative, hardness-based indicator of polymerization-related mechanical performance rather than as a direct measurement or quantitative estimate of monomer conversion. Nevertheless, Vickers microhardness provides a relatively simple, reproducible, and practical method for evaluating the mechanical consequences of polymerization under different curing conditions.

Although previous studies have investigated the influence of ceramic thickness, translucency, shade, or restorative material type on resin-cement polymerization, the available evidence remains heterogeneous because different restorative materials, cement formulations, thicknesses, optical classifications, and experimental protocols have been used. Moreover, previous investigations have generally focused on selected restorative material characteristics or individual cement formulations rather than evaluating restoration thickness, translucency, and resin cement type simultaneously within the same standardized experimental design. In particular, limited information is available regarding whether the effects of CAD/CAM material thickness and translucency on polymerization-related mechanical performance vary according to resin cement formulation. Evaluating these factors simultaneously may therefore provide a more comprehensive understanding of how restorative material characteristics interact with cement composition to influence the mechanical performance of resin cements beneath indirect restorations.

Therefore, the aim of the present study was to simultaneously evaluate the effects of CAD/CAM material thickness (2 and 4 mm), translucency (high and low), and resin cement type on the Vickers microhardness of an adhesive resin cement and a self-adhesive dual-cure resin cement. In addition, the bottom-to-top hardness ratio was calculated as a relative measure of the hardness gradient between the two surfaces of the cement specimens. By evaluating these three factors within the same standardized experimental design, this study sought to determine whether the effects of CAD/CAM material thickness and translucency on polymerization-related mechanical performance vary according to resin cement formulation.

The null hypotheses were that: (1) resin cement type would have no significant effect on Vickers microhardness or the bottom-to-top hardness ratio; (2) CAD/CAM material thickness would have no significant effect on Vickers microhardness or the bottom-to-top hardness ratio; (3) CAD/CAM material translucency would have no significant effect on Vickers microhardness or the bottom-to-top hardness ratio; (4) there would be no significant interaction between resin cement type and CAD/CAM material thickness, resin cement type and translucency, or CAD/CAM material thickness and translucency; and (5) there would be no significant three-way interaction among resin cement type, CAD/CAM material thickness, and translucency for either outcome.

2. Materials and Methods

The CAD/CAM blocks were sectioned at Ankara University, Turkey. All other laboratory procedures were performed at the Department of Restorative Dentistry, Gazi University.

Sample size determination was carried out using G*Power software 3.1.9.7 (https://g-power.apponic.com/) through an a priori power analysis. Based on an anticipated effect size of 0.50, an alpha level of 0.05, and a statistical power of 80%, the minimum required sample size was calculated as 10 specimens per group. Accordingly, a total of 80 resin cement specimens were prepared and equally allocated among the eight experimental groups (n = 10 per group).

2.1. Preparation of Samples

2.1.1. Resin Cements Selected for the Study

In this study, an adhesive resin cement (RelyX Ultimate) and a self-adhesive resin cement (RelyX U200) were evaluated. Detailed information about the composition of the cements is presented in Table 1.

Table 1. Resin Cements Used in the Study and Their Chemical Composition.

Product	Material-Shade	Composition
RelyX Ultimate (3M ESPE, St. Paul, MN, USA) (LOT: 11495690)	Adhesive Resin Cement	Base: methacrylate monomers, silanated fillers, initiator components, stabilizers, rheological additives Catalyst: methacrylate monomers, alkaline fillers, silanated fillers, initiator components, stabilizers, pigments, rheological additives, fluorescence dye, and dark cure activator for Scotchbond Universal adhesive
RelyX U200 (3M ESPE, St. Paul, MN, USA) (LOT: 11357522)	Self-Adhesive Resin Cement	Base: methacrylate monomers containing phosphoric acid groups, methacrylate monomers, silanated fillers, initiator components, stabilizers, and rheological additives Catalyst: methacrylate monomers, alkaline fillers, silanated fillers, initiator components, stabilizers, pigments, and rheological additives

2.1.2. Ceramic Material Included in the Study

To simulate an indirect CAD/CAM restoration, lithium disilicate-reinforced glass-ceramic blocks (Initial LiSi Block, GC Corporation, Tokyo, Japan) were used. Two variants of the material were evaluated according to the manufacturer's translucency classification: Initial LiSi Block HT and Initial LiSi Block LT. Both materials were evaluated in the same shade, A2, to minimize the potential effect of shade on light transmission and resin cement polymerization. The HT variant was classified as high translucency (HT), whereas the LT variant was classified as low translucency (LT) according to the manufacturer's classification.

