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COLOR REPRODUCTION ABILITY OF POLYMER-INFILTRATED CERAMIC-NETWORK MATERIALS AND LITHIUM DISILICATE GLASS-CERAMICS

PhD thesis

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List of Abbreviations

AT	acceptability threshold
CAD/CAM	computer-aided manufacturing/computer-aided design
CIE	Commission Internationale de l'Éclairage (International Commission on Illumination)
HT	high translucency
LDGC	lithium disilicate glass-ceramic
LT	low translucency
PICN	polymer-infiltrated ceramic-network
PT	perceptibility threshold
SCE	specular component excluded
SCI	specular component included
T	translucent

1. Introduction

The field of esthetic dentistry has undergone significant advancements in recent decades, largely attributable to the integration of digital technologies and the development of advanced materials.[1-3] The application of dental ceramic materials in the 21st century is extensive, due to their exceptional optical and mechanical properties.[4] The evolution of computer-aided design/computer-aided manufacturing (CAD/CAM) technology, which has the effect of simplifying machinability, has further increased the popularity of these materials.[5-7] Furthermore, the structural modifications resulted in an increase in flexural strength, thereby enabling the monolithic application of certain silicate ceramics as well.[8,9] The objective of digital dentistry has been consistent since its inception: to attain plannable, reproducible quality through a process comprising the minimum number of steps.[10] The technological capabilities to produce lifelike, high-quality restorations are extant; however, the decision regarding the selection of the most appropriate material for a given application resides with the dentist. The primary consideration is the appropriate indication according to the forces acting on the restoration and its mechanical properties.[11] Beyond that, esthetics also have a significant impact on patient satisfaction.[12-15] It is important to possess a comprehensive understanding of the optical properties of the materials utilized in the fabrication of dental restorations, as this knowledge is indispensable for ensuring the authenticity of the restorations.[16-18] The mounting requirements and expectations of patients and dentists have prompted a shift in research focus towards the examination of the optical properties of the ceramic materials employed in these applications. In the present dissertation, a summary of the extant literature is provided, with a focus on the factors that may influence the color reproduction ability of two modern dental ceramic types and their clinical relevance. The thesis is based on the results of original studies investigating their optical properties.[19,20] As an introduction to the dissertation, the materials used will be contextualized in the classification of dental ceramics, their main properties will be summarized and an insight into the physical-optical background of the study will be provided. The limited scope of the thesis does not allow for a complete presentation of the classification of ceramics, but this is not necessary for a clear overview and understanding of the thesis.

1.1. Overview of the ceramic materials used in the research

The abundance of products available, coupled with the rapid rate at which new products are being introduced, has resulted in a decision-making process that is both intricate and multifaceted for contemporary clinicians when selecting a ceramic restorative material for a specific indication.[21] To make the right choice, it is essential to know the mechanical and optical properties of the materials and their indications for use, which is greatly assisted by a clear classification system (***Table 1***). The classification of ceramics according to their composition represents a rational approach that aligns with current scientific standards.[21]

Table 1. *Classification system for dental ceramics according to Gracis et al.[21] The dissertation discusses the materials marked in red. (the author's own figure)*

Dental ceramics		
Glass-matrix ceramics	Feldspathic	
	Synthetic	Leucite-based
		Lithium disilicate-based and derivatives
		Fluorapatite-based
	Glass-infiltrated	Alumina
		Alumina and magnesium
		Alumina and zirconia
Polycrystalline ceramics	Alumina	
	Stabilized zirconia	
	Zirconia-toughened alumina	
	Alumina-toughened zirconia	
Resin-matrix ceramics	Resin nanoceramic	
	Polymer-infiltrated ceramic-network	

1.1.1. Polymer-infiltrated ceramic-network materials

Prior to the advent of resin-matrix ceramics, metal-free materials that could be processed by milling and were suitable for the fabrication of permanent dental restorations could essentially be classified into two groups: ceramics and composites.[22] The primary objective underlying the development of resin-matrix ceramics was to engineer a material that would combine the advantageous properties of ceramic and composite materials.[8,23-

[25] This material was conceived to exhibit mechanical and optical characteristics similar to those of natural tooth tissues.[22,26,27] The two primary groups of resin-matrix ceramics are resin nanoceramics and polymer-infiltrated ceramic-network materials (PICN).[28,29] VITA ENAMIC (VITA Zahnfabrik, Bad Säckingen, Germany) is the sole product in its category available for purchase since its release in 2013 (***Figure 1***).[28] The structure of the

Figure 1. *VITA ENAMIC CAD/CAM block.*[19]

material consists of a sintered, porous ceramic matrix (86% in weight) and an infiltrated polymer matrix (14% in weight). The polymer matrix is polymerized at high temperature and high pressure during the material's production.[30] A significant benefit of the material is that it does not necessitate the processes of burning or sintering following milling, thereby rendering it a potentially optimal selection for applications in chair-side dentistry. According to the manufacturer, the indications of PICN encompass a range of dental restorations, including single tooth restorations such as anterior and posterior crowns (including implant-supported restorations), inlays, onlays, partial crowns, table tops, and veneers.[31] A multitude of studies have concluded that the properties of PICN materials are similar to those of dentin and enamel.[22,32-34] These materials have been shown to cause less abrasion on antagonistic teeth surfaces than other dental ceramic materials.[35-37] Furthermore, PICN materials exhibit greater hardness than composites, thereby conferring enhanced wear resistance.[26,28,31]

In the case of materials exhibiting translucent properties, the appearance of the restoration is not solely determined by the material itself. The visual outcome is also influenced by the surrounding environment, including elements positioned behind or beneath the restoration. In the context of all-ceramic systems, numerous studies have examined the factors influencing the esthetics of the final restoration. These factors include the color of the abutment, the thickness and translucency of the ceramic, and the color and layer thickness of the luting cement.[16,38-49] Despite the decade-long availability of PICN materials on the market, there is a paucity of research addressing their masking ability.[45-50]

1.1.2. Lithium disilicate glass-ceramics

In contemporary esthetic dentistry, the utilization of glass-ceramics has become an indispensable element, owing to their remarkable translucency, low thermal conductivity, optimal mechanical properties, biocompatibility, and wear resistance.[9,51-53] These characteristics position glass-ceramics as preeminent monolithic restorative materials in modern dentistry. Despite the advent of the first dental glass-ceramics on the market in 1984, ongoing structural modifications aimed at enhancing their mechanical properties have persisted.[54,55] Among the glass-ceramic materials that are currently available, lithium disilicate glass-ceramics (LDGC) are the most widely utilized. They have been demonstrated to possess the greatest resistance, with flexural strength ranging from 370 to 460 MPa.[51,56-58] The pioneer LDGC was introduced in 1998 under the designation IPS Empress II (Ivoclar Vivadent, Schaan, Liechtenstein) and was fabricated using the lost-wax technique and pressing.[59,60] The dissemination of CAD/CAM technology and chair-side dentistry necessitated the development of a millable LDGC material by the year 2005 (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein).[59,61] The material is available in the form of a purple, precrystallized block with a low flexural strength of approximately 130 MPa (***Figure 2***). This property enables rapid milling and reduced wear on milling

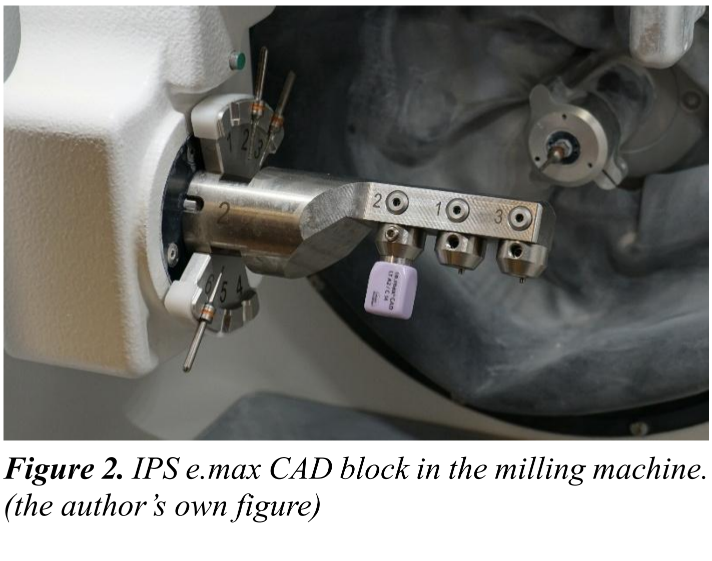

Figure 2. *IPS e.max CAD block in the milling machine. (the author's own figure)*

tools.[58,62] Following the milling process, the final color is obtained during the final crystallization stage, which necessitates a ten-minute sintering at 850°C.[58,60] The flexural strength of 360 MPa that was achieved resulted in the expansion of the material's indication area. Monolithic inlays, onlays, partial and full crowns, and bridges (up to three units) can be fabricated from the material.[9,63] The wide range of applications of IPS e.max CAD is made possible by its availability in five different translucencies: high translucency (HT), medium translucency (MT), low translucency (LT), medium opacity (MO), and impulse (I).

A large number of studies has demonstrated that the final color of the ceramic restoration is influenced not only by the shade of lithium disilicate glass-ceramic, but also by the substrate and cement beneath the restoration, and by the translucency and layer thickness of the ceramic.[5,16,39,64-76] While the color-modifying effects of the ceramic translucency, layer thickness and substrate color have been demonstrated to be significant in several cases, quantitative, numerical results regarding the relationship between color difference and these parameters are still lacking.

1.2. The physical background of the research

1.2.1. Possible interactions of light with a solid

Light is the range of electromagnetic radiation between 380 and 750 nm in wavelength that the human eye can perceive. When light reaches the surface of a solid, it can interact with it in various ways. The incident light can be reflected, absorbed, scattered, or transmitted (***Figure 3***).[77,78]

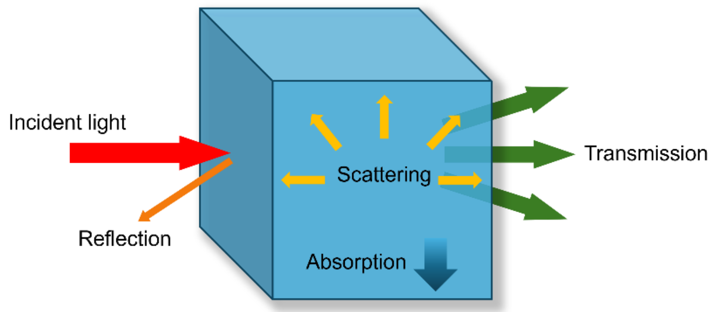

Figure 3. *Possible interactions of light with a solid. (the author's own figure)*

1.2.1.1. Reflection

A ray of light incident on an interface is ideally reflected at the same angle as the angle at which it was incident, that is called specular reflection. In real life, objects reflect the incident light more or less in all directions. Such diffuse reflection is caused by the roughness of the surface, which exists even in the most perfectly reflecting surfaces (***Figure 4***).[77] The reflectivity of a surface for light of different colors (wavelengths) can

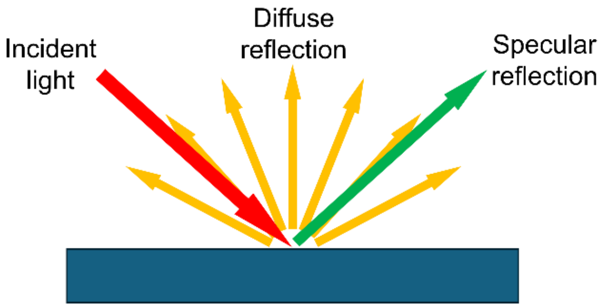

Figure 4. *Specular and diffuse reflection. (the author's own figure)*

be different. The color of a solid depends on how its reflectivity changes over the entire wavelength range. An absolutely white body reflects perfectly at all wavelengths, while an absolutely black body absorbs everything and reflects nothing. A diagram that shows how the spectral reflectance of a material changes depending on wavelength is called a reflectance spectrum.[77] It follows from the above that to study the colorimetric properties of an object, we need to know its reflectance spectrum.

1.2.1.2. Scattering

Light scattering occurs when particles of a medium with a refractive index different from that of the medium radiate the incident light in directions other than the direction of incidence.[77] A special case of light scattering is when the size of the scattering particles is much smaller than the wavelength of the incident light: this is called Rayleigh scattering. In this case, the scattering is very dependent on both the size of the scattering particle and the wavelength of the light. Shorter wavelength blue light is scattered more than longer wavelength red light. If the scattering is not negligible, it affects the color of the object. In the case of Rayleigh scattering, this means that when the object is viewed under scattered light, the color of the object shifts towards blue, and when viewed under transmitted light, towards red. This phenomenon is called opalescence.[77,78]

1.2.1.3. Absorption

The atoms and molecules of a solid can absorb the energy of the incident light, which usually results in a weaker or stronger heating. Less commonly, chemical reactions can also occur, or the light-absorbing material itself emits photons and starts to glow, this is fluorescence.[77] Typically, blue or ultraviolet light induces fluorescence, which appears in the visible wavelength range.[78] Natural teeth, due to certain dentin proteins, are able to emit fluorescent light when illuminated with ultraviolet light.[79] Fluorescent additives (e.g. lanthanide oxides) are added to certain composites and ceramics to give them a more realistic appearance.[80] The absorption spectrum shows how the spectral absorption coefficient or the absorbance changes depending on wavelength.

1.2.1.4. Transmission

The part of light incident on an object that is not reflected, scattered, or absorbed, is transmitted through the material. If an object allows light to pass through completely, it is called transparent, if only partially because of the scattering, it is called translucent. An object that does not allow light to pass through is called opaque. Dental ceramics and composites are translucent materials.[78] The concepts of transparency, translucency and opacity can be used to describe the overall behavior of a material in the entire visible light range, but can also be used for a single wavelength because transmittance also depends on the wavelength, or in the case of complex light, on its spectral composition.[77] The color of an object that we see under transmitted light depends on how its transmittance changes over the entire wavelength range. A diagram that shows how the spectral transmittance of a material changes depending on wavelength is called a transmission spectrum.

1.2.2. Measurement of color

Color perception is the result of a physiological response to a physical stimulus. Although the human side of color vision is subjective, the spectral composition of the light reaching the eye can be objectively described.[78] Reflection, scattering, and absorption are the phenomena that primarily play a role in the formation of color. Transmission is a consequence of the former phenomena.

The color of dental materials is most often measured in reflected light. The perception of color is significantly influenced by the surface properties of an object, including its reflectivity, in addition to the previously mentioned parameters. Light reflection can be categorized as specular, diffuse, or a combination of these two modes of behavior, with varying proportions among them.[81] Spectrophotometers are the most widely used color measuring devices. They determine the color of an object by illuminating it with their own light source and subsequently measuring the reflection. It is therefore imperative that the measurement setting is correctly adjusted during the procedure. Laboratory spectrophotometers equipped with integrating spheres are well-suited for conducting high-precision examinations of various dental materials. Depending on the specific parameters of the measurement, these spectrophotometers have the capability to include or exclude the specular component of the reflection. Consequently, the spectral reflectance of an object can be obtained, which may facilitate further comparisons.

