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Effect of thickness on irradiance loss and temperature rise in indirect restorative materials: an in vitro study

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Abstract

Background The polymerization extent of resin cement used for bonding indirect restorations is contingent upon the light transmittance of the indirect restoration materials and the light intensity of the employed light device. The temperature increase during the polymerization of these resin cements via light is a critical factor in preserving pulp health. The present study aimed to assess the optical properties of different thicknesses of indirect restorative materials such as feldspathic ceramics [Vitablocs Mark II, (VBM)], indirect composites [Gradia, (GRA)] and 3D printing resins [VarseoSmile Crown Plus, (VSC)] and the temperature rise on the undersurface of the materials during LED light application.

Methods The irradiance loss, absorbance, and absorbance coefficient values of three indirect restorative materials (VBM, GRA, and VSC) with four different thicknesses (0.5, 1.0, 1.5, and 2.0 mm) were analyzed. A Valo Cordless (Ultradent, USA) LED light device was used as the light source. Light transmittance was measured using a radiometer, and the averages were recorded. The temperature variation (Δt) was recorded using a K-type thermocouple during light application. Data were statistically analyzed at a significance level of 0.05.

Results It was revealed that irradiance loss and absorption values increased, and absorption coefficient values decreased with the increase in thickness in the material groups. The irradiance loss values for VBM and GRA were comparable across all thicknesses. The irradiance loss value for the VSC group was comparable to that of the GRA group and distinct from the VBM group across all thicknesses, except at 0.5 mm ($p < 0.05$). The assessment of thickness and material groups regarding temperature increase revealed that temperature differential values diminished with more thickness, although no significant difference was seen between the groups ($p > 0.05$).

Conclusion The absorbance and irradiance loss values of indirect restorative materials escalated with greater thickness, particularly in the VSC group. The efficacy of light-polymerized resin cements may be negatively impacted; therefore, it is advisable to prolong the curing duration for thicker materials. Moreover, as the thickness grows, the thermal exposure of the materials diminishes, resulting in a reduced danger to pulp health.

Keywords Composite resin, Curing light, Polymerisation, Temperature, Vita Mark II

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Introduction

Indirect restorations denote restorative methods necessitated by significant material loss and abnormalities in the tooth resulting from caries, typically fabricated in a laboratory setting before being affixed to the tooth. These restorations are often fabricated from materials like porcelain, ceramics, and composites [1, 2]. While indirect restorations are deemed successful, optimizing their clinical efficacy necessitates careful consideration of the optical properties of restorative materials, the polymerization of resin cements during application, and the properties of the light device employed during curing [3, 4].

Light applied to the material during light curing, a crucial phase in the application of indirect restorations, may be reflected, scattered, absorbed, or transmitted [5]. The optical qualities are contingent upon the material's kind, color, and thickness [3, 5–8]. The polymerization of the resin cement during the application of indirect restorative materials may be compromised, hence impacting clinical performance [3, 5, 6]. Furthermore, light exposure to indirect restorative materials is transformed into thermal energy, necessitating consideration of the temperature's impact on the pulp [5, 9].

Studies on material qualities and production techniques in dentistry continue to advance the development of optimal indirect restorations, which are widely used in clinical practice and play a significant role in long-term dental health. Despite their widespread use, variations in light-curing procedures, material properties, and thicknesses are often not fully understood, potentially leading to suboptimal clinical outcomes such as incomplete polymerization or thermal damage to the pulp. This study aimed to assess the optical properties of feldspathic ceramic [Vitablocs Mark II (VBM)], indirect composite [Gradia (GRA)], and 3D printing resins [VarseoSmile Crown Plus (VSC)], which are widely used indirect restorative materials with varying thicknesses, as well as the temperature rise on their bottom surfaces following LED light exposure. By specifically investigating absorbance as a key optical property, this study seeks to bridge the gap between material science and clinical practice, ensuring that restorative materials are selected and utilized in a manner that optimizes polymerization efficiency while minimizing thermal risks to the pulp. Understanding these optical characteristics is essential for enhancing the clinical success of indirect restorations, preventing incomplete polymerization, and reducing potential adverse effects on pulpal health. Feldspathic ceramics, indirect composites, and 3D printing resins were chosen for their distinct compositions, manufacturing processes, and clinical applications, which influence their optical behavior and response to light-curing procedures. Feldspathic ceramics are widely used for their superior esthetics and translucency, whereas indirect composites offer enhanced polymerization control and mechanical properties. Meanwhile, 3D printing resins represent a rapidly evolving category in digital dentistry, with increasing clinical adoption due to their efficiency and customizability. The null hypotheses tested were:

$H_0$1: Different material types and thicknesses have no effect on the optical properties of indirect restorative materials.