Initial LiSi Block was selected because lithium disilicate-reinforced glass ceramics are clinically relevant CAD/CAM restorative materials used for indirect restorations and are commercially available in different translucency levels. The availability of HT and LT variants within the same ceramic system allowed the effects of translucency and material thickness to be investigated under standardized material conditions. Using the same shade for both translucency variants further minimized potential differences in light attenuation attributable to shade. Therefore, this experimental design allowed the effects of thickness and translucency to be evaluated while minimizing differences in chemical composition, microstructure, and shade between the restorative materials.

Ceramic specimens with dimensions of approximately 10 × 10 mm and two different thicknesses (2 and 4 mm) were prepared. The specimens were obtained from the CAD/CAM blocks using a precision cutting machine (Secotom-60, Struers, Ballerup, Denmark) at Ankara University.

Following sectioning, the thickness of each ceramic specimen was measured using a caliper, and additional cutting was performed when necessary to obtain the target thicknesses of 2.0 and 4.0 mm. After thickness adjustment, the cut surfaces of the ceramic specimens were polished using a sanding and polishing device (Mecapol P230, Presi, Grenoble, France) with 2000-grit silicon carbide abrasive paper to obtain smooth and standardized surfaces. The final thickness of each specimen was measured again using a caliper and verified before its use in the polymerization procedure. Two translucency levels, high translucency (HT) and low translucency (LT), were evaluated according to the manufacturer's classification.

2.1.3. Preparation of Resin Cement Specimens Under Ceramic Blocks

A total of 80 resin cement specimens were prepared, with 10 specimens allocated to each experimental group. The group distribution is presented in Table 2.

Table 2. Grouping of Test Samples (HT: high translucency, LT: low translucency).

Group	Cement–CAD/CAM Material Thickness–Translucency
1	Rely X U 200–2 mm–HT
2	Rely X U 200–4 mm–HT
3	Rely X U 200–2 mm–LT
4	Rely X U 200–4 mm–LT
5	Rely X Ultimate–2 mm–HT
6	Rely X Ultimate–4 mm–HT
7	Rely X Ultimate–2 mm–LT
8	Rely X Ultimate–4 mm–LT

The resin cements were prepared according to the manufacturers' instructions and placed into cylindrical Plexiglass molds with dimensions of 1 mm in thickness and 6 mm in internal diameter. A 1 mm specimen thickness was selected to provide a standardized laboratory geometry for evaluating differences between the top and bottom surfaces. This thickness was used as an experimental condition rather than as a direct simulation of the clinical resin cement film thickness. Mylar strips were placed on the top and bottom surfaces of the molds to obtain standardized and smooth specimen surfaces.

For polymerization, the prepared ceramic specimens were not bonded to the resin cement. Instead, each ceramic specimen was placed directly in contact with the upper Mylar strip covering the uncured resin cement specimen. Thus, the ceramic specimen was positioned between the resin cement and the light-curing unit and served as an interposed CAD/CAM restorative material through which the curing light had to pass.

The dual-cure resin cements were polymerized through the ceramic specimens using an LED light-curing unit (D-Light Pro, GC, Tokyo, Japan) with an irradiance of 1200 mW/cm^2 for 20 s. The ceramic specimens were kept in the same position throughout light activation. Immediately after polymerization, the ceramic specimens and Mylar strips were removed, and the resin cement specimens were allowed to polymerize under standardized conditions (Figure 1).

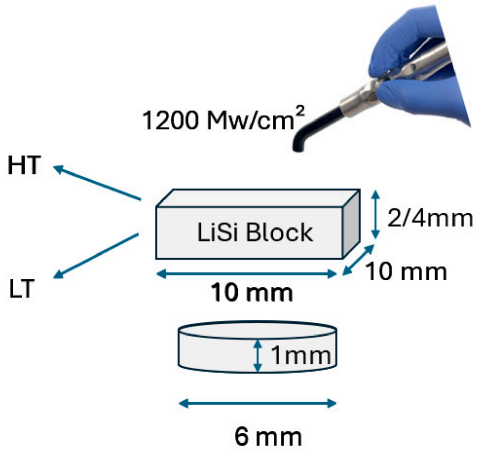


Figure 1. Schematic representation of specimen preparation and polymerization procedure. The resin cement was placed in a cylindrical Plexiglass mold (1 mm thickness × 6 mm internal diameter) and