Based on the measured reflectance spectra, L*, a*, b* values corresponding to the CIELAB color space of International Commission on Illumination (Commission Internationale de l'Éclairage, CIE) can be calculated (***Figure 5***). These parameters

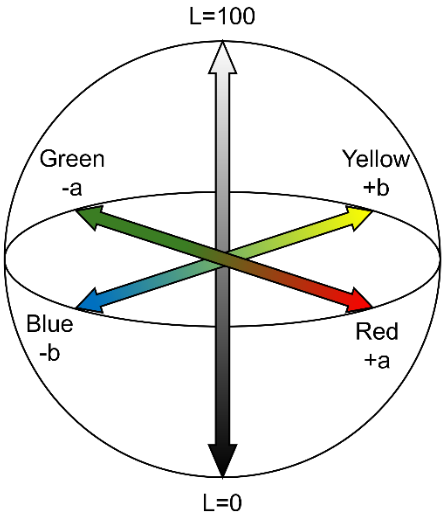

Figure 5. *The CIELAB color system. (the author's own figure)*

precisely define the color of an object in the three-dimensional coordinate system. The lightness value (L*) defines black at 0 and white at 100. The a* axis is relative to the green–red opponent colors, with negative values toward green and positive values toward red. The b* axis represents the blue–yellow opponents, with negative numbers toward blue and positive toward yellow. CIELAB is calculated relative to a reference white, for which the CIE recommends the use of CIE standard illuminant D65. CIE standard illuminant D65 is intended to represent average daylight having a correlated color temperature of approximately 6500 K. According to the CIE, it should be used in all colorimetric calculations requiring representative outdoor daylight.[82] The color difference between two objects can be characterized by their distance in the coordinate system.

The integrating sphere of the spectrophotometer is equipped with two ports: the viewing port and the specular port (***Figure 6***). The detectors that measure the reflected light are situated behind the viewing port, while the specular port can be opened or closed in

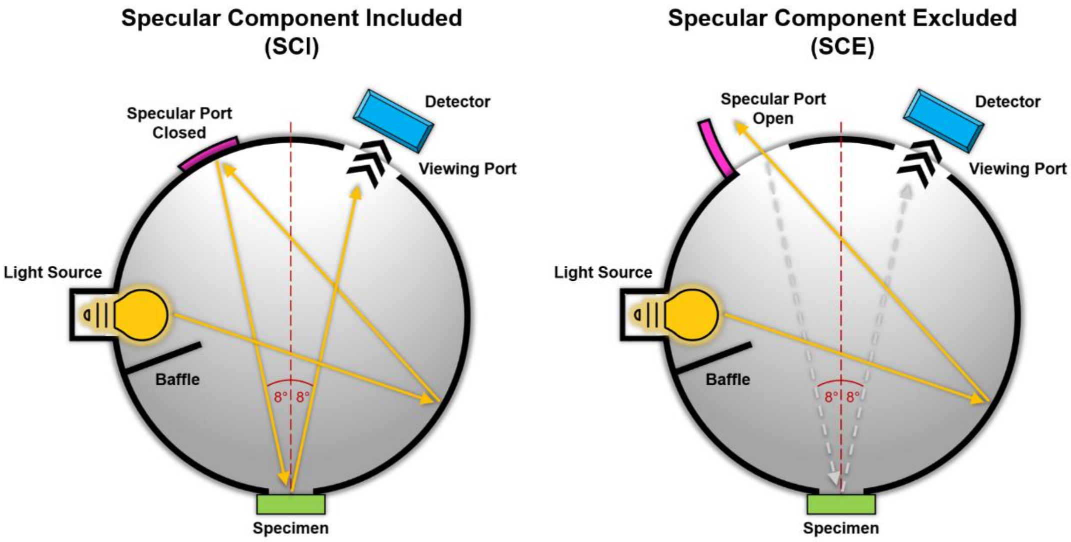

Figure 6. *The spectrophotometer's integrating sphere with specular component included (SCI) and specular component excluded (SCE) settings.*[19]

accordance with the selected setting. In an open setting (Specular Component Excluded, SCE), the light is not reflected onto the surface of the sample from the area of the sphere corresponding to the port. Rather, it leaves the integrating sphere, which means that the component of the reflection that would be specularly reflected from the sample does not even reach it and is excluded from the measurement. In theory, if our sample were a mirror with 100% specular reflection, the spectrophotometer would measure the object's color as black. Employing the Specular Component Included (SCI) setting enables the specular component of the reflection to be reflected from the inner surface of the sphere and subsequently reach the sample, thus allowing it to be detected by the spectrophotometer. This method allows for the accurate measurement of the sample's true color data, irrespective of the surface properties.

2. Objectives

The aim of the *in vitro* studies underlying the present dissertation was to determine, by spectrophotometric methods, how the color reproduction ability of (a) a polymer-infiltrated ceramic-network material and (b) a lithium disilicate glass-ceramic material was affected by the ceramic layer thickness, ceramic translucency and the color of the background substrate material. An additional objective was to determine the correct (SCE or SCI) spectrophotometric measurement setting by testing the PICN material.

The null hypotheses of the studies are detailed below:

a) The null hypotheses of the PICN material study:
    - a/1) PICN material reflects light only diffusely, without specular component.
    - a/2) The color reproduction ability of the PICN material is not significantly affected by the layer thickness of the ceramic.
    - a/3) The color reproduction ability of the PICN material is not significantly affected by the substrate color.
    - a/4) The color reproduction ability of the PICN material is not significantly affected by the translucency of the ceramic.

b) The null hypotheses of the LDGC material study:
    - b/1) The color reproduction ability of the LDGC is not significantly affected by the layer thickness of the ceramic.
    - b/2) The color reproduction ability of the LDGC is not significantly affected by the substrate color.
    - b/3) The color reproduction ability of the LDGC is not significantly affected by the translucency of the ceramic.

3. Methods

3.1. Ceramic specimen preparation

3.1.1. PICN specimen preparation

PICN specimens were prepared of 2M2 shade VITA ENAMIC material (VITA Zahnfabrik, Bad Säckingen, Germany) with 2 different levels of translucency (high translucent [HT] and translucent [T]) for *in vitro* examination. Rectangular ceramic specimens were made of PICN blocks in 0.5 mm; 1.0 mm; 1.5 mm; 2.0 mm and 2.5 mm (+/- 0.05 mm) layer thicknesses (3 pieces of each thickness, n=30) with side lengths of 12 mm x 14 mm. To cut and size the ceramic slices, a diamond disc slicer (T-CG-04 01/2016, Tenzi, Budapest, Hungary), a grinding machine (T-CG-05 04/2018, Tenzi, Budapest, Hungary) and SiC800 grinding powder were used under continuous water cooling. Afterwards, both surfaces of the ceramic specimens were polished with a suspension of 0.5 µm cerium oxide powder and water, using a polishing plate. Thickness of the PICN slices was validated with a digital micrometer (Mitutoyo, Kawasaki, Japan). As a reference, 2M2 shade VITA ENAMIC blocks were used with HT and T translucencies. The surfaces of the PICN blocks were polished as detailed above.

3.1.2. LDGC specimen preparation

LDGC specimens were prepared of A2 shade IPS e.max CAD material (Ivoclar Vivadent, Schaan, Liechtenstein) with 2 different levels of translucency (high translucency [HT] and low translucency [LT]) for *in vitro* examination (***Figure** 7*).

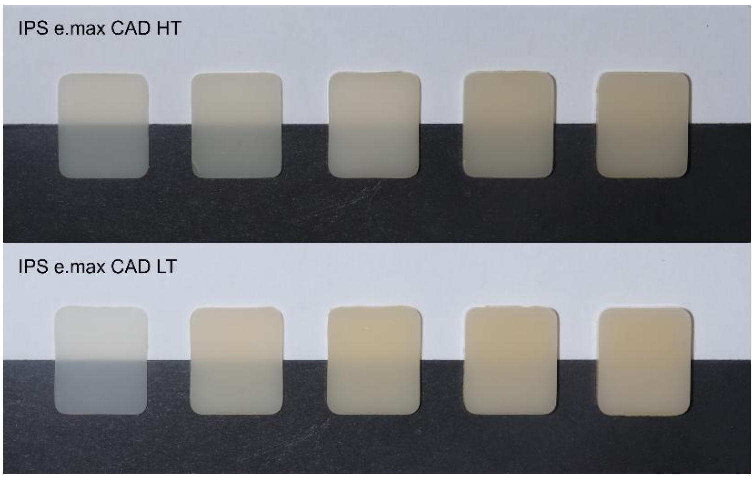

***Figure 7.** High and low translucency lithium disilicate glass-ceramic specimens with thicknesses of 0.5 mm; 1.0 mm; 1.5 mm; 2.0 mm; and 2.5 mm (from left to right).*[20]

Rectangular ceramic specimens were made of precrystallized LDGC blocks with side lengths of 12 mm × 14 mm. The thickness was calculated so that subsequent to the final crystallization and linear shrinkage of 0.2%,[63] ceramic specimens with layer thicknesses of 0.5 mm; 1.0 mm; 1.5 mm; 2.0 mm and 2.5 mm (+/- 0.05 mm) were obtained (3 pieces of each thickness, n=30). To cut and size the precrystallized ceramic slices, a diamond disc slicer (T-CG-04 01/2016, Tenzi, Budapest, Hungary), a grinding machine (T-CG-05 04/2018, Tenzi, Budapest, Hungary) and SiC800 grinding powder were used under continuous water cooling. The final crystallization of the samples was carried out in a furnace (Programat P300, Ivoclar Vivadent, Schaan, Liechtenstein) according to the manufacturer's instructions. Afterwards, both surfaces of the ceramic specimens were polished with a suspension of 0.5 µm cerium oxide powder and water, using a polishing plate. The thickness of the ceramic slices was validated by a digital micrometer (Mitutoyo, Kawasaki, Japan). As a reference, A2 shade HT and LT IPS e.max CAD blocks were used, which were also crystallized according to the manufacturer's instructions. The surfaces of the ceramic blocks were polished as detailed above.

3.2. Substrate preparation

In the studies, substrate materials were also used as backgrounds to simulate the prepared abutment. Substrates were made of a special light-curing composite (IPS Natural Die Material, Ivoclar Vivadent, Schaan, Liechtenstein) in nine shades (ND1, ND2, ND3, ND4, ND5, ND6, ND7, ND8 and ND9) (***Figure 8***). A rectangular cuboid template with

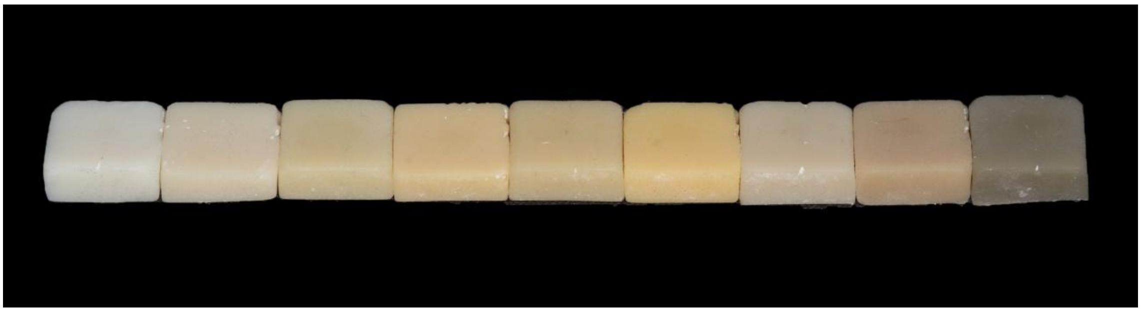

Figure 8. *Light-curing composite substrates in nine shades (ND1-ND9, from left to right).*[19]

side lengths of 20 mm × 20 mm × 8 mm was constructed using transparent silicone impression material (Exaclear, GC, Tokyo, Japan). The silicone template was infused with the composite material in a layer-by-layer fashion to prevent the formation of air bubbles. Polymerization was performed using a light polymerization apparatus (EyeVolution, Dreve ProDiMed, Unna, Germany). In order to achieve optimal polymerization, a one-minute illumination period was repeated after each layer of the substrate during the production process.

3.3. Assemblage of layered specimens

Layered specimens were assembled using ceramic specimens, substrates and transparent try-in paste (Variolink Esthetic Try-In Paste (Neutral), Ivoclar Vivadent, Schaan, Liechtenstein) as an optical medium with a layer thickness of 100 µm. In order to guarantee the uniform thickness of the try-in paste, a steel spacer with a thickness of 100 µm and an automatic pipette were employed (***Figure 9***). Each type of the ceramic samples was combined with all the substrates, resulting in a total of 180 layered specimens for examination.

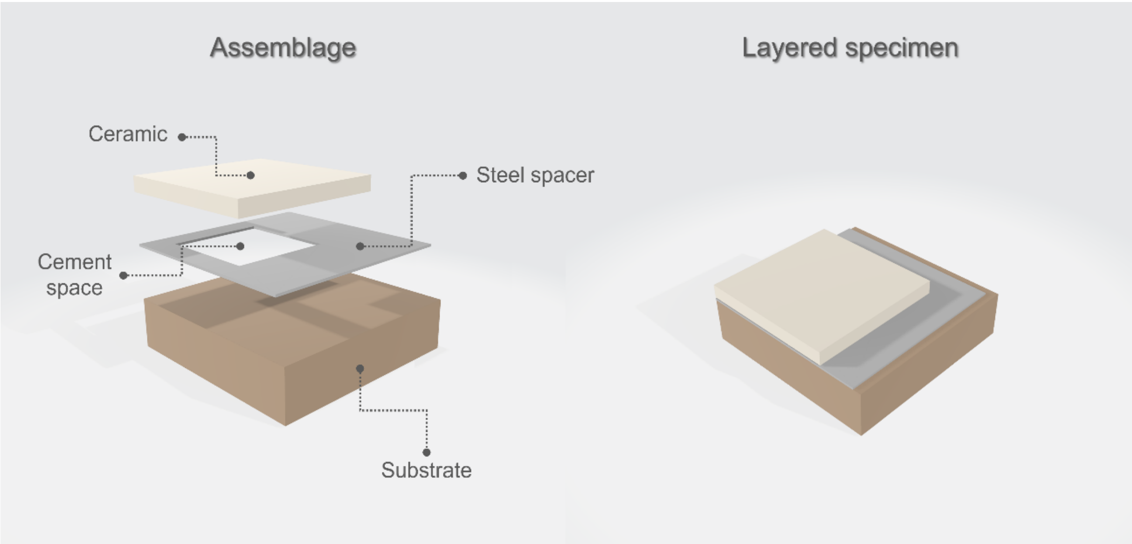

Figure 9. *Schematic figure of the assemblage of a layered specimen.*[20]

3.4. Spectrophotometric measurements

3.4.1. Setting of the spectrophotometer

Spectrophotometric measurements of reference blocks and layered specimens were conducted using a Konica Minolta CM-3720d spectrophotometer (Konica Minolta, Tokyo, Japan) within a wavelength range of 360 nm to 740 nm at a 10 nm pitch, employing a d/8 (diffuse illumination/8° viewing angle) measurement geometry. The device is equipped with a 6-inch barium sulfate-coated integrating sphere, which exhibits superior optical characteristics, enabling the measurement of the spectral reflectance of the samples. The L*, a*, b* values were calculated in accordance with the CIE standard illumination D65. These values can be converted to polar coordinates L* (lightness), C* (chroma), h° (hue) which are preferred for industrial calculations because they more closely resemble the way the human eye perceives colors. Three measurements were conducted without replacement, and the resulting values were averaged. In order to examine the specular component of the reflection, the spectral reflectance of the 2.5 mm thick T PICN specimen was measured using the SCI and SCE settings of the spectrophotometer.