$H_0$2: Different material types and thicknesses have no effect on temperature rise following LED light exposure.

Materials and methods

Table 1 presents the chemical compositions and manufacturers of the indirect restorative materials examined in the study.

Sample preparation

A 12 × 12 mm non-stick mold composed of polyvinyl chloride, with heights of 0.5, 1, 1.5, and 2 mm, was utilized for the fabrication of GRA samples. A clear strip of tape was affixed to a glass surface, and the mold was positioned atop the transparent tape. Gradia composite was inserted into the mold slot, and surplus material was eliminated using a mouth spatula. A second layer of transparent tape and cement glass was applied, followed by the application of light pressure. The samples were subsequently polymerized for 20 s using an LED light device (Valo Cordless, Ultradent - USA) with an irradiance of 1000 mW/cm^2. The light apparatus was positioned perpendicularly to the sample during the polymerization process. A black rubber ring was affixed to the end of the light device to prevent light from dispersing into

Table 1 The composition and manufacturers of the materials tested in this study

Group	Material/Shade	Polymer	Filler	Manufacturer
GRA	Gradia, A2	UDMA, methacrylate copolymer	Microfine ceramic/prepolymerized filler, 75% by mass	GC (Tokyo, Japan)
VSC	VarseoSmile Crown Plus, A2	Esterification products of 4.4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid. Silanized dental glass, methyl benzoylformate, diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide.	Total content of inorganic fillers (particle size 0.7 μm) is 30–50% by mass.	BEGO (Bremen, Germany)
VBM	Vitablocs Mark II, A2	-	Feldspathic crystalline particles (4 μm) in glassy matrix	Vita Zahnfabrik, Germany

the surroundings, ensuring it was directed solely onto the sample and shielding the sample from daylight exposure.

The samples of the VSC group (dimensions: 12 × 12 mm, thicknesses: 0.5, 1, 1.5, and 2 mm) were designed using standard tessellation language (STL) in Blender version 3.4.1. The 3D samples of the VSC group were fabricated using a Varseo XS printer (Bego, Bremen, Germany) utilizing digital light processing. The residual monomers on the surfaces of the disks produced by the printer were cleansed with 90% isopropanol. The samples were subsequently subjected to 1500 flashes on the top and bottom surfaces using an auto flash equipment (Bego, Bremen, Germany) as per the manufacturer's recommendations.

Samples belonging to the VBM group were cut using a diamond disc (Buehler-Series 15HC Diamond, Buehler Ltd, Lake Bluff, IL, USA) under cooled water irrigation on a metallographic precision cutter (Isomet 2000, Buehler Ltd) to minimize the temperature effects on the ceramic surfaces of the material blocks for CAD/CAM (Vitablocks Mark II). Samples of 12 × 12 mm were procured in four distinct thicknesses for each category of restorative material: 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm.

Five samples from each group (total $n = 20$) were made in A2 color. Samples were manually wet ground using a sequence of SiC abrasive papers: 600, 1200, and 2000 grits. Sample thicknesses were quantified with a digital micrometer (ABS Digimatic, Mitutoyo Corp., Kawasaki, Japan) with an accuracy of 0.1 mm.

Irradiance loss and light absorbance measurements of indirect restorative materials of different thicknesses

The light transmittance of the materials was assessed three times using a radiometer (Hilux, Ultra Plus Curing Units, Benlioglu Dental), and the mean of the three measurements was documented as mW/cm². LED light device (Valo Cordless, Ultradent - USA) was employed as the light source.

Calculation of irradiance loss:

The irradiance loss for each sample was calculated as the ratio of the irradiance measured from the sample (a) to the total irradiance from the light source without the sample (b), subtracted from 100 [6].

$100*(1-a/b)$.

Absorbance (AU) and absorbance coefficients (ε) were calculated according to the formula:

$AU = -\log(I/I_0)$.

$\varepsilon = AU/mm$.

where I is the irradiance value for each assessed sample, I_0 is the irradiance for control groups, and mm is the sample thickness (in mm).