covered with Mylar strips. The CAD/CAM ceramic block was positioned directly on the upper Mylar strip and served as an interposed material between the resin cement and the LED light-curing unit. The resin cement was polymerized through the CAD/CAM block using an LED light-curing unit (D-Light Pro, GC, Japan) at an irradiance of 1200 mW/cm^2 for 20 s. HT, high translucency; LT, low translucency; CAD/CAM, computer-aided design/computer-aided manufacturing.

All specimens were stored in an incubator at 37 °C under dark and dry conditions for 24 h before microhardness measurements.

2.2. Vickers Microhardness Measurement and Calculation of the Bottom-to-Top Hardness Ratio

Vickers microhardness measurements were performed after the specimens had been stored at 37 °C under dry and dark conditions for 24 h. Measurements were obtained from both the top and bottom surfaces of each polymerized resin cement specimen using a Vickers microhardness tester (HMV-700 Microhardness Tester, Shimadzu Corporation, Kyoto, Japan) with a load of 50 gf (approximately 0.49 N) applied for 15 s. Three indentations were made on each surface of each specimen, and the mean of the three measurements was calculated and recorded as the Vickers microhardness value for that surface. The top surface was defined as the surface directly exposed to the curing light, whereas the bottom surface was defined as the surface opposite to the curing-light direction. Vickers microhardness values were expressed in Vickers hardness units (HV).

For each specimen, the bottom-to-top hardness ratio was calculated individually before statistical analysis by dividing the mean Vickers microhardness value of the bottom surface by the mean Vickers microhardness value of the top surface and multiplying the result by 100:

$$\text{Bottom-to-top hardness ratio (\%)} = (\text{Bottom-surface Vickers microhardness}/\text{Top-surface Vickers microhardness}) \times 100$$

The individual bottom-to-top hardness ratios were subsequently used for statistical analysis. This ratio was considered a relative, hardness-based indicator of polymerization-related mechanical performance rather than a direct measurement or quantitative estimate of monomer conversion.

2.3. Statistical Analysis

IBM SPSS Statistics 22 software was used for statistical analysis. The normality of the data was assessed using the Kolmogorov–Smirnov and Shapiro–Wilk tests, while the homogeneity of variances was assessed using Levene's test. Since the assumptions of normality and homogeneity of variances were satisfied ($p > 0.05$), a three-way analysis of variance (ANOVA) was performed to evaluate the effects of resin cement type, CAD/CAM material thickness, and translucency on Vickers microhardness and the bottom-to-top hardness ratio. Statistical significance was set at $p < 0.05$. Following significant ANOVA results, pairwise comparisons between the experimental groups were performed using the Tukey HSD post hoc test.

3. Results

3.1. Microhardness Results

There was no statistically significant difference in microhardness levels between the RelyX U200–2 mm–HT group and the RelyX U200–4 mm–HT group ($p = 0.449$). Similarly, no statistically significant difference was found between the RelyX Ultimate–2 mm–HT group and the RelyX Ultimate–4 mm–HT group in terms of microhardness values ($p = 0.821$) (Table 3, Figure 2A).

Table 3. Evaluation of microhardness according to cement, translucency and thickness.

		Microhardness		
		Rely X U200	Rely X Ultimate	
Translucency	**Thickness**	**Mean ± SD**	**Mean ± SD**	***p***
HT	2 mm	41.53 ± 1.23	39.58 ± 1.61	0.064
	4 mm	40.87 ± 1.39	39.35 ± 1.45	0.130
	p	0.449	0.821	
LT	2 mm	37.71 ± 0.69	35.64 ± 0.87	0.003 *
	4 mm	34.51 ± 0.71	34.78 ± 0.74	0.575
	p	0.001 *	0.129	
HT-LT	2 mm *p*	0.001 *	0.001 *	
	4 mm *p*	0.001 *	0.001 *	

Three-way ANOVA Test. * $p < 0.05$.