3.4.2. Color difference calculation and statistical methods

To determine the color reproduction ability of the ceramic specimens, color difference (ΔE_{00}) between two samples was calculated using the CIEDE2000 formula[83] (valid since 2000) recommended by the International Commission on Illumination[84]:

$$\Delta E_{00}^{*} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}}$$

The formula had been proved to provide higher degree of fit to visual perception than CIE76.[85] The parameters denoted by $\Delta L'$, $\Delta C'$, and $\Delta H'$ are defined as the differences in lightness, chroma, and hue values of two samples. R_T is the hue rotation term applied to weighted hue and chroma differences. S_L, S_C, and S_H represent weighting factors, while the parametric factors k_L, k_C, and k_H serve as correction terms to address variations in experimental conditions.[84] The evaluation of color difference results was conducted by employing $PT_{50:50\%} = 0.8$ (50:50% perceptibility threshold) and $AT_{50:50\%} = 1.8$ (50:50% acceptability threshold) ΔE_{00} values.[86,87]

To evaluate the difference between SCE and SCI settings, obtained reflectance spectra of the 2.5 mm thick T PICN specimen were compared with each other, and statistical evaluation was performed by linear regression analysis ($p < 0.05$).

The effect of ceramic translucency, layer thickness and substrate color on the color reproduction ability of PICN material and LDGC was examined using layered specimens. In order to evaluate the color reproduction ability, color differences (ΔE_{00}) were calculated between individual layered specimens and specific reference samples. The results of layered specimens containing HT PICN material were compared with the results of the HT PICN block (as a target color), and the results of layered specimens containing T PICN material were compared with the results of the T PICN block. In case of the LDGC, the results of layered specimens containing HT LDGC were compared with the results of the HT LDGC block, and the results of layered specimens containing LT LDGC were compared with the results of the LT LDGC block (***Figure 10***). The Kruskal–Wallis test was used to analyze whether samples had the same distribution ($p < 0.05$). The effects of layer thickness and substrate color on the color reproduction ability were analyzed using linear regression ($p < 0.05$). The statistical package Stata (StataCorp LLC, Collage Station, Texas, USA) was used for data handling and analysis.

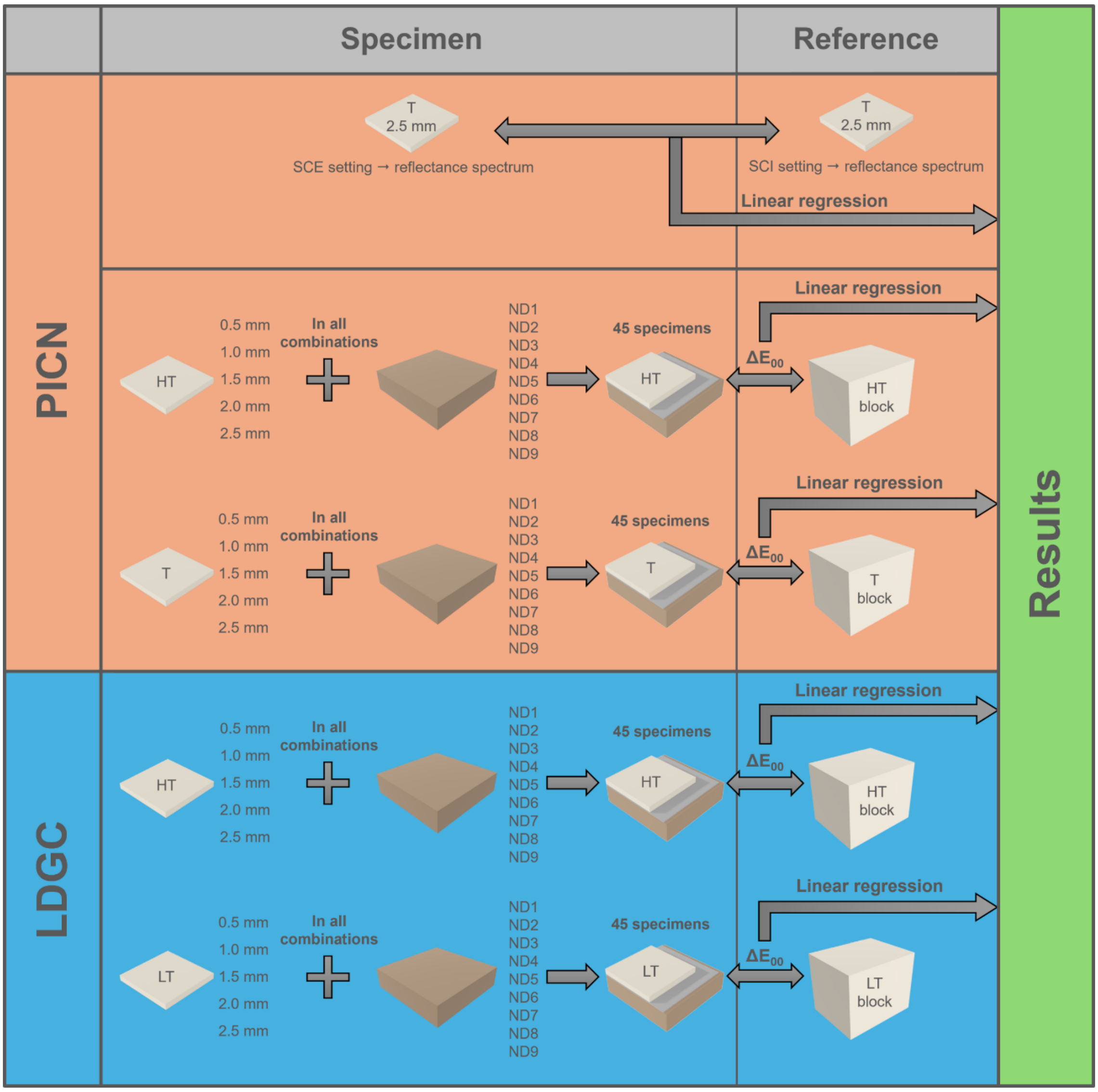

__Figure 10.__ Overview of measurements taken during the research. (the author's own figure)

4. Results

4.1. Polymer-infiltrated ceramic-network material

4.1.1. Specular component of the reflection

The SCE data exhibited values that were below the SCI range with regard to the specular component of the reflection of the PICN material (***Figure 11, 12***).

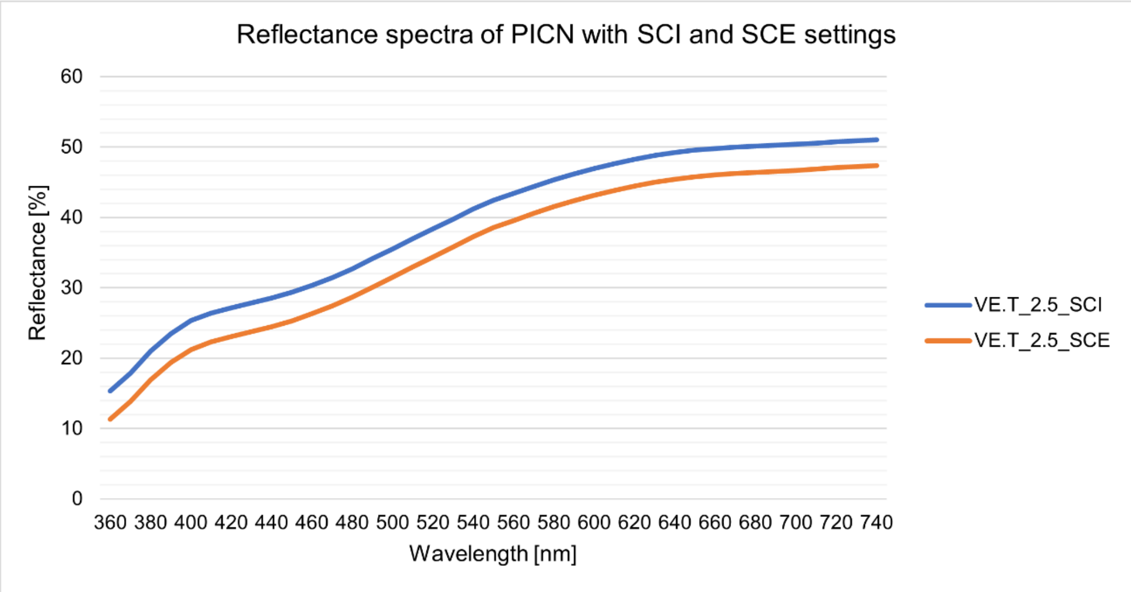

Figure 11. *Reflectance spectra of translucent PICN sample of 2.5 mm thickness with SCE and SCI settings.*[19]

In the event of a match, the blue data points (referred to as "observations") would align with the red line of equivalence. Conversely, in the event of a random fluctuation, the aforementioned points would be situated randomly above or below the line.

The dependence of SCE-SCI differences on wavelength was investigated (***Figure 13***). A U-shaped relationship was identified that can be modeled with linear regression, exhibiting a high degree of fit to the observed data points. A systematic discrepancy exists between SCE and SCI data, contingent upon the wavelength and the SCI value ($p < 0.0001$). The red area corresponds to the 95% confidence interval of the modeled correlation.

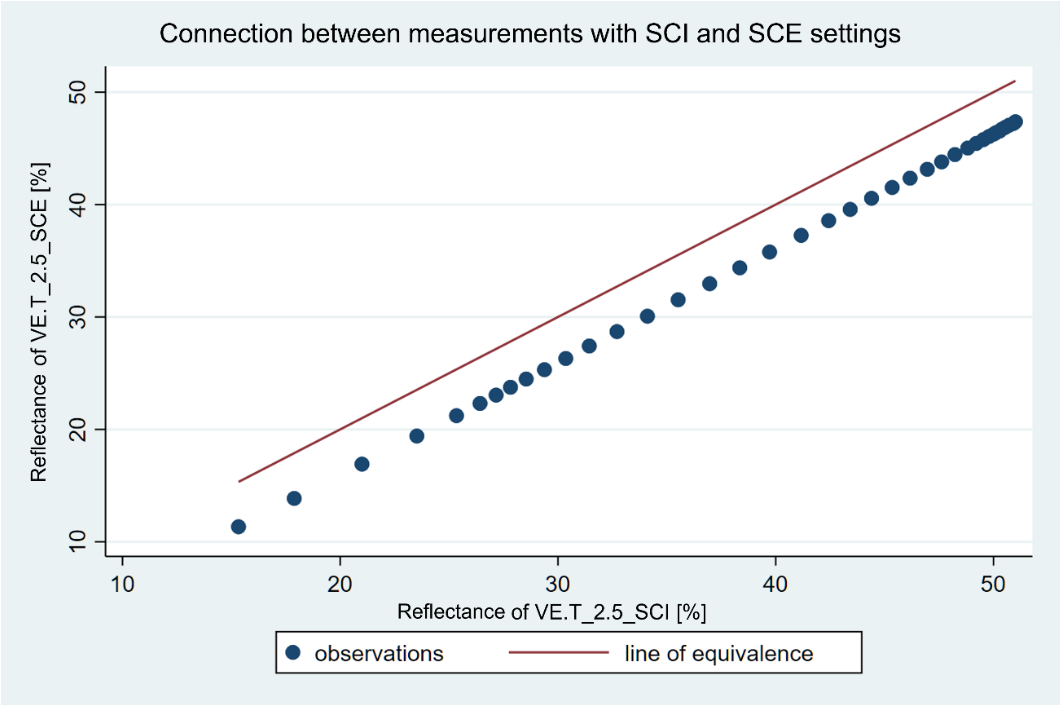

Figure 12. *Relationship of reflectance measurements of the PICN sample with SCE and SCI settings.*[19]

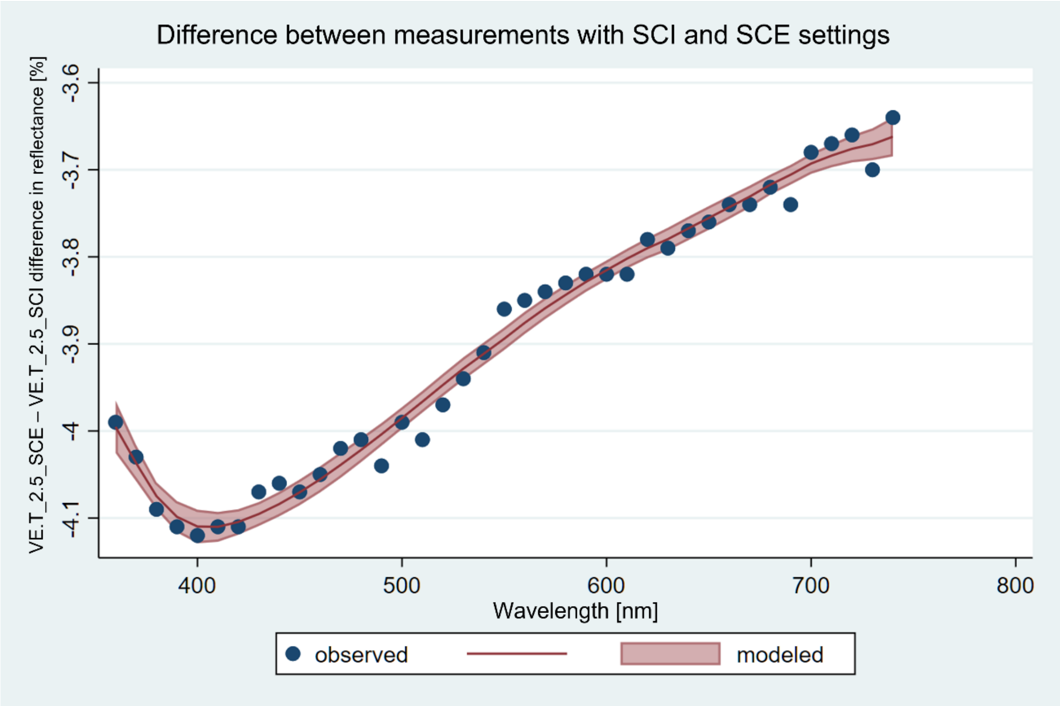

Figure 13. *Modeled U-shaped relationship of difference between measurements with SCE and SCI settings and wavelength obtained by linear regression analysis.*[19]

4.1.2. HT and T PICN blocks

A comparative analysis of the reflectance spectra of the HT and T PICN blocks was conducted to assess the fundamental reflection characteristics of the two ceramic varieties (***Figure 14***). The relationship between the difference in spectral reflectance between the two materials and the wavelength was analyzed using linear regression (***Figure 15***). The linear correlation coefficient (R), calculated with a number of observations of $n = 39$, is 0.9914, indicating a highly significant level of linear correlation ($p < 0.05$).