Thermal permeability assessment of indirect restorative materials across various thicknesses

For the measurement of thermal conductivity, a K-type thermocouple tip (EMPI. PENTA Ltd. Şti., Istanbul, Türkiye) is positioned in contact.

Samples at ambient temperature (27 °C) were exposed to illumination for 20 s using an LED light device (Valo Cordless, Ultradent - USA) with an irradiance of 1000 mW/cm².

The temperature difference (ΔT) was calculated by subtracting the initial temperature (T_{Inital}) from the maximum temperature attained by the materials (T_{Max}). Measurements were repeated 3 times for each sample and averaged. The measurement was conducted after the samples cooled to room temperature.

$\Delta T = T_{Max} - T_{Initial}$.

Statistical analysis

Statistical analysis of the data obtained from this study was performed using SPSS Statistics software (version 26.0, SPSS, Chicago, IL, USA). The heat and light transmittance changes of the samples were subjected to nonparametric statistical analysis by Kruskal-Wallis analysis with a pre-set alpha of 0.05. The difference between groups were assessed with post hoc Bonferroni adjustment. Linear regression analysis was conducted to examine the absorbance and absorbance coefficient values based on material thickness.

Results

Irradiance loss for indirect materials at different thicknesses

The Irradiance Loss values for indirect restorative materials of varying thicknesses are given in Table 2. No statistically significant difference was observed between 0.5- and 1-mm thick samples of all materials tested in terms of Irradiance Loss values ($p > 0.05$). Moreover,

Table 2 Median irradiance loss (lowest value; maximum value) of indirect restorative materials at varying thicknesses (mm)

Irradiance loss	0.5 mm	1 mm	1.5 mm	2 mm	p
GRA	52.1 (51.3;55.3) a B	71.2 (70.1;73.9) ab AB	79 (69.7;79.5) ab AB	79.9 (79.1;80.6) b AB	0.001
VSC	69.2 (69;70.3) a A	75.4 (74.7;76.4) ab A	83.8 (83.1;84.3) bc A	89.4 (89.3;90.1) c A	< 0.001
VBM	57.8 (57;60.4) a AB	63.3 (62.8;65.2) ab B	68.4 (67.7;69.2) bc B	71.8 (69.4;72.8) c B	< 0.001
p	0.002	0.002	< 0.002	< 0.002	

*Lowercase letters denote varying thicknesses of the material within the same row, while uppercase letters signify statistical differences (Kruskal-Wallis) among different materials in the same column samples with thicknesses of 1.5 mm and 2 mm demonstrated comparable transmittance values ($p > 0.05$).

The 0.5 mm thick samples from the VSC and VBM groups exhibited decreased Irradiance Loss values compared to the 1.5- and 2-mm thick samples ($p < 0.001$). Furthermore, 2 mm thick samples exhibited greater Irradiance Loss values compared to 0.5- and 1-mm thick samples ($p < 0.001$). In the GRA group, a statistically significant difference was found only between 0.5- and 2-mm thick samples ($p = 0.001$).

At a thickness of 0.5 mm, the GRA group exhibited a significantly lower Irradiance Loss value ($p = 0.002$) compared to the VSC group, but this value was comparable at other thicknesses ($p > 0.05$).

In 0.5 mm thick samples, the VBM group exhibited an Irradiance Loss value comparable to that of the VSC group ($p > 0.05$), however in 1 mm, 1.5 mm, and 2 mm thick samples, the VBM group had a lower Irradiance Loss value than the VSC group ($p < 0.002$). Upon considering all thicknesses, it is observed that the GRA and VBM groups exhibit comparable Irradiance Loss values ($p > 0.05$).

Light absorbance of indirect restorative materials at different thickness

Absorbance through and absorbance coefficient (ε) through values of different thicknesses of indirect restorative materials, along with the results of the linear regression analysis, are presented in Figs. 1 and 2. Overall, VBM exhibited reduced absorbance levels relative to other materials. An increase in absorbance values was noted with the increase in material thickness. The rate of absorption change exhibited a nearly linear relationship with increasing sample thickness for all materials. The absorption coefficient (ε) values diminish with increasing thickness across all materials (Fig. 2). At 0.5 mm, GRA exhibited the lowest ε values, whereas VSC demonstrated the highest values. A significant reduction is noted from 0.5 mm to 1.0 mm across all materials, and ε values diminish as thickness increases.