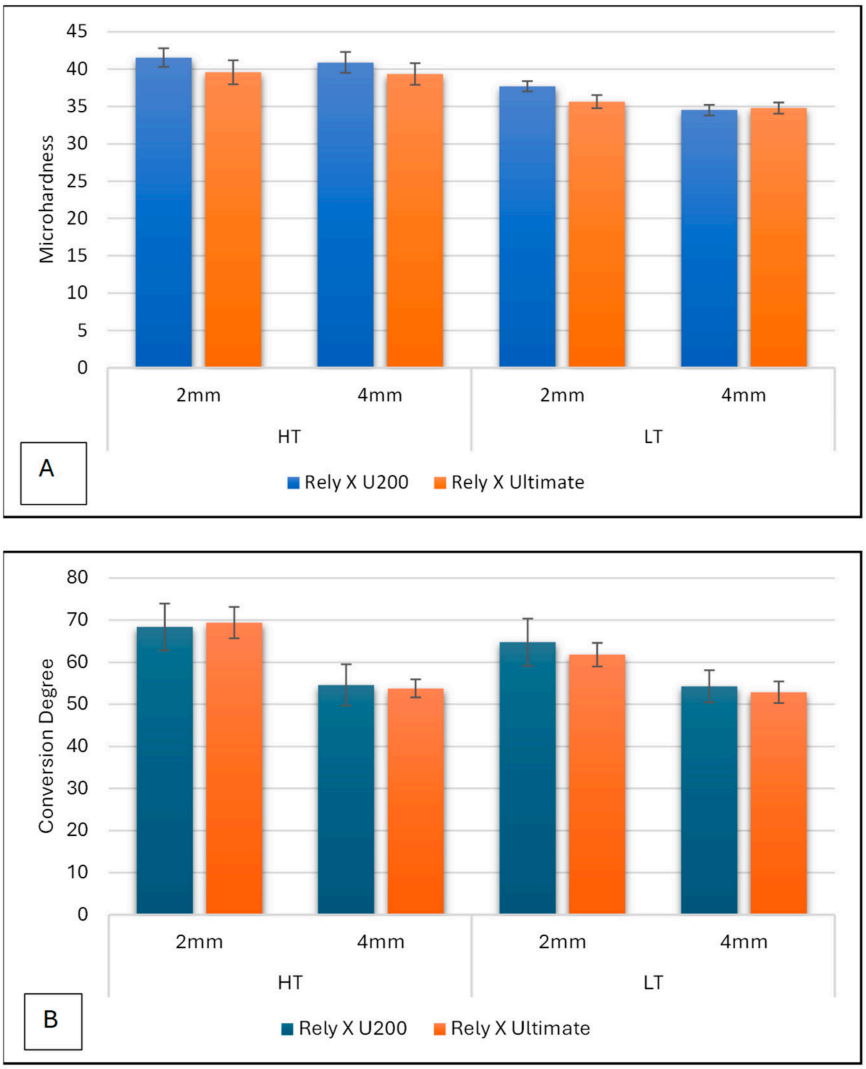


Figure 2. (**A**) Evaluation of microhardness according to cement, translucency and thickness, (**B**) Evaluation of the effect of cement, translucency and thickness on the degree of conversion.

The microhardness values of the RelyX U200–2 mm–LT group were significantly higher than those of the RelyX U200–4 mm–LT group ($p = 0.001$), whereas no statistically significant difference was observed between the RelyX Ultimate–2 mm–LT and RelyX Ultimate–4 mm–LT groups ($p = 0.129$) (Table 3, Figure 2A).

The microhardness values of the RelyX U200–2 mm–HT group were significantly higher than those of the RelyX U200–2 mm–LT group (p = 0.001). Similarly, the RelyX U200–4 mm–HT group also exhibited significantly higher microhardness values compared to the RelyX U200–4 mm–LT group (p = 0.001) (Table 3, Figure 2A).

The microhardness values of the RelyX Ultimate–2 mm–HT group were significantly higher than those of the RelyX Ultimate–2 mm–LT group (p = 0.001). Likewise, the RelyX Ultimate–4 mm–HT group showed significantly higher microhardness values than the RelyX Ultimate–4 mm–LT group (p = 0.001) (Table 3, Figure 2A).

3.2. Bottom-to-Top Hardness Ratio Results

There was no statistically significant difference in the bottom-to-top hardness ratio between the RelyX U200–2 mm–HT group and the RelyX Ultimate–2 mm–HT group (p = 0.739), as well as between the RelyX U200–4 mm–HT group and the RelyX Ultimate–4 mm–HT group (p = 0.749) (Tables 4 and 5, Figure 2B).