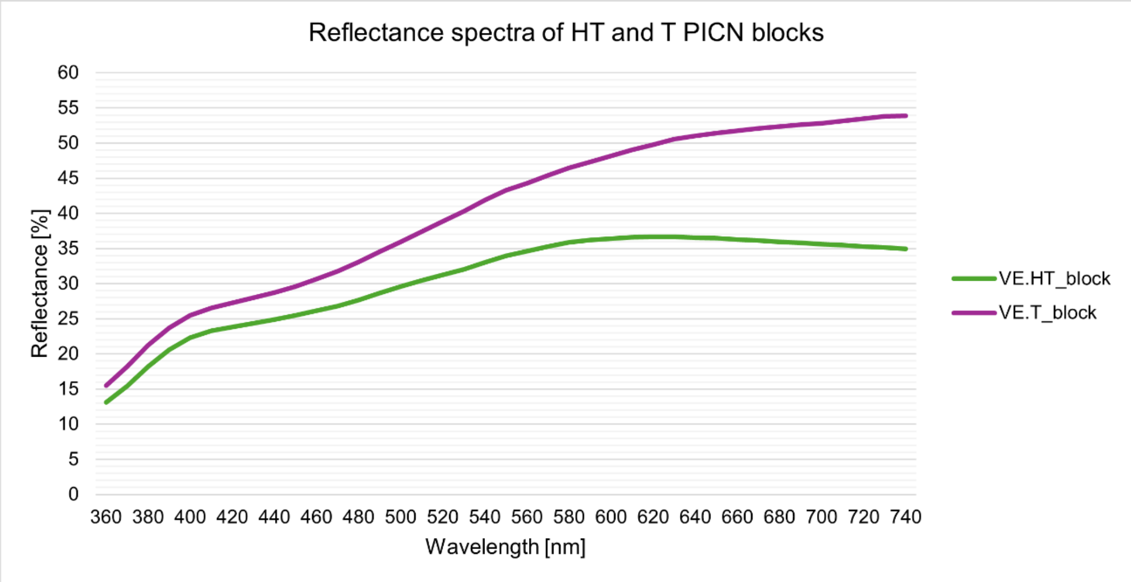

Figure 14. *Reflectance spectra of HT and T PICN blocks. (the author's own figure)*

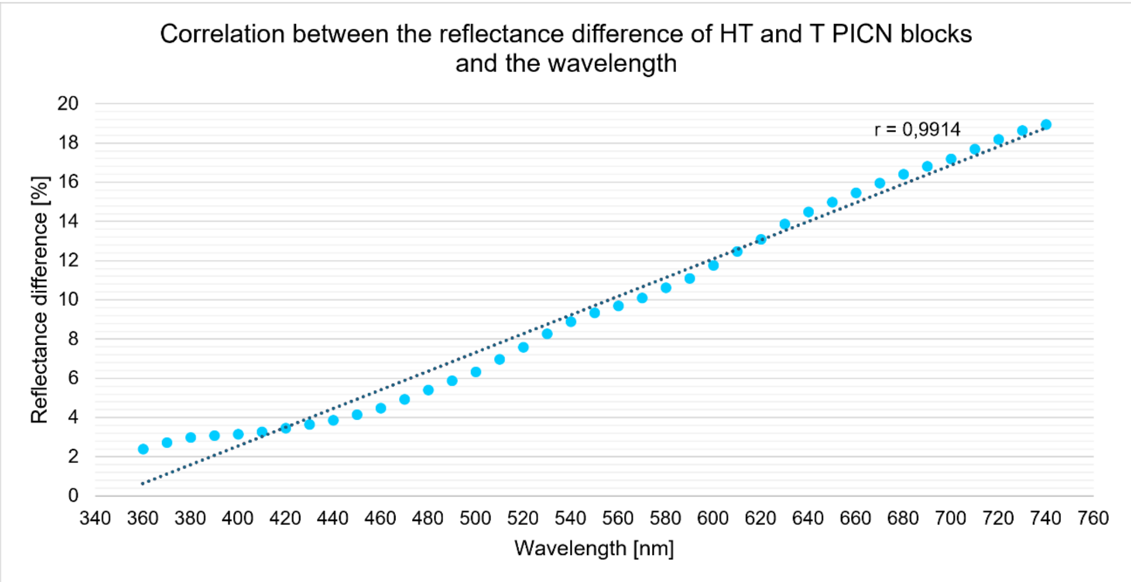

Figure 15. *Linear correlation between the difference in the reflectance of HT and T PICN blocks and the wavelength (r = 0.9914). (the author's own figure)*

4.1.3. The effect of the ceramic thickness

The influence of ceramic thickness on the ΔE_{00} values of HT and T layered specimens was investigated (***Figure 16, 17***). For each layer thickness, there is a set of nine observations corresponding to the measurements taken with the nine substrates.

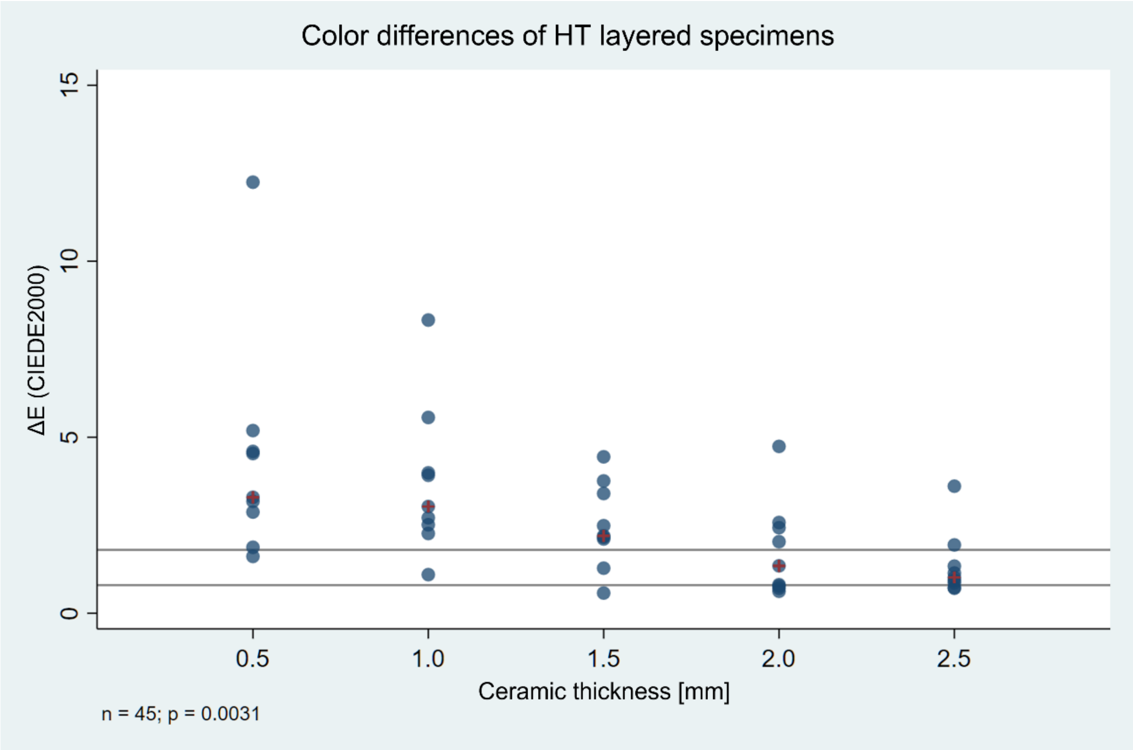

Figure 16. *Dependence of ΔE_{00} values of HT layered specimens on the ceramic thickness. Reference sample: HT block. The median of each group is indicated by a red cross. $PT_{50:50\%}$ = 0.8 and $AT_{50:50\%}$ = 1.8 are marked on the diagram.*[19]

The median value for each group is indicated by a red cross. The horizontal lines on the diagrams indicate the perceptibility ($PT_{50:50\%}$ = 0.8) and acceptability ($AT_{50:50\%}$ = 1.8) thresholds.

The results of the linear regression analysis are presented in ***Figure 18, 19***. The nine panels present the results for the nine substrates. The analysis demonstrated that within the examined range of 0.5 to 2.5 millimeters in thickness, there is a consistent multiplier-based change in color difference as the thickness increases. In the case of HT specimens, an increase in thickness by 0.5 mm (assuming no change in the substrate material) results in a decrease in ΔE_{00} to 0.735 times the initial value, or 73.5% of it, as estimated by the model. This relationship is observed across all samples, with layer thicknesses differing by 0.5 mm.

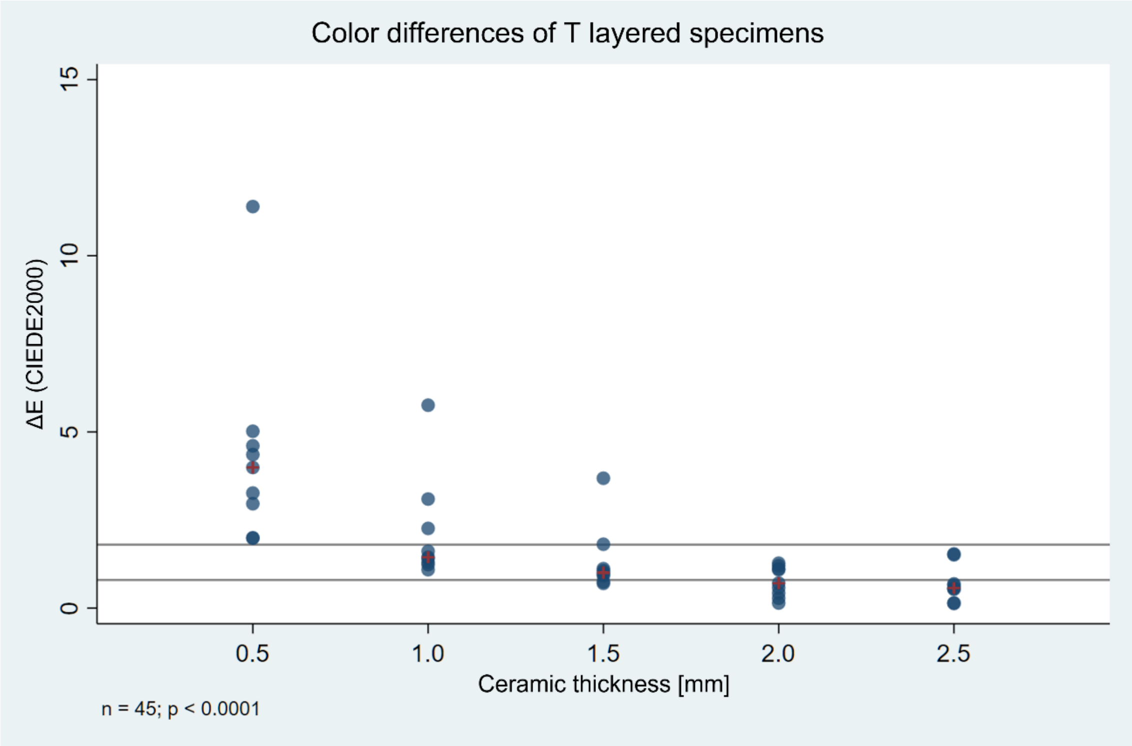

Figure 17. *Dependence of ΔE_{00} values of T layered specimens on the ceramic thickness. Reference sample: T block. The median of each group is indicated by a red cross. $PT_{50:50\%} = 0.8$ and $AT_{50:50\%} = 1.8$ are marked on the diagram.*[19]

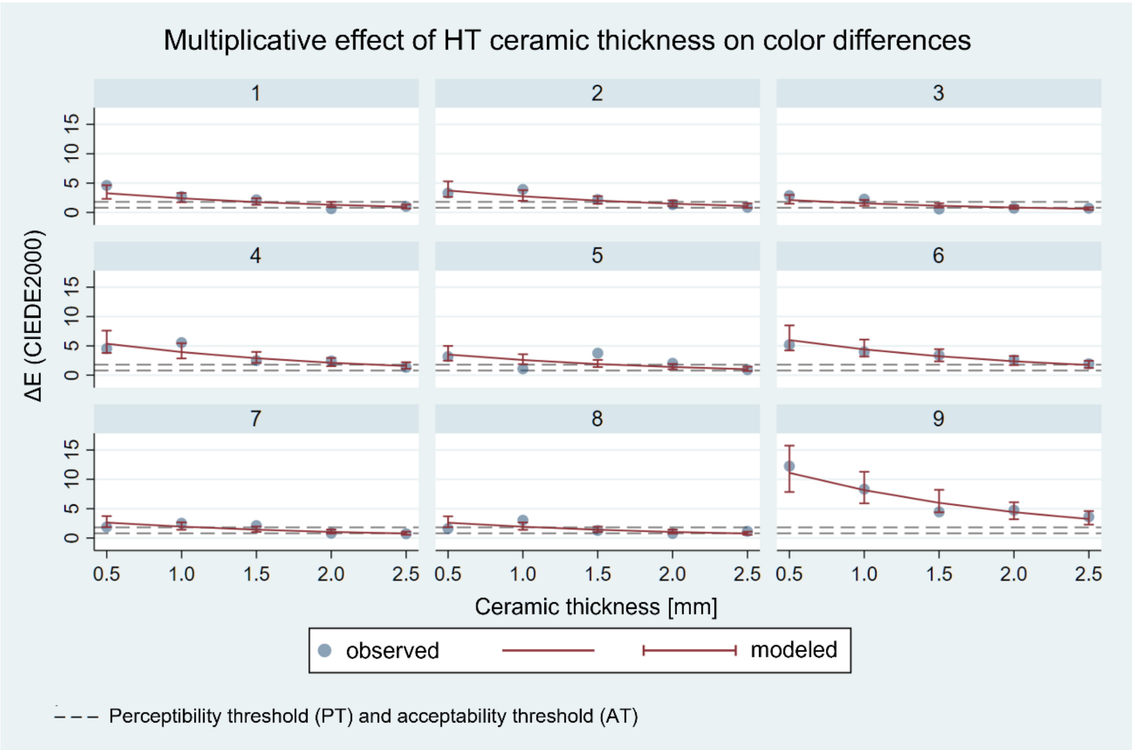

Figure 18. *Multiplicative effect of ceramic thickness on ΔE_{00} values of HT layered specimens modelled by linear regression analysis. Each panel corresponds to the measurements of the indicated substrate.*[19]