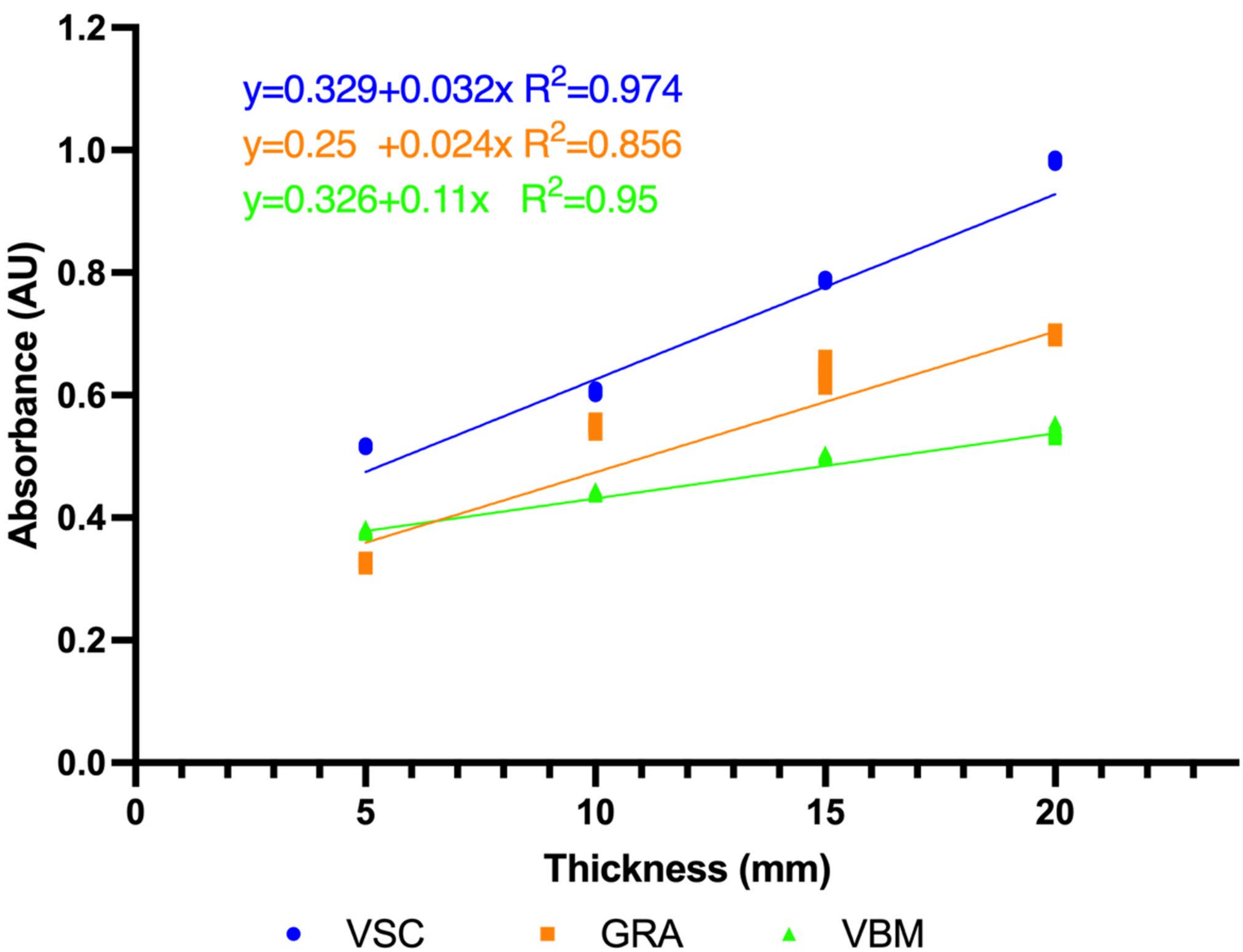

Fig. 1 Absorbance through each indirect restorative material (AU) at different thicknesses