Table 4. Top/bottom surface microhardness values according to cement type, translucency, and thickness used in the calculation of the degree of conversion.

		Microhardness (Top Surface/Bottom Surface)	
		Rely X U200	Rely X Ultimate
Translucency	**Thickness**	**Mean ± SD**	**Mean ± SD**
HT	2 mm	41.53 ± 1.23/28.37 ± 1.88	39.58 ± 1.61/27.44 ± 0.66
	4 mm	40.87 ± 1.39/22.25 ± 1.34	39.35 ± 1.45/21.15 ± 0.96
LT	2 mm	37.71 ± 0.69/24.40 ± 1.82	35.64 ± 0.87/22.01 ± 0.72
	4 mm	34.51 ± 0.71/18.72 ± 1.12	34.78 ± 0.74/18.38 ± 0.76

Table 5. Evaluation of the effect of cement, translucency and thickness on the degree of conversion.

		Conversion Degree		
		Rely X U200	Rely X Ultimate	
Translucency	**Thickness**	**Mean ± SD**	**Mean ± SD**	p
HT	2 mm	68.40 ± 5.56	69.43 ± 3.73	0.739
	4 mm	54.57 ± 4.93	53.76 ± 2.12	0.749
	p	0.003 *	0.001 *	
LT	2 mm	64.76 ± 5.60	61.79 ± 2.83	0.321
	4 mm	54.27 ± 3.81	52.87 ± 2.58	0.516
	p	0.008 *	0.001 *	
HT-LT	2 mm p	0.332	0.006 *	
	4 mm p	0.918	0.569	

Three-way ANOVA Test. * $p < 0.05$.

Similarly, no statistically significant difference was found between the RelyX U200–2 mm–LT group and the RelyX Ultimate–2 mm–LT group (p = 0.321), or between the RelyX U200–4 mm–LT group and the RelyX Ultimate–4 mm–LT group (p = 0.516) in terms of the bottom-to-top hardness ratio (Tables 4 and 5, Figure 2B).

The bottom-to-top hardness ratio of the RelyX U200–2 mm–HT group was significantly higher than that of the RelyX U200–4 mm–HT group (p = 0.003), and the RelyX Ultimate–2 mm–HT group also showed significantly higher values than the RelyX Ultimate–4 mm–HT group (p = 0.001) (Tables 4 and 5, Figure 2B).

The RelyX U200–2 mm–LT group exhibited significantly higher bottom-to-top hardness ratio than the RelyX U200–4 mm–LT group (p = 0.008), and similarly, the RelyX

Ultimate–2 mm–LT group had significantly higher values than the RelyX Ultimate–4 mm–LT group ($p = 0.001$) (Tables 4 and 5, Figure 2B).

No statistically significant difference was found between the RelyX U200–2 mm–HT and RelyX U200–2 mm–LT groups ($p = 0.332$), or between the RelyX U200–4 mm–HT and RelyX U200–4 mm–LT groups ($p = 0.918$) regarding the bottom-to-top hardness ratio (Tables 4 and 5, Figure 2B).

The RelyX Ultimate–2 mm–HT group showed a significantly higher bottom-to-top hardness ratio compared to the RelyX Ultimate–2 mm–LT group ($p = 0.006$), whereas no statistically significant difference was found between the RelyX Ultimate–4 mm–HT and RelyX Ultimate–4 mm–LT groups ($p = 0.569$) (Tables 4 and 5, Figure 2B).

4. Discussion

This study evaluated the effects of CAD/CAM material thickness and translucency on the Vickers microhardness and bottom-to-top hardness ratio of two dual-cure resin cements. The main finding was that increasing CAD/CAM block thickness from 2 to 4 mm significantly reduced the bottom-to-top hardness ratio for both resin cements under both translucency conditions. In addition, high-translucency blocks were associated with higher microhardness values than low-translucency blocks at both tested thicknesses. However, the effect of thickness on microhardness varied according to resin cement type and translucency, indicating that the response of resin cements to light attenuation is material dependent.

The success of restorative treatment with CAD/CAM materials depends on the mechanical properties of the material and the adhesive cement [21]. The success of restoration cementation is influenced by factors such as the type of cement (composition and activation mode), type of polymerization, and polymerization protocol [21–24]. Resin cements are the most commonly preferred due to their optimal physicochemical properties for cementation [21–25]. In addition to light-cured resin cements, dual-cure resin cements have been designed to ensure polymerization in areas where light curing is difficult [21,26,27]. Both cements used in this study are dual-cure resin cements.