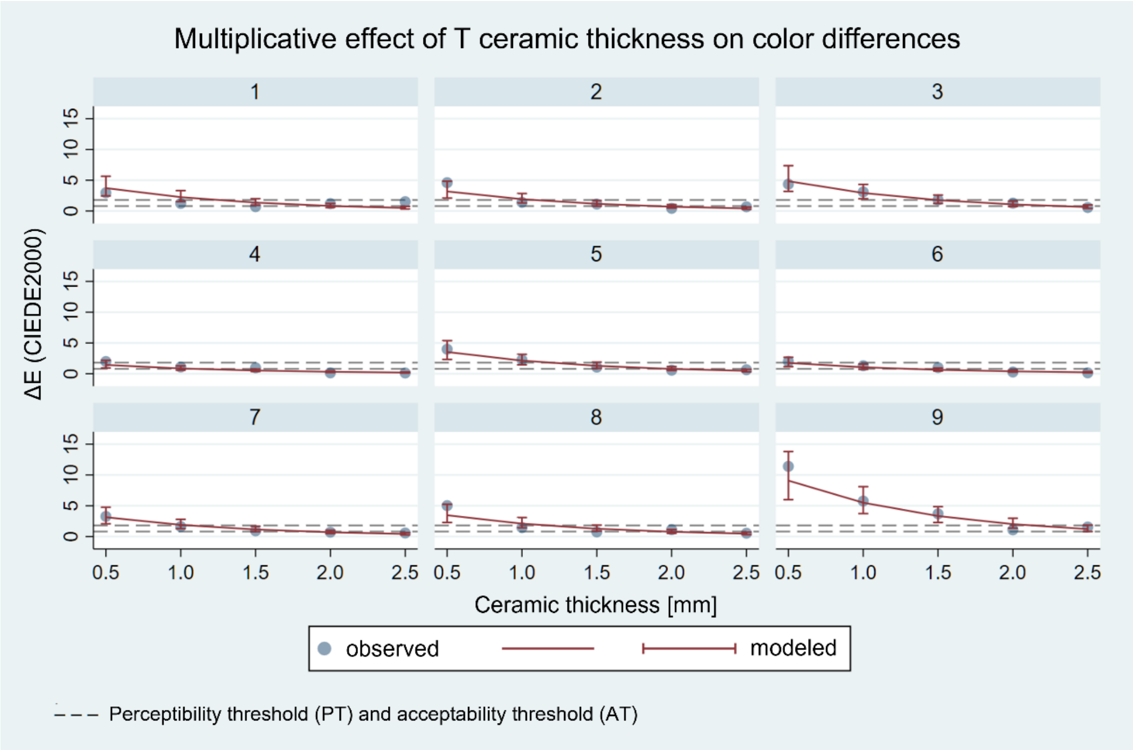

Figure 19. *Multiplicative effect of ceramic thickness on ΔE_{00} values of T layered specimens modelled by linear regression analysis. Each panel corresponds to the measurements of the indicated substrate.*[19]

The observed effect is highly significant ($p < 0.0001$), with a 95% confidence interval ranging from 0.682 to 0.791. An increase in the thickness difference results in a more pronounced effect. For instance, a 1.5 mm increase in thickness leads to a reduction in the ΔE_{00} value by a factor of 0.735^3. In the case of T specimens, an increase in thickness of 0.5 mm results in a reduction of the ΔE_{00} value to 60.5% ($p < 0.0001$). The 95% confidence interval for this value ranges from 0.553 to 0.661.

4.1.4. The effect of the substrate color

The influence of the substrate color on the ΔE_{00} values of HT and T layered specimens was investigated (***Figure 20, 21***). For each substrate, a set of five observations is provided, corresponding to the measurements taken with the five distinct ceramic thicknesses. The median value for each group is indicated by a red cross. The horizontal lines on the diagrams indicate the perceptibility ($PT_{50:50\%} = 0.8$) and acceptability ($AT_{50:50\%} = 1.8$) thresholds.

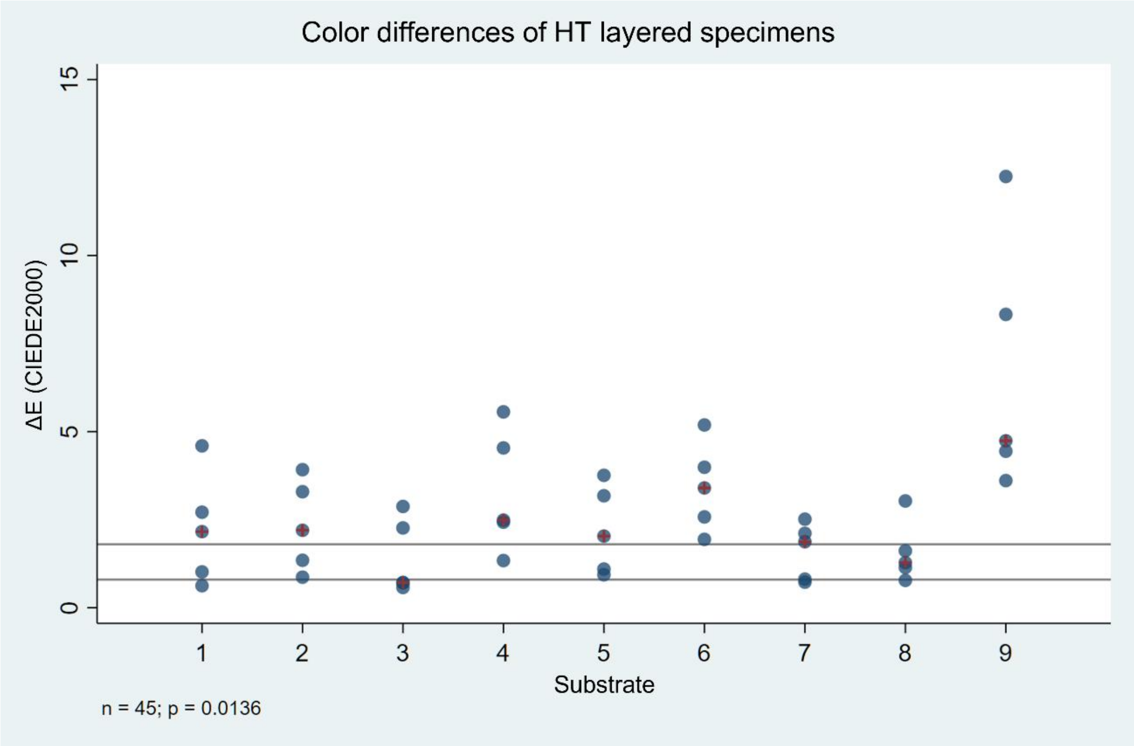

Figure 20. *Dependence of ΔE_{00} values of HT layered specimens on the substrate. Reference sample: HT block. The median of each group is indicated by a red cross. $PT_{50:50\%} = 0.8$ and $AT_{50:50\%} = 1.8$ are marked on the diagram.*[19]

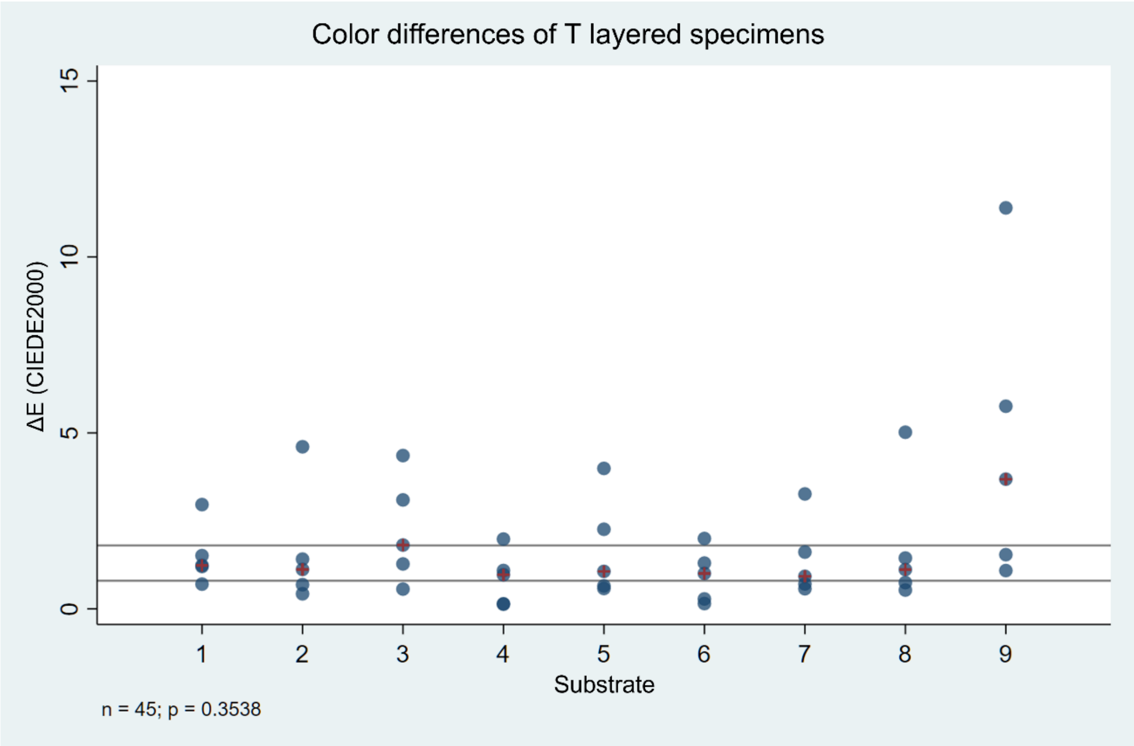

Figure 21. *Dependence of ΔE_{00} values of T layered specimens on the substrate. Reference sample: T block. The median of each group is indicated by a red cross. $PT_{50:50\%} = 0.8$ and $AT_{50:50\%} = 1.8$ are marked on the diagram.*[19]

The results of the linear regression analysis are presented in ***Figure 22, 23***. The five panels present the results for the five ceramic thicknesses.

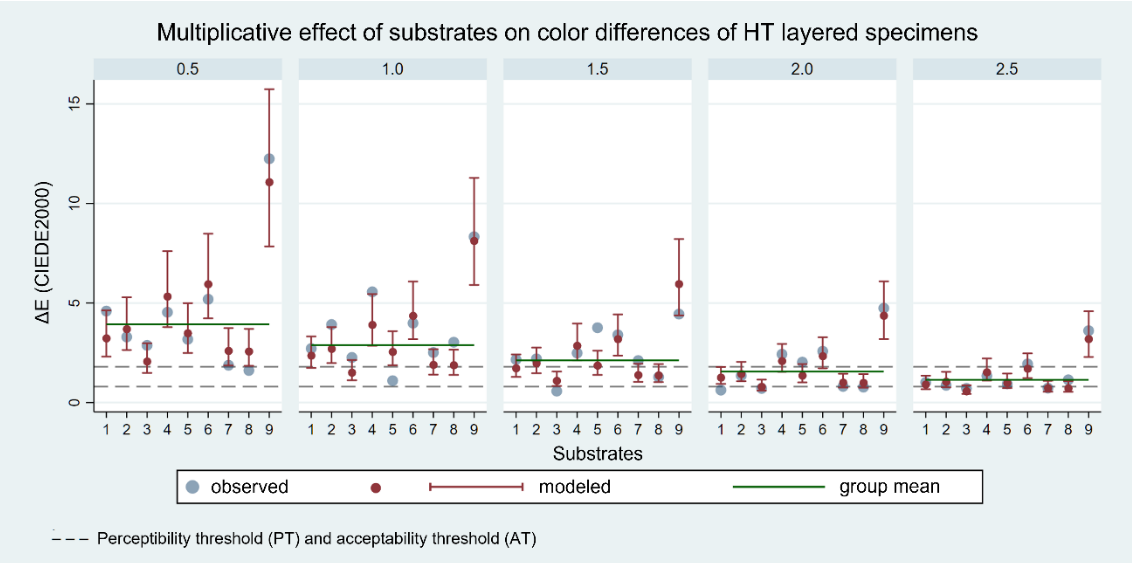

Figure 22. *Multiplicative effect of the substrate on ΔE_{00} values of HT layered specimens modelled by linear regression analysis. Each panel corresponds to the measurements of the indicated ceramic thickness. Group means are indicated by green lines.*[19]

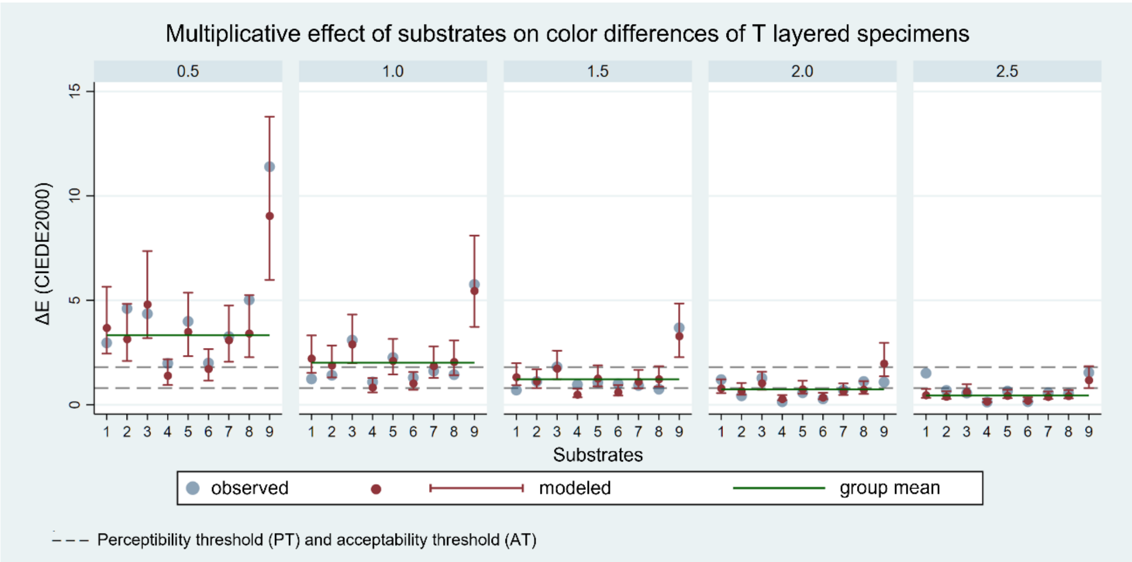

Figure 23. *Multiplicative effect of the substrate on ΔE_{00} values of T layered specimens modelled by linear regression analysis. Each panel corresponds to the measurements of the indicated ceramic thickness. Group means are indicated by green lines.*[19]

The impact of the substrate can be represented by a constant multiplier, which is a defining attribute of the material. This multiplier estimates the relationship between the average ΔE_{00} observed in the specified ceramic thickness group and the ΔE_{00} values of the layered specimens. The mean color difference within the panels (green line) is contingent upon the thickness of the ceramic material. The effect can be represented by a mathematical model that is independent of layer thickness and remains constant. In the diagrams, a positive or negative deviation from the mean value is considered significant ($p < 0.05$), if the confidence intervals, marked in red, do not intersect the green line representing the mean value.