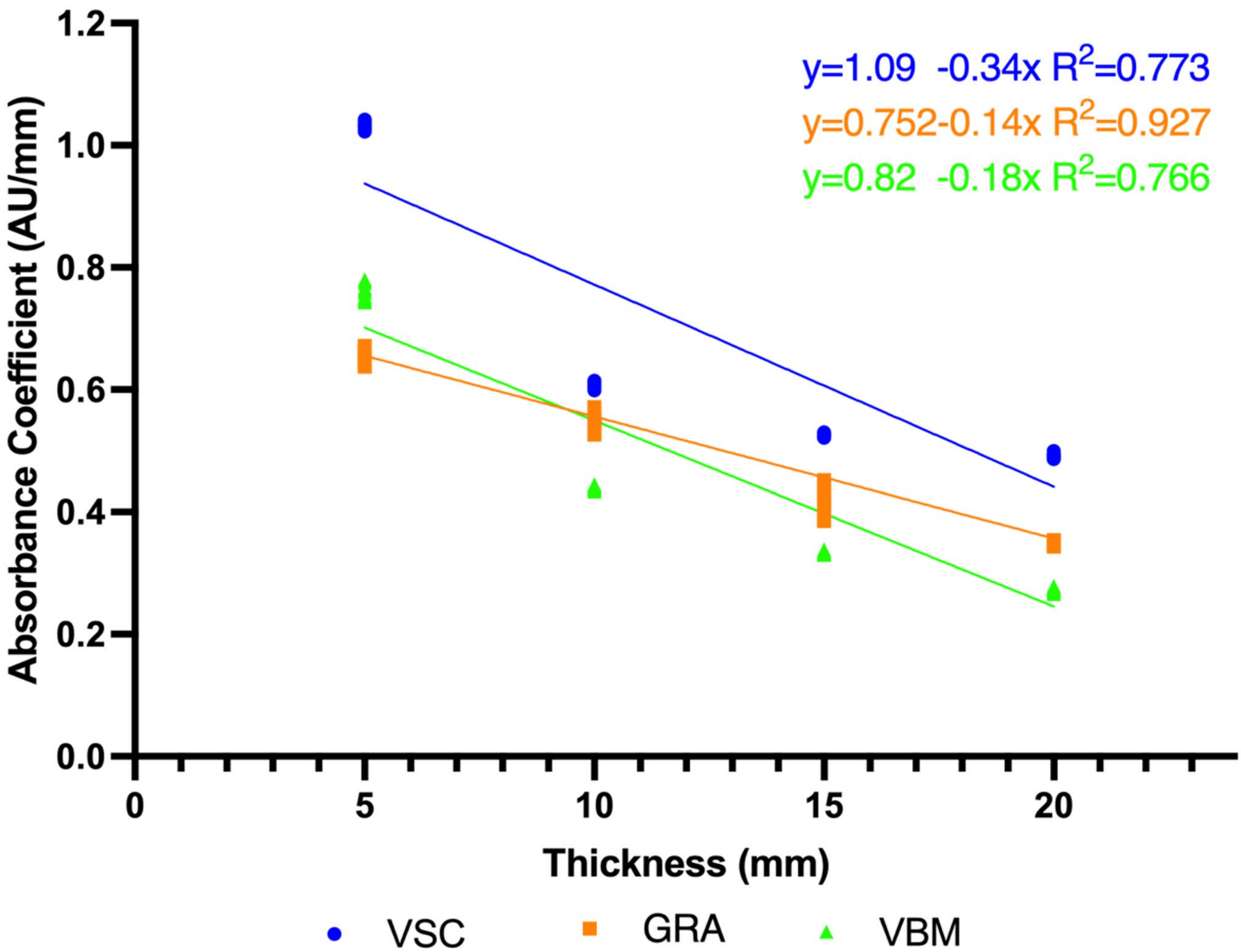

Fig. 2 Absorbance coefficient (ε) through each indirect restorative material (AU/mm) at different thicknesses

Table 3 Temperature change median (minimum value; maximum value) in °C of indirect restorative materials with different thicknesses (mm)

Δt	0.5 mm	1 mm	1.5 mm	2 mm	*p*
GRA	14.4 (12.6;16.4) [a]	13.7 (10.6;14.8) [a]	9.3 (8.5;10.6) [ab]	7.9 (6.1;8.7) [b]	0.001
VSC	12.4 (10.5;14.5) [a]	11.2 (10.3;12.2) [a]	8.7 (7.8;9.5) [ab]	7.4 (6.3;7.6) [b]	0.003
VBM	13 (11.7;15.8) [a]	11.2 (6.2;11.9) [ab]	9.8 (7.6;11) [ab]	8.1 (7.6;9.4) [b]	0.006
p	0.373	0.16	0.44	0.102	

*Lowercase letters denote varying thicknesses of the material within the same row

Temperature change of each indirect restorative material at different thicknesses

Temperature changes of indirect restorative materials with different thicknesses are presented in Table 3. Following a 20-second light application, the maximum temperature variation recorded was 14.4 °C at a thickness of 0.5 mm in the GRA group, whereas the minimum temperature variation was 7.4 °C at a thickness of 2 mm in the VSC group.