Alovisi et al. [27] reported significant differences in microhardness between dual-cure resin cements and attributed these differences to variations in filler characteristics and monomer composition. Similarly, differences in microhardness were observed between RelyX U200 and RelyX Ultimate under some experimental conditions in the present study. These differences may be related to variations in resin matrix composition, monomer chemistry, filler characteristics, filler loading, and cross-link density. However, these material-dependent factors were not independently evaluated in the present study; therefore, differences in microhardness cannot be attributed solely to differences in polymerization or degree of conversion.

The effect of CAD/CAM material thickness represents an important aspect of the present findings and can be considered together with previous evidence regarding changes in the optical properties and polymerization of restorative materials. Kaya et al. [28] reported that increasing CAD/CAM block thickness from 1.5 to 2 mm significantly decreased translucency and increased contrast ratio. For IPS e.max CAD, TP00 decreased from 9.45 ± 0.13 to 8.68 ± 0.10, while contrast ratio increased from 0.67 ± 0.00 to 0.76 ± 0.08. Similarly, for Cerasmart, TP00 decreased from 10.78 ± 0.18 to 9.29 ± 0.29 and contrast ratio increased from 0.60 ± 0.01 to 0.65 ± 0.01 [28]. These findings demonstrate that increasing CAD/CAM material thickness can alter optical characteristics and may consequently affect light transmission to the underlying resin cement. Consistent with this concept, the present study showed that increasing block thickness from 2 to 4 mm significantly reduced the bottom-to-top hardness ratio for both RelyX U200 and RelyX Ultimate under

both translucency conditions. For RelyX U200, the ratio decreased from 68.40 ± 5.56% to 54.57 ± 4.93% under HT conditions and from 64.76 ± 5.60% to 54.27 ± 3.81% under LT conditions. For RelyX Ultimate, it decreased from 69.43 ± 3.73% to 53.76 ± 2.12% under HT conditions and from 61.79 ± 2.83% to 52.87 ± 2.58% under LT conditions (Table 5). However, thickness did not produce a uniform effect on absolute microhardness: a significant reduction was observed only for RelyX U200 under LT conditions, whereas no significant thickness-related difference was detected for the other cement/translucency combinations. Thus, the effect of thickness on polymerization-related mechanical performance appears to depend on both cement formulation and the optical characteristics of the CAD/CAM material. Borges et al. [29] similarly reported a thickness-related reduction in the microhardness of light-cured resin cement. For example, under the A3.5 shade and high-translucency condition, microhardness decreased from 468.46 ± 43.45 at 1.5 mm to 435.79 ± 31.41 at 2.0 mm. This finding supports the potential influence of restoration thickness on the polymerization-related mechanical properties of resin cements, although differences in curing mode, restorative material, cement formulation, and testing conditions should be considered when comparing these results with the present study.

The influence of CAD/CAM material translucency was also evident in the present findings. Sheibani et al. [30] reported that ceramic translucency influences light transmission and the microhardness of the underlying resin cement. Similarly, Pechteewang and Salimmee [31] demonstrated differences in resin cement microhardness after light activation through monolithic zirconia with different translucencies. In agreement with these findings, the present study showed that resin cements polymerized under high-translucency CAD/CAM blocks generally exhibited higher Vickers microhardness values than those polymerized under low-translucency blocks. This finding is consistent with the principle that increased opacity or reduced translucency may increase light scattering and decrease the amount of curing light reaching the resin cement [32–37]. However, the effect of translucency on the bottom-to-top hardness ratio was less consistent. For RelyX U200, no statistically significant difference between high- and low-translucency conditions was observed at either thickness. For RelyX Ultimate, the high-translucency group showed a significantly higher bottom-to-top hardness ratio than the low-translucency group at 2 mm, whereas no significant difference was observed at 4 mm. This pattern suggests that the influence of translucency may become less distinguishable as restoration thickness increases, although this interpretation should be considered cautiously because transmitted irradiance was not directly measured in the present study.