4.1.5. The effect of the ceramic translucency

The impact of translucency was assessed by undertaking a comparative analysis of the results obtained from the HT and T materials. The analysis of the effect of ceramic thickness revealed that an increase in thickness of 0.5 mm resulted in a notable reduction in color difference from the reference sample. In the case of HT ceramic, the color difference decreased to 73.5%, while in the case of T ceramic, it decreased to 60.5%. As illustrated in Figure 22 and 23, the mean results for the two translucencies at ceramic thicknesses of 0.5 mm and 1.0 mm exceed the $AT_{50:50\%}$ threshold, but at a thickness of 1.5 mm, the T ceramic already falls below the acceptability threshold. The results of the HT specimens with layer thicknesses of 2.0 mm and 2.5 mm fall within the range of 0.8-1.8 ΔE_{00}. In comparison, the T ceramic shows group means below $PT_{50:50\%}$ at this thickness.

4.2. Lithium disilicate glass-ceramic material

4.2.1. HT and LT LDGC blocks

A comparative analysis of the reflectance spectra of the HT and LT LDGC blocks was conducted to assess the fundamental reflection characteristics of the two ceramic varieties (***Figure 24***). The relationship between the difference in spectral reflectance between the two materials and the wavelength was analyzed using linear regression (***Figure 25***). The linear correlation coefficient (R), calculated with a number of observations of $n = 39$, is 0.9848, indicating a highly significant level of linear correlation ($p < 0.05$).

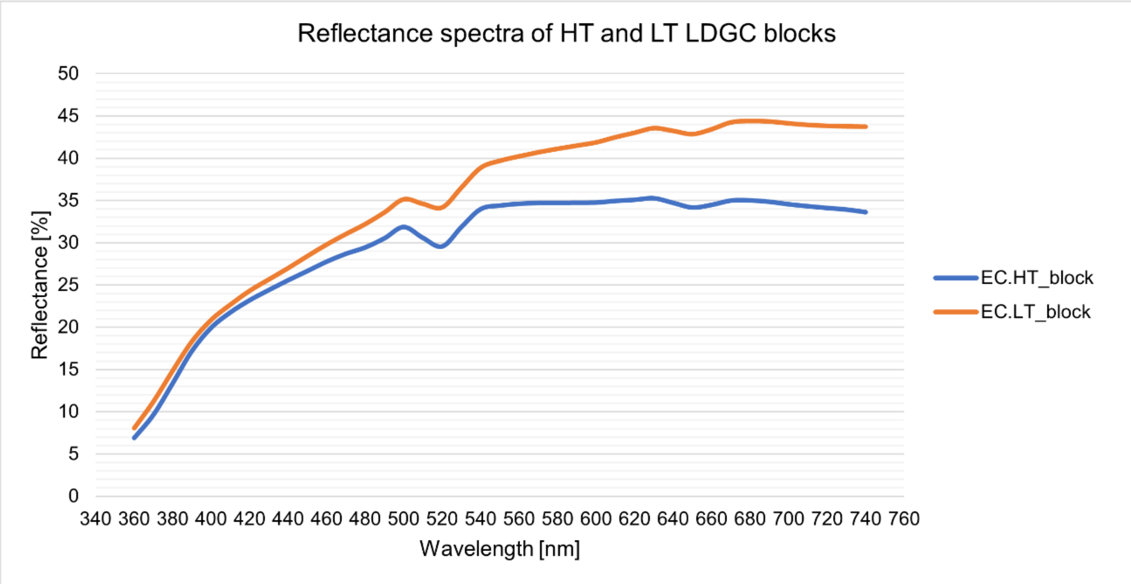

Figure 24. *Reflectance spectra of HT and LT LDGC blocks.*[20]

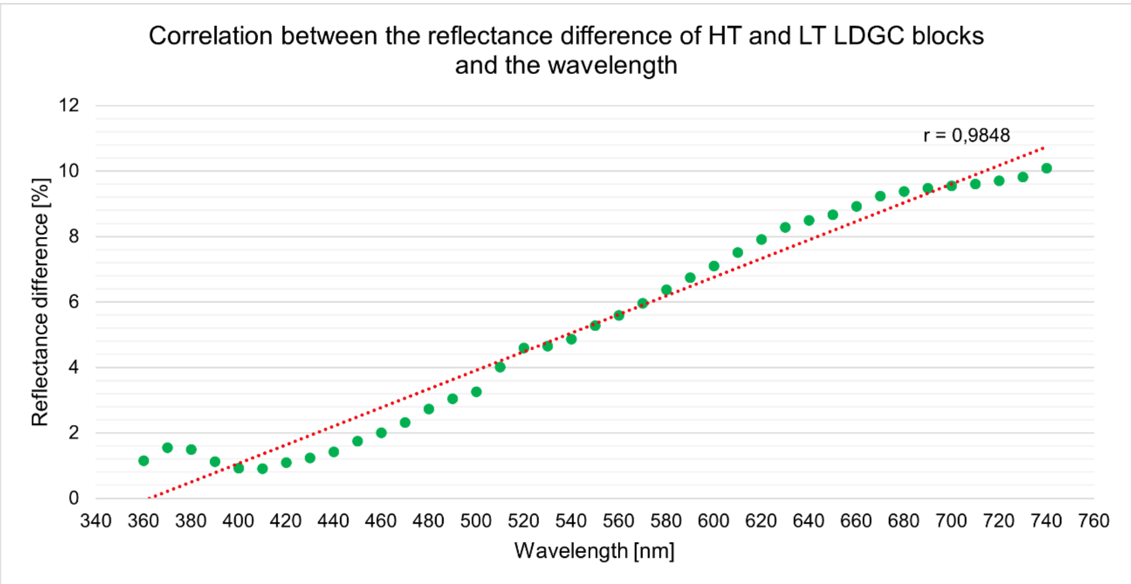

Figure 25. *Linear correlation between the difference in the reflectance of HT and LT LDGC blocks and the wavelength (r = 0.9848).*[20]

4.2.2. The effect of the ceramic thickness

The influence of ceramic thickness on the ΔE_{00} values of HT and LT layered specimens was investigated (***Figure 26, 27***). For each layer thickness, there is a set of nine observations corresponding to the measurements taken with the nine substrates. The median value for each group is indicated by a red cross. The horizontal lines on the diagrams indicate the perceptibility ($PT_{50:50\%} = 0.8$) and acceptability ($AT_{50:50\%} = 1.8$) thresholds.

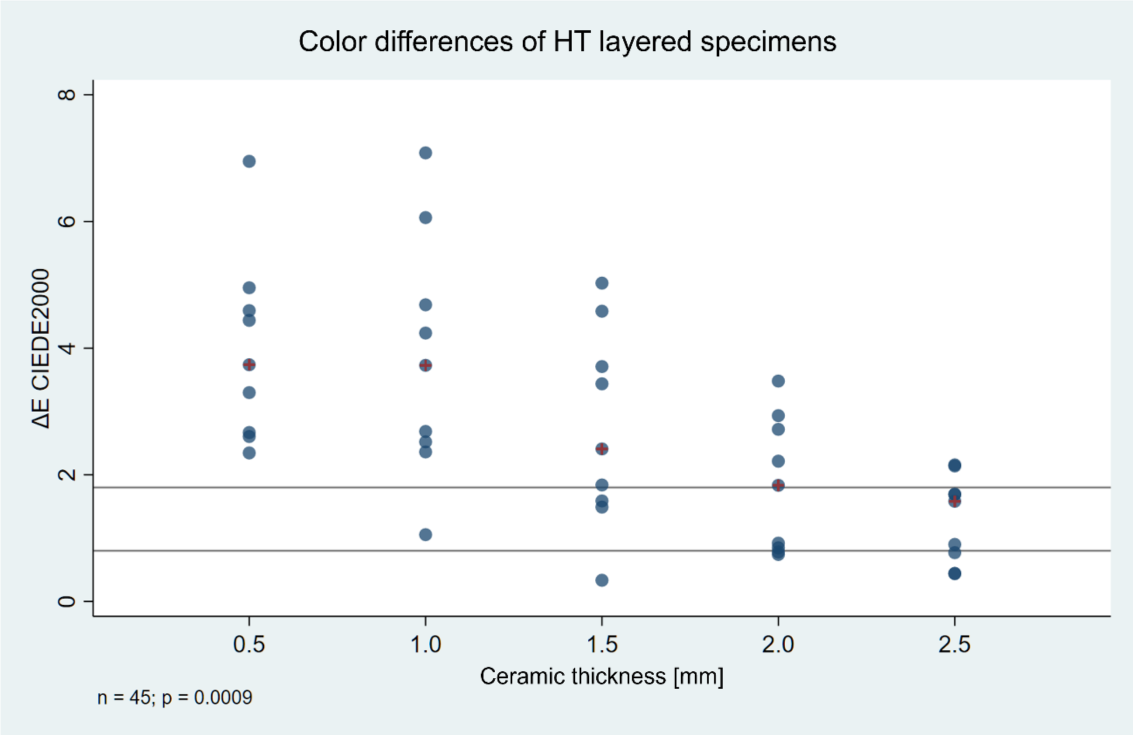

Figure 26. *Dependence of ΔE_{00} values of HT layered specimens on the ceramic thickness. Reference sample: HT block. The median of each group is indicated by a red cross. $PT_{50:50\%} = 0.8$ and $AT_{50:50\%} = 1.8$ are marked on the diagram.*[20]

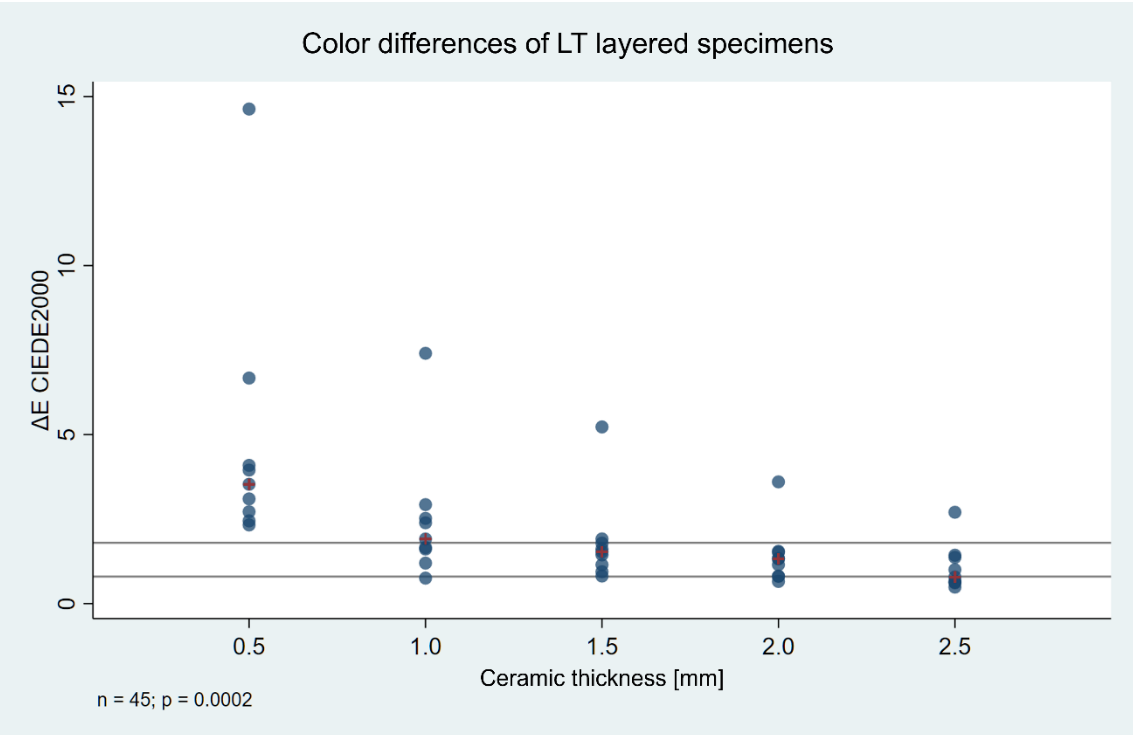

Figure 27. *Dependence of ΔE_{00} values of LT layered specimens on the ceramic thickness. Reference sample: LT block. The median of each group is indicated by a red cross. $PT_{50:50\%} = 0.8$ and $AT_{50:50\%} = 1.8$ are marked on the diagram.*[20]

The results of the linear regression analysis are presented in ***Figure 28, 29***. The nine panels present the results for the nine substrates. The analysis demonstrated that within the examined range of 0.5 to 2.5 millimeters in thickness, there is a consistent multiplier-based change in color difference as the thickness increases. In the case of HT specimens, an increase in thickness by 0.5 mm (assuming no change in the substrate material) results in a decrease in ΔE_{00} to 0.728 times the initial value, or 72.8% of it, according to the model. This relationship is observed across all samples, with layer thicknesses differing by 0.5 mm. The observed effect is highly significant ($p < 0.0001$), with a 95% confidence interval ranging from 0.683 to 0.775. In the case of LT specimens, an increase in thickness of 0.5 mm results in a reduction of the ΔE_{00} value to 71.1% ($p < 0.0001$). The 95% confidence interval for this value ranges from 0.674 to 0.750.