The 0.5 mm thick samples exhibited a greater temperature change than the 2 mm thick ones ($p < 0.001$).

No statistically significant difference was observed between the material groups for temperature change ($p > 0.05$).

Discussion

Indirect restorations must not only replicate the morphology and composition of missing dental tissue but also exhibit biocompatibility and closely resemble the optical characteristics of real teeth, including color, translucency, opacity, and fluorescence [1]. Consequently, it is essential that the restorative materials employed in indirect restoration possess adequate light transmittance to achieve aesthetic quality.

Light directed at the restorative material may be reflected, absorbed, or transmitted through it. Enhanced light transmission in indirect restorative materials augments the polymerization of the underlying adhesive resin cement, significantly enhancing the bonding qualities between the restoration and the tooth [3]. The thickness and opacity of indirect restorative materials significantly influence light transmission; yet, assessing the optimal light transmission across various materials remains a pertinent topic due to the expanding array of available options.

This study assessed irradiance loss, absorbance, and absorption coefficients of three different indirect restorative materials (GRA, VBM, and VSC) at varying thicknesses, alongside evaluating temperature changes during polymerization. The findings highlight that material thickness significantly influences irradiance loss and absorbance, impacting the clinical performance of indirect restorations. Thus, our first null hypothesis ($H_0$1) was rejected.

Irradiance loss refers to the reduction of light as it passes through a material, while transmittance represents the amount of light that successfully traverses it; these two parameters are inversely related [3, 6]. The literature indicates that transmittance values are predominantly used to assess the optical properties of materials [3, 5]. In indirect restorations, high transmittance and low irradiance loss are essential for the proper polymerization of resin cements [3]. Transmittance is influenced by factors such as the material's opacity, color, chemical composition, and thickness [5, 10]. As opacity increases, light scattering intensifies, transmittance decreases, and irradiance loss rises [11]. Therefore, in this study, the material groups were selected to have identical opacity values. Additionally, A2 shade is widely used in research on the optical properties of restorative materials, and it was chosen in this study to ensure standardization and facilitate comparisons with existing literature [12].

The study comparing irradiance loss values of VBM with zirconium and resin ceramic materials indicated that the VBM group exhibited the lowest values. It has been reported that this is due to the fact that the glass matrix transmits more light due to the crystal density of VBM being less than 20% and having micro particle sizes [6]. In another study analyzing the transmittance value of VBM [5], 32 restorative materials were assessed and it was determined that VBM was one of the materials with a higher transmittance value, that is, a lower irradiance loss value. Within this material group, Gradia Direct A2 showed significantly lower transmittance values than VBM. We found in our study that the GRA group and VBM had statistically similar irradiance loss values at all thicknesses. Gradia Direct A2, being a non-indirect composite, likely had a lower transmittance rating than VBM due to increased light absorption during polymerization. The comparable values of GRA and VBM can be attributed to the presence of microparticles in GRA [13], resulting in analogous light transmission through its matrix as observed in VBM. There are only a limited number of studies on the optical properties of VSCs in the literature [7, 14]. But there are no studies comparing the irradiance loss values of VSCs with GRA or VBM. As a result of this study, except for the 0.5 mm thick samples, the VSC group showed statistically similar results to GRA but different results compared to VBM.In the study comparing VSC with other resin materials generated by three-dimensional printers, the translucency values of VSC were determined to be inferior to those of the other groups [7]. This indicates that the irradiance loss value of VSC is higher. In this study, the irradiance loss values of all samples in the VSC group were also higher than those of the other groups. Therefore, modified curing protocols or alternative cementation strategies may be required for the optimal bonding of restorations produced with VSC.

The results indicate that irradiance loss increased with material thickness across all groups, which aligns with previous research demonstrating reduced light transmittance in thicker restorative materials [5, 6, 15]. This suggests that clinicians should adjust curing times for thicker restorations to ensure adequate polymerization.