The relationship between resin cement hardness and degree of conversion should also be considered when interpreting these results. Previous studies have reported associations between microhardness and degree of conversion in resin cements [11,20,31,38]. However, microhardness should not be regarded as a direct measurement of monomer conversion. Hardness is a mechanical property influenced by several factors, including resin matrix composition, monomer chemistry, filler content and characteristics, filler distribution, and cross-link density. In contrast, Fourier-transform infrared spectroscopy (FTIR) provides a more direct chemical assessment of polymer conversion by monitoring changes in carbon–carbon double-bond absorption during polymerization. Therefore, differences in microhardness or bottom-to-top hardness ratio between experimental groups cannot be attributed exclusively to differences in degree of conversion. In the present study, these parameters were consequently interpreted as indicators of polymerization-related mechanical performance rather than direct measurements of monomer conversion. This distinction is particularly important because RelyX U200 exhibited higher microhardness values than RelyX Ultimate under some experimental conditions, whereas no statistically significant difference between the two cements was observed in the bottom-to-top hardness ratio under

the corresponding conditions. Such findings may reflect differences in the intrinsic material properties of the two cements in addition to differences in their polymerization behavior.

David-Pérez et al. [39] reported that degree of conversion values between approximately 60% and 75% may be considered clinically acceptable under certain experimental conditions. However, such thresholds cannot be applied to the present study because degree of conversion was not directly measured. Accordingly, the present findings should be interpreted on the basis of Vickers microhardness and the relative hardness gradient between the top and bottom surfaces rather than as evidence of a specific degree of monomer conversion.

The clinical relevance of these findings should be considered in relation to the optical and geometric characteristics of indirect restorations. Dual-cure resin cements may provide an advantage when light transmission is limited because the chemical-curing component can contribute to polymerization in regions receiving reduced irradiance [13,20]. The present results suggest that restoration thickness should be considered when selecting a resin cement and polymerization protocol, particularly because increasing CAD/CAM thickness from 2 to 4 mm significantly reduced the bottom-to-top hardness ratio in both cement systems. Similarly, low-translucency CAD/CAM materials were generally associated with lower microhardness values. Previous studies have demonstrated that ceramic thickness, shade, and translucency can influence light transmission and the polymerization-related properties of resin cements [12,17–19,22–24,29,34,40]. A recent study by Çiftçibaşı et al. [41] further demonstrated that CAD/CAM material type and thickness influenced the translucency parameter and polymerization-related microhardness of a light-cured resin cement. These findings collectively emphasize the importance of considering the optical characteristics and thickness of the restorative material when planning cementation procedures.

Clinically, thick and/or low-translucency CAD/CAM restorations may therefore present a greater challenge for light-dependent polymerization because less curing light may reach the underlying resin cement [19,28,29]. In such situations, clinicians should consider the use of resin cements with an appropriate chemical-curing component rather than relying exclusively on light activation [13,20,42]. The manufacturer's recommended curing protocol should also be followed, including the specified irradiation time and curing conditions. When clinically feasible, adequate positioning of the curing-light tip and the use of a curing unit capable of delivering sufficient irradiance may help maximize light delivery through the restoration [11,20,27]. Nevertheless, the present results should not be interpreted as evidence that one specific resin cement is universally superior. Only two dual-cure resin cements and one lithium disilicate-reinforced glass-ceramic CAD/CAM system were evaluated. Although RelyX U200 showed higher microhardness values under several experimental conditions, microhardness is influenced by material-dependent factors beyond monomer conversion, including resin matrix composition, filler characteristics, filler loading, and cross-link density. Therefore, this finding alone does not establish clinical superiority. Resin cement selection should instead consider restoration thickness and optical characteristics together with the cement's polymerization mechanism, manufacturer recommendations, and the specific clinical circumstances.

Inadequate polymerization or reduced degree of conversion of resin cements has been associated with undesirable material properties, including increased water sorption, reduced color stability, and potentially compromised marginal behavior [11,43]. Although degree of conversion was not directly measured in the present study, the observed differences in microhardness and bottom-to-top hardness ratio indicate differences in polymerization-related mechanical performance under the tested conditions. These findings support the importance of considering both the optical characteristics of the CAD/CAM restoration and the formulation of the resin cement when selecting materials for indirect restorations.