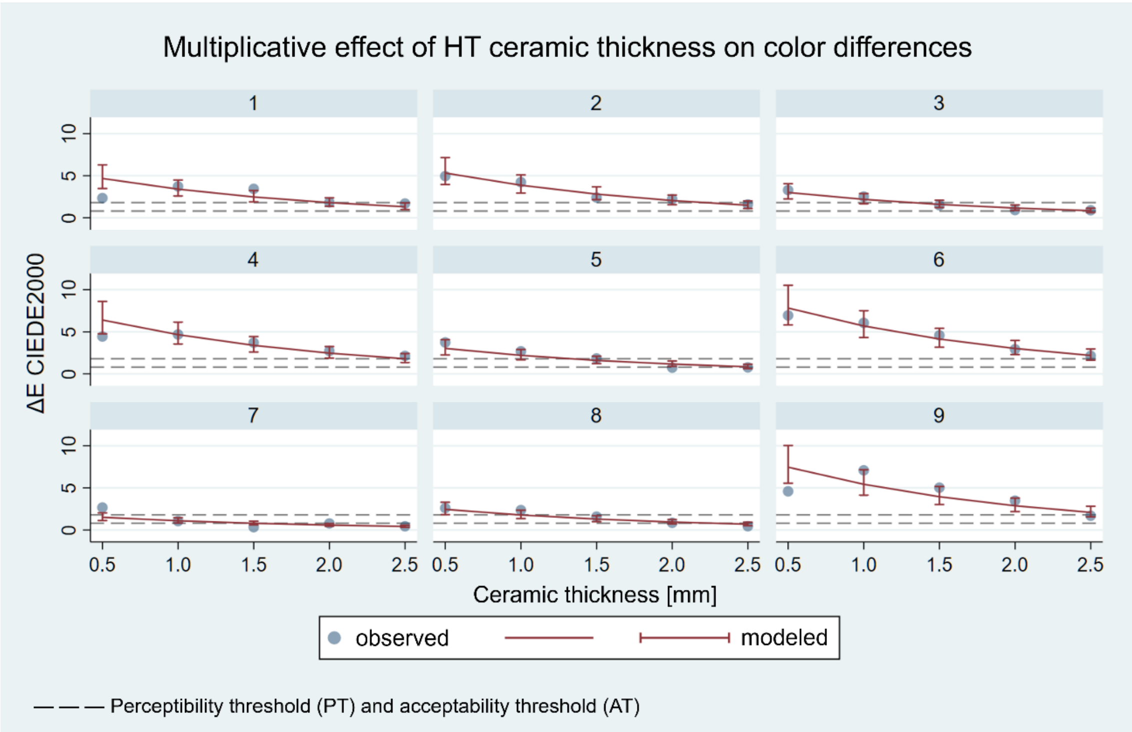

Figure 28. *Multiplicative effect of ceramic thickness on ΔE_{00} values of HT layered specimens modelled by linear regression analysis. Each panel corresponds to the measurements of the indicated substrate.*[20]

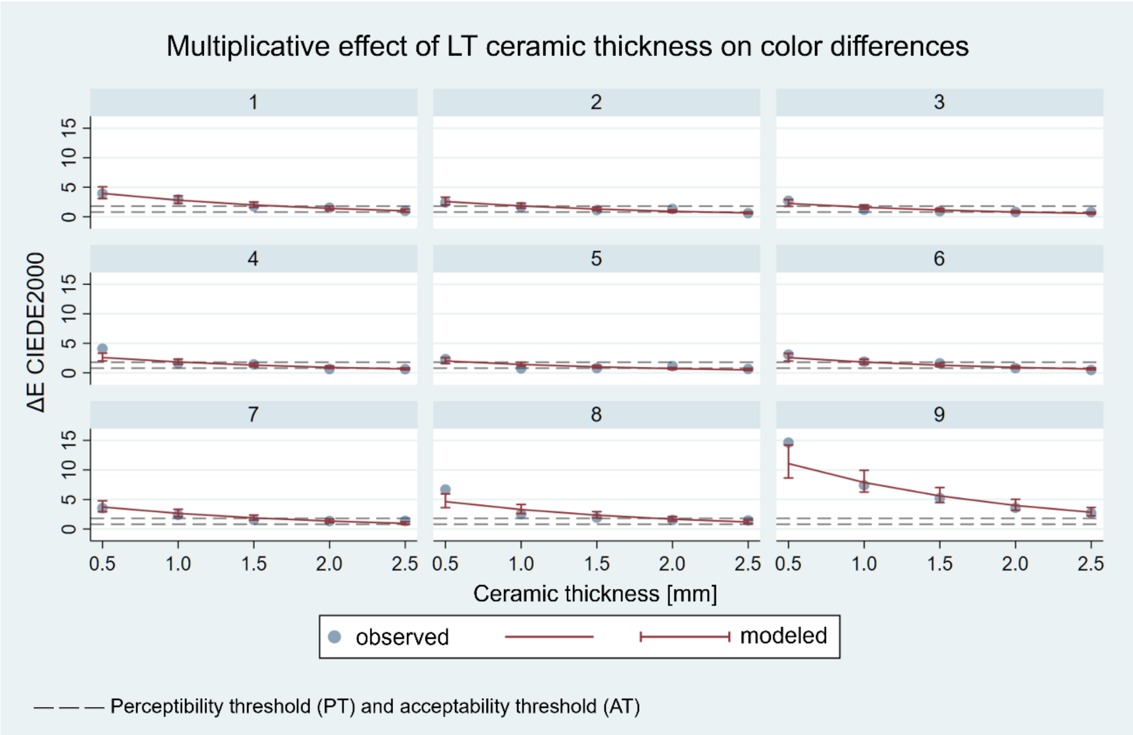

Figure 29. *Multiplicative effect of ceramic thickness on ΔE_{00} values of LT layered specimens modelled by linear regression analysis. Each panel corresponds to the measurements of the indicated substrate.*[20]

4.2.3. The effect of the substrate color

The influence of the substrate color on the ΔE_{00} values of HT and LT layered specimens was investigated (***Figure 30, 31***). For each substrate, a set of five observations is provided, corresponding to the measurements taken with the five distinct ceramic thicknesses. The median value for each group is indicated by a red cross. The horizontal lines on the diagrams indicate the perceptibility ($PT_{50:50\%}$ = 0.8) and acceptability ($AT_{50:50\%}$ = 1.8) thresholds.

The results of the linear regression analysis are presented in ***Figure 32, 33***. The five panels present the results for the five ceramic thicknesses. The impact of the substrate can be represented by a constant multiplier, which is a defining attribute of the material. This multiplier estimates the relationship between the average ΔE_{00} observed in the specified ceramic thickness group and the ΔE_{00} values of the layered specimens. The mean color difference within the panels (green line) is contingent upon the thickness of the ceramic material. The effect can be represented by a mathematical model that is independent of layer thickness and remains constant. In the diagrams, a positive or negative deviation from the mean value is considered significant ($p < 0.05$), if the confidence intervals, marked in red, do not intersect the green line representing the mean value.

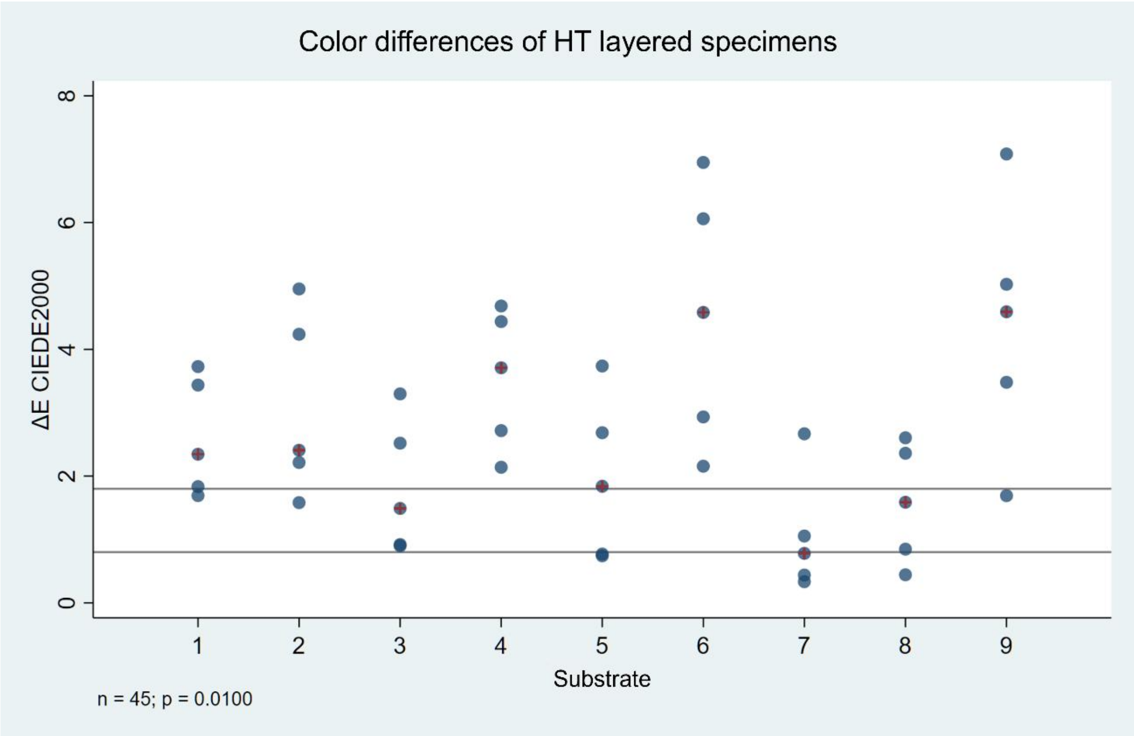

Figure 30. *Dependence of ΔE_{00} values of HT layered specimens on the substrate. Reference sample: HT block. The median of each group is indicated by a red cross. $PT_{50:50\%} = 0.8$ and $AT_{50:50\%} = 1.8$ are marked on the diagram.*[20]

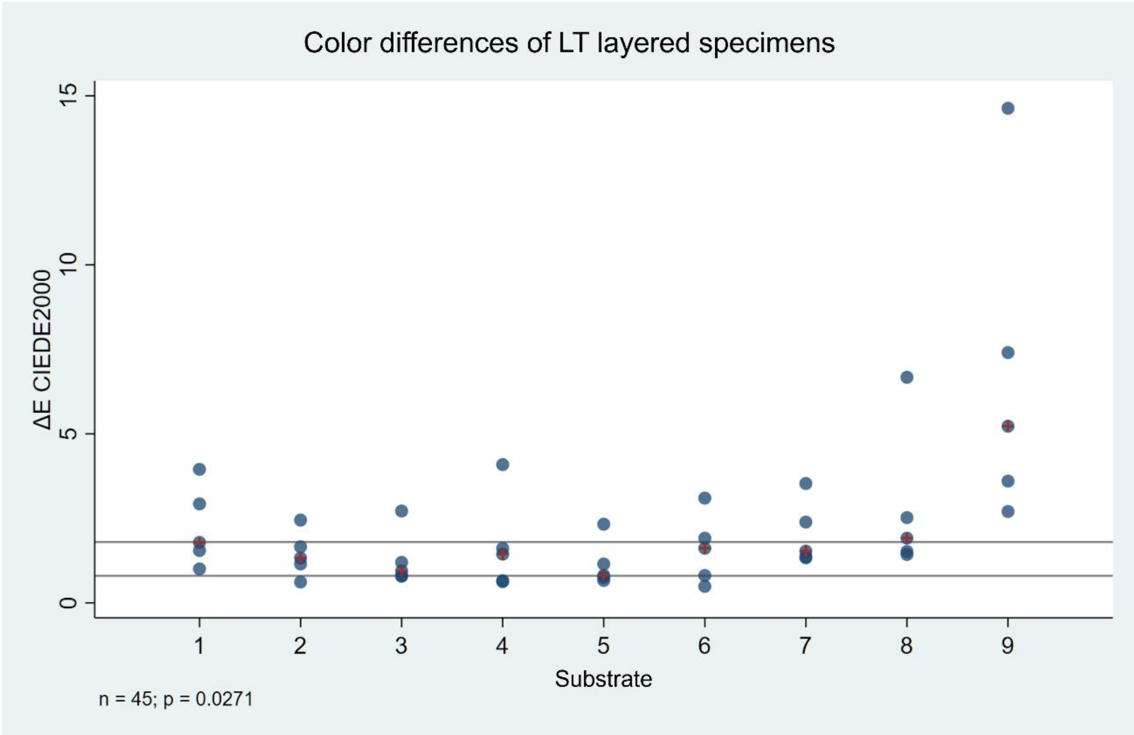

Figure 31. *Dependence of ΔE_{00} values of LT layered specimens on the substrate. Reference sample: LT block. The median of each group is indicated by a red cross. $PT_{50:50\%} = 0.8$ and $AT_{50:50\%} = 1.8$ are marked on the diagram.*[20]

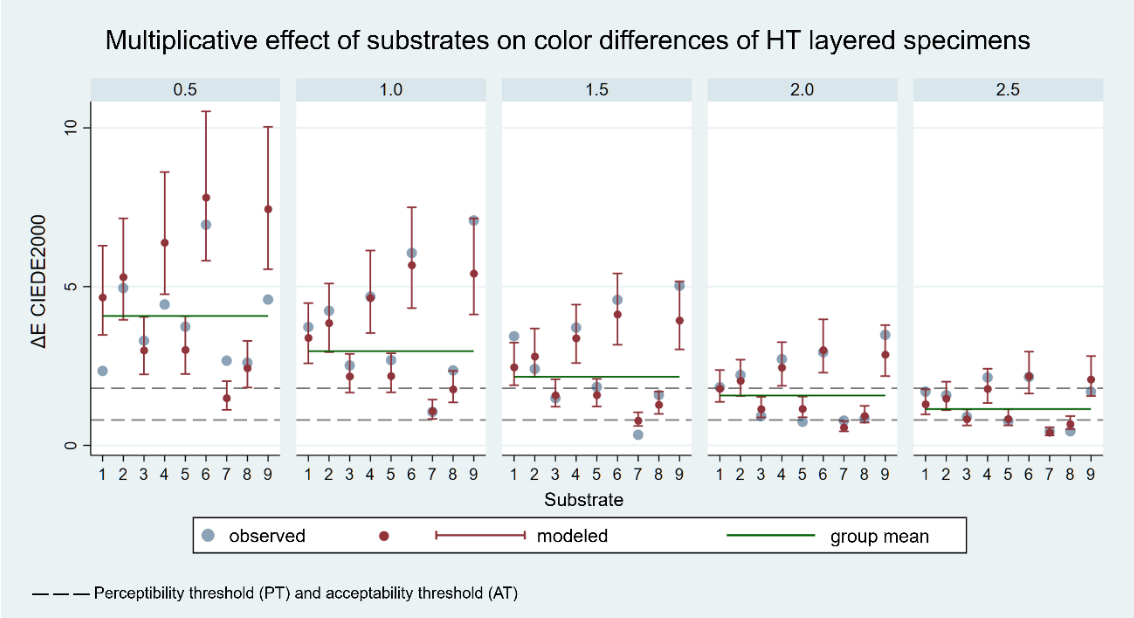

Figure 32. *Multiplicative effect of the substrate on ΔE_{00} values of HT layered specimens modelled by linear regression analysis. Each panel corresponds to the measurements of the indicated ceramic thickness. Group means are indicated by green lines.*[20]

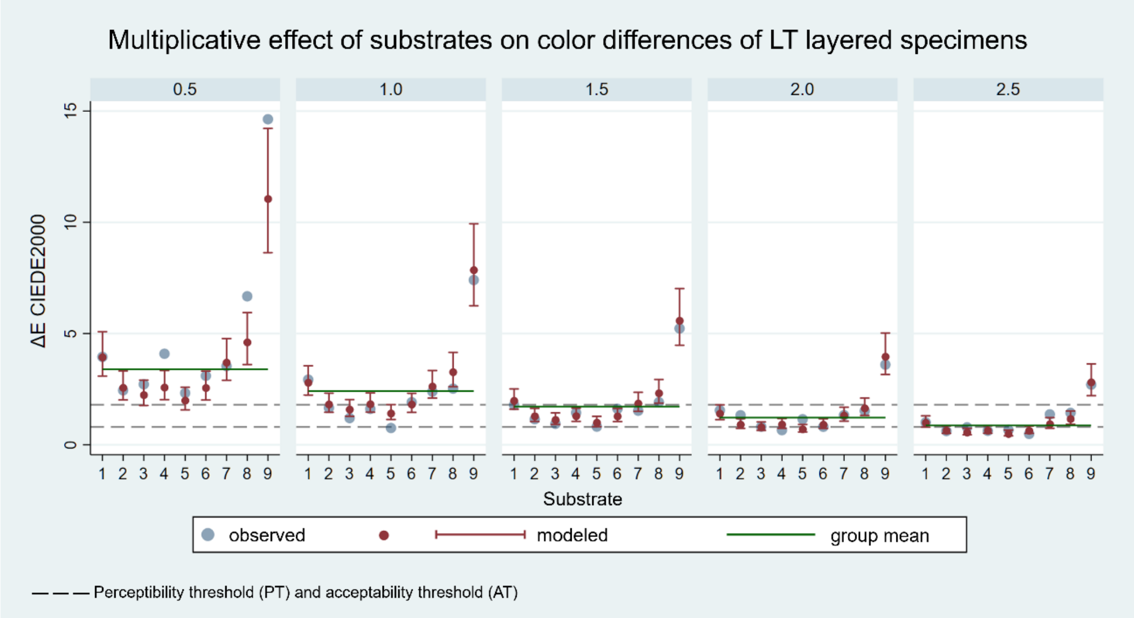

Figure 33. *Multiplicative effect of the substrate on ΔE_{00} values of LT layered specimens modelled by linear regression analysis. Each panel corresponds to the measurements of the indicated ceramic thickness. Group means are indicated by green lines.*[20]

4.2.4. The effect of the ceramic translucency

The impact of translucency was assessed by undertaking a comparative analysis of the results obtained from the HT and LT materials. The analysis of the effect of ceramic thickness revealed that an increase in thickness of 0.5 mm resulted in a notable reduction in color difference from the reference sample. In the case of HT ceramic, the color difference decreased to 72.8%, while in the case of LT ceramic, it decreased to 71.1%. In figures illustrating the relationship between the ΔE_{00} values of the HT and LT layered specimens and the layer thickness, the group medians demonstrate disparate values for the two materials. In the case of the HT ceramic, the group median exceeds the acceptability threshold at a layer thickness of up to 2.0 mm; conversely, at a thickness of 2.5 mm, the group median is below the acceptability threshold. The LT group median is already within the acceptable range at a layer thickness of 1.5 mm, and at a thickness of 2.5 mm, it is below the perceptibility threshold.

5. Discussion

5.1. Polymer-infiltrated ceramic-network material

5.1.1. Specular component of the reflection

The a/1) null hypothesis was rejected on the grounds that specular reflection is a defining attribute of the PICN material. Significant difference was observed between the data obtained with SCE and SCI settings, which was not merely attributable to random fluctuations. A plot of the difference between the two measurement settings and the wavelength relationship revealed that the difference is not uniform across the entire wavelength range. A U-shaped relationship was obtained through curve fitting, indicating that the largest difference is observed in the 400-420 nm range. Prior studies also corroborates the glossy behavior of the surface of resin-matrix ceramics, with resin nanoceramics exhibiting particularly noteworthy results. However, PICN is also distinguished by this property.[81,88]

5.1.2. HT and T PICN blocks

An analysis of the reflectance spectra of the HT and T PICN blocks revealed that they exhibited analogous characteristics; however, the reflectance of the T ceramic block was higher across the entire range of wavelengths that were investigated. This discrepancy exhibited a direct proportionality to the wavelength, manifesting as a linear correlation. The lower reflectance of HT ceramics means that the amount of light absorbed, scattered, or transmitted by the material is greater than that of T ceramics. According to Aydin et al., the difference in the chemical composition of the two materials may lead to the different reflectance.[89] The aforementioned effect was most pronounced in the near-red region of the spectrum.

5.1.3. The effect of the ceramic thickness

The a/2) null hypothesis was rejected. As illustrated in the descriptive statistical diagrams of the results, the increase in layer thickness is reflected in a gradual decline in group medians. The linear regression analysis demonstrated that an increase in the layer thickness of the ceramic resulted in a corresponding enhancement in the material's color reproduction ability. The observed effect is of considerable significance ($p < 0.0001$) for both HT and T ceramics. Previous studies have not provided a numerical model of the effect of ceramic thickness on color reproduction ability. However, they have clearly demonstrated the phenomenon, and our results correlate with these findings.[45,46,49] In their examination of high translucent multi-color PICN materials, Ruiz-López et al. observed that the lightness and chroma of the samples increased with thickening. However, they noted that this trend was not as evident in the correlation with hue.[46] In their study, Alfouzan et al. investigated the masking ability of hybrid ceramics. A correlation was identified between layer thickness and masking ability, irrespective of ceramic type and background.[45] Pop-Ciutrila et al. conducted an investigation into the translucency of leucite-reinforced glass ceramics, feldspar ceramics, zirconia-reinforced lithium-silicate glass ceramics, and PICN ceramics with varying layer thicknesses. The results demonstrated that an increase in ceramic thickness resulted in a reduction in translucency, indicating an enhancement in the material's masking ability.[49]

5.1.4. The effect of the substrate color

Given that the color reproduction ability of the PICN material is contingent upon the substrate color, the a/3) null hypothesis was rejected. The results of the linear regression analysis indicated that the outcomes of the layered specimens diverged from the group means. In regard to the modeled confidence intervals, it was observed that for HT ceramics, substrate ND1, ND2, ND4, and ND5 exhibited average performance, while ND6 and ND9 demonstrated significantly inferior results and ND3, ND7, and ND8 exhibited significantly superior results. In the case of T ceramics, ND1, ND2, ND3, ND5, ND7, and ND8 exhibited average performance, while ND9 demonstrated significantly worse performance than average. Conversely, ND4 and ND6 exhibited significantly better performance. The effect of substrate or background color has been previously examined in a number of studies, albeit with a limited sample size of substrate materials.[45,47] In a recent study, Afouzan et al. examined the masking ability of hybrid ceramics. They evaluated these ceramics on substrates made of amalgam, titanium, and composite filling material (to simulate enamel and dentin). In contrast to the present study, it was found that although the substrate material affected the color appearance of the samples, these values were not statistically significant.[45] Porojan et al. utilized three composite substrates to examine hybrid ceramics. The findings, as reported by Porojan et al., indicated that the substrate's color had a significant impact on the color reproduction ability of the ceramic.[47]

5.1.5. The effect of the ceramic translucency

The a/4) null hypothesis was rejected, as the impact of translucency on the color reproduction ability was evident in the variation of multipliers associated with the linear regression analysis and the disparity in group ΔE_{00} averages. In the case of T ceramics with a thickness of 2.0 mm, a result that is significantly below the acceptability threshold can be achieved with any substrate material except ND9. With HT ceramics, however, this cannot be stated with such certainty even with a thickness of 2.5 mm. To the best of our knowledge, previous studies on the color reproduction ability of hybrid ceramics examined the materials only in one translucency, with the exception of one publication in 2021.[49] Similar to the present research, Pop-Ciutrila et al. examined PICN materials in two translucencies (T and HT). The researchers found that the color reproduction ability of hybrid ceramics of the same shade and thickness, but of different translucency, is significantly different from one another. Therefore, the results of the present study are in accordance with the findings of the aforementioned study.[49]

5.2. Lithium disilicate glass-ceramic material

5.2.1. HT and LT LDGC blocks

An analysis of the reflectance spectra of the HT and LT ceramic blocks revealed that they exhibited analogous characteristics; however, the reflectance of the LT ceramic block was higher across the entire range of wavelengths that were investigated. This discrepancy exhibited a direct proportionality to the wavelength, manifesting as a linear correlation. According to the spectra, the HT ceramics reflected less light in the entire visible spectrum than the LT ceramics. This indicates that the absorption and transmission of light through the material were greater. The aforementioned effect was most pronounced in the near-red region of the spectrum. Pecho et al. also concluded in their study that the transmittance of the evaluated LT and HT LDGC increases with wavelength.[18] The different translucencies of the HT and LT ceramics, and consequently their disparate reflectance spectra, are attributable to the varying proportions and dimensions of lithium disilicate crystals present within the respective materials.[18,39,63] HT ceramics are characterized by a predominance of larger crystals, with an average size of 1.5 × 0.8 μm. In contrast, LT ceramics exhibit a higher concentration of smaller crystals, with an average size of 0.8 × 0.2 μm.[62]

5.2.2. The effect of the ceramic thickness

Based on the results of the ceramic thickness, the b/1) null hypothesis was rejected. The effect of an augmentation in ceramic thickness was manifested in the uniform decline of group medians, evidenced by the diminution in the ΔE_{00} values of the HT and LT specimens. Linear regression analysis provided a quantitative characterization of the influencing effect of the layer thickness, which also appears to be a constant multiplier in the case of HT and LT ceramics. The findings align closely with the model's predictions, and the observed effect was deemed to be statistically significant ($p < 0.0001$). In the case of the HT ceramics with a thickness of 0.5 mm, the ΔE_{00} value of not even one sample was below the acceptability threshold. In contrast, with a layer thickness of 2.5 mm, seven samples yielded acceptable results, three of which were below the perceptibility threshold. In the case of LT ceramics, a thickness of 0.5 mm did not yield acceptable results. However, with a ceramic thickness of 2.5 mm, the color difference of eight samples became acceptable, with five of these samples falling below the perceptibility threshold. The present findings are consistent with those of prior studies on the subject of thickness.[16,39,67,69-71,74,75] Pala et al. investigated the effects of ceramic thickness, translucency, and cement color on the masking capacity of lithium disilicate glass-ceramics. The investigation was conducted on substrates made of bovine dentin that had been stained with black tea.[67] In this study, human evaluators were utilized to assess color differences, as opposed to spectrophotometric devices. The findings of the research indicated that the masking ability was significantly influenced by the layer thickness of the ceramic. This thickness was contingent upon the translucency and cement color. The examined color difference was covered by ceramics with a thickness ranging from 0.4 to 0.6 mm.[67] In the course of spectrophotometric analysis of lithium disilicate crowns, Czigola et al. ascertained that, while ceramic thickness exerts an influence on masking capacity, its function is constrained in the context of HT ceramics.[39] According to Fachinetto et al., the ceramic thickness of lithium disilicate glass-ceramics has a significant impact on the ΔE_{00} values.[74]

5.2.3. The effect of the substrate color

The effect of substrate color on the color reproduction ability of the ceramic was found to be statistically significant, thereby rejecting the b/2) null hypothesis. The findings of the linear regression analysis indicated that, in the context of the HT ceramics, the ND1 and ND2 substrates exerted no significant influence on the ΔE_{00} values when compared to the group mean. The results for the specimens with ND4, ND6, and ND9 substrates were significantly worse than the group mean. Conversely, the results for the specimens with ND3, ND5, ND7, and ND8 substrates were significantly better than the group mean ($p < 0.05$). In the case of the LT ceramics, the results for the ND1 and ND7 substrates were not significantly different from the mean. The results for the specimens with ND8 and ND9 substrates were significantly worse than the group mean, while those with ND2, ND3, ND4, ND5, and ND6 substrates were significantly better ($p < 0.05$). The disparity in outcomes observed between HT and LT ceramics can be attributed to the varying degrees of translucency exhibited by these materials. It has been demonstrated that HT samples exhibit a higher transmission of substrate color. Consequently, their effect on the ΔE_{00} value of the entire layered sample is more significant. Correspondingly, within each group categorized by layer thickness, the standard deviation of the ΔE_{00} values is greater. This also leads to a larger deviation of the individual samples from the group mean. In the case of the LT samples, the influence of outliers on the group mean is amplified due to the reduced standard deviation of the ΔE_{00} values within the groups, which is attributable to the lower translucency. Therefore, significant differences are obtained in the case of several samples. The most severely discolored ND9 substrate yielded results that were significantly higher than the group mean for both ceramic types. The impact of substrate or background color has been a subject of inquiry in prior studies, albeit predominantly with a limited number of substrate samples.[5,16,66,68-71,73] Comba et al. conducted a study to evaluate the effects of substrate and cement shades on the translucency and color of lithium disilicate and zirconia CAD/CAM materials.[66] The results indicated that background shade exerted a significant influence on the translucency and color of the ceramic materials that were examined. Furthermore, the final color of high translucency lithium disilicate restorations is predominantly influenced by the shade of the core material.[66] Czigola et al. utilized twelve distinct substrates to assess the impact of substrate color, ceramic thickness, translucency, and cement shade on the color difference from a reference color of lithium disilicate crowns.[39] The study revealed that there was no combination under the $AT_{50:50\%}$ ($\Delta E_{00} = 1.8$) with gold alloy substrates, and only one combination was below the $AT_{50:50\%}$ with Co-Cr substrates (1.5

mm LT crown, light plus try-in paste). The lowest ΔE_{00} values were observed for LT crowns with a thickness of 1.5 mm.[39] Sancaktar et al. conducted a study to investigate the effect of ceramic thickness, cement and background shade on the translucency of lithium disilicate and zirconia reinforced lithium silicate ceramics.[70] In this study, despite the utilization of low translucent ceramic materials, the background color exerted a discernible influence on the ultimate translucency of the resultant materials.[70]

5.2.4. The effect of the ceramic translucency

It has been demonstrated that translucency exerts a significant influence on the color reproduction ability of lithium disilicate glass-ceramics. Consequently, the b/3) null hypothesis was rejected. The disparate behaviors exhibited by the HT and LT ceramics are evident in a number of results. A comparison of the reflectance spectra of the two types of materials revealed that the reflectance of the HT ceramic is lower in the red regions of the visible spectrum. That is to say, the reflected light contains fewer yellowish-reddish components than in the case of the LT ceramics. This phenomenon can result in a grayer, cooler shade of the high translucency material. As previously indicated, the color reproduction ability of the two materials is impacted differently by the increase in layer thickness, which is reflected in the varying multipliers. The location of the group medians calculated for each ceramic thickness also indicates the disparate optical behaviors exhibited by the two translucencies. While a thickness of 0.5 mm did not yield acceptable outcomes