Absorption refers to the uptake of light by atoms or molecules inside restorative materials, including resin components, filler particles, photo inhibitor molecules, and pigments [5, 16]. The literature indicates that as the material thickness increases, light absorption also increases, and our study has yielded findings consistent with this trend [6]. The VBM group exhibited the lowest absorption level compared to other materials. This aligns with existing literature highlighting VBM's superior translucency and reduced light attenuation, making it a favorable choice for aesthetic restorations among various composite and ceramic blocks [5, 6, 17].

The VSC group exhibited the highest absorption values. In the literature, most studies on the optical properties of VSC have focused on translucency [7, 14, 18–20]. However, translucency and absorption are opposing concepts; a material with high translucency typically has lower absorption [6, 7]. No literature exists comparing VSC with composite resins or various ceramic materials, making our work the inaugural study on this topic. This study demonstrated that VSC exhibited higher absorption compared to VBM and GRA. This difference may be attributed to variations in filler size, filler-matrix ratio, and internal composition of the materials [3, 5, 7, 14, 21].

Theoretically, absorption increases as material thickness increases, but the absorption coefficient (ε) is expected to remain independent of thickness [6]. However, our findings revealed that the absorption coefficient decreased with increasing material thickness. This deviation from theoretical expectations may result from surface characteristics and light scattering properties, emphasizing the need for careful material selection based on clinical requirements [6].

When light is absorbed by the substance, this energy is transformed into heat energy [5]. The temperature rise is contingent upon the applied light intensity, material thickness, and composition [15]. As the thickness increases, the transmission of light to the bottom surface diminishes, leading to a presumed reduction in the measured temperature. This study demonstrated that material thickness significantly impacted temperature rise, with thicker materials exhibiting reduced temperature increases. However, no statistically significant differences were observed among material types regarding temperature changes. Thus, H_02 was partially accepted.

The rise in temperature of the restorative material is a critical aspect regarding pulp damage [22]. A study by Zach and Cohen on monkey [23]teeth demonstrated that a temperature increase of 5.6 °C in the pulp can result in pulp necrosis at a rate of 15%. Our study revealed that the maximum temperature recorded from the surface of the materials was 14.4 °C in the GRA group with 0.5 mm samples, whereas the minimum temperature increase was observed in the VSC group with 2 mm samples at 7.4 °C. This may appear hazardous for pulp damage. Al-Qudah et al. recorded a temperature increase of 36.3 °C in 2 mm thick composite samples, highlighting that these temperatures pertain to the rise in restorative materials [9]. In this case, they stated that the release of vasoactive mediators in the pulp would lead to arteriolar dilatation and increased pulpal circulation, as well as heat dissipation through periodontal and osseous circulation, so that the temperature increase in the pulp would be much lower than measured [9]. We consider that the temperature increase in the material groups in our study is the temperature measured from the materials and that the temperature increase in the pulp is negligible considering that there will be cement and dentin in between.

We consider that our study, which assessed the optical properties of VSC, current material, and indirect restorations and the temperature increase caused by curing, will make a significant contribution to the literature. Nonetheless, the limited number of material groups assessed and the omission of light devices with varying wavelengths represent constraints of our work. It is advisable to undertake more extensive experiments involving more material groups and employing various wavelength light devices.

Conclusion

Increased material thickness led to higher irradiance loss and absorbance which may compromise the polymerization efficiency of resin cements used for bonding. Therefore, adjusting curing duration based on material thickness is crucial. Additionally, while temperature rise decreased with increasing thickness, no significant differences were observed among material groups. However, the findings suggest that thicker materials may help minimize thermal exposure, potentially reducing the risk of pulp damage. These insights provide valuable guidance for optimizing restorative protocols to enhance clinical outcomes and longevity in dental restorations.

Author contributions

Conceptualization: [A.B., S.S.D], Methodology: [S.S.D., F.S.], Formal analysis and investigation: [F.S., P.C.], Writing - original draft preparation: [A.B., N.O.S., P.C.], Writing - review and editing: [A.B., F.S.], Resources: [A.B., N.O.S.], Supervision: [F.S., P.C.]

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Data availability

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Ethical approval is not applicable as this is an in vitro study in which humans and animals, including materials/data, are not used for experimental purposes.

Consent for publication

As this article is an in vitro study not involving human use, consent for publication is not required.

Competing interests

The authors declare no competing interests.

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