A recent study by Çiftçibaşı et al. [41] demonstrated that both CAD/CAM material type and thickness can influence the translucency parameter and polymerization-related microhardness of light-cured resin cement. The authors reported material- and thickness-dependent differences in microhardness, further emphasizing that the effect of restoration thickness cannot be considered independently of the optical characteristics and composition of the CAD/CAM material. This is relevant to the present study because only one lithium disilicate-reinforced glass-ceramic system was used, allowing the effects of thickness and manufacturer-defined translucency to be investigated under standardized material conditions while limiting the generalizability of the findings to other CAD/CAM materials.

Several limitations should be acknowledged. First, the degree of conversion was not directly measured using a spectroscopic method such as FTIR. Vickers microhardness and the bottom-to-top hardness ratio were used as hardness-based indicators of polymerization-related mechanical performance. Although these measurements are relatively simple and reproducible, they are influenced by multiple material-dependent factors and therefore cannot distinguish the contribution of monomer conversion from other determinants of hardness. Future studies combining depth-dependent FTIR analysis with microhardness measurements may provide a more comprehensive assessment of both chemical conversion and mechanical consequences of polymerization.

Second, the translucency of the CAD/CAM blocks was based on the manufacturer's high-translucency (HT) and low-translucency (LT) designations rather than objective spectrophotometric characterization. In addition, the irradiance transmitted through the CAD/CAM blocks was not directly measured. Consequently, the effects of thickness and translucency on light transmission were inferred from the observed changes in microhardness and bottom-to-top hardness ratio rather than directly demonstrated by transmitted-light measurements. Future investigations should incorporate objective optical characterization and direct measurement of transmitted irradiance to clarify the relationship among CAD/CAM material thickness, translucency, light transmission, and resin cement polymerization.

Third, the 24 h storage period before microhardness measurements should be considered when interpreting the findings. Because specimens were stored at 37 °C under dark and dry conditions, the measured hardness may reflect both initial light-activated polymerization and continued post-curing associated with the chemical-curing component of the dual-cure resin cements. Dry storage was selected to standardize the testing conditions and minimize the influence of moisture on hardness measurements; however, these conditions do not reproduce the oral environment. Therefore, caution is required when extrapolating the present findings to clinical conditions, and future studies should incorporate clinically relevant aging protocols.

Finally, only one CAD/CAM ceramic system, a lithium disilicate-reinforced glass ceramic, was evaluated. Although the use of a single ceramic system enabled the effects of thickness and manufacturer-defined translucency to be investigated under standardized conditions, it limits the generalizability of the findings to other ceramic and hybrid CAD/CAM materials. Zirconia, feldspathic ceramics, and resin-based CAD/CAM materials may exhibit different compositions, microstructures, and optical properties and may therefore influence light transmission and resin cement polymerization differently. Consequently, the present findings should not be directly extrapolated to other CAD/CAM materials. Further studies involving different restorative materials are warranted to determine whether similar polymerization-related mechanical behavior is observed across different CAD/CAM systems.

5. Conclusions

Within the limitations of this in vitro study, increasing CAD/CAM material thickness from 2 to 4 mm significantly reduced the bottom-to-top hardness ratio for both RelyX U200 and RelyX Ultimate under both high- and low-translucency conditions. High-translucency CAD/CAM materials were associated with significantly higher Vickers microhardness values than low-translucency materials for both resin cements at both tested thicknesses. The effect of CAD/CAM material thickness on Vickers microhardness varied according to resin cement type and translucency condition. For the bottom-to-top hardness ratio, translucency significantly affected the results for RelyX Ultimate at 2 mm, whereas no significant translucency-related difference was observed for RelyX U200 at either thickness or for RelyX Ultimate at 4 mm.

These findings were observed under the specific experimental conditions and materials evaluated in the present study and should not be interpreted as evidence of clinical success or long-term durability. Because degree of conversion and transmitted irradiance were not directly measured, the observed differences in Vickers microhardness and bottom-to-top hardness ratio should be interpreted as differences in polymerization-related mechanical performance rather than as direct evidence of differences in monomer conversion or light transmission.

Further in vitro studies incorporating direct analytical methods, such as Fourier-transform infrared spectroscopy (FTIR), as well as objective optical, rheological, and flowability measurements, are warranted to directly assess degree of conversion and to further elucidate the potential relationships among light transmission, cement properties, CAD/CAM material characteristics, and polymerization-related mechanical performance.

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Abbreviations

CAD/CAM	computer-aided design/computer-aided manufacturing
HT	High Translucency
LT	Low Translucency
FTIR	Fourier-transform infrared spectroscopy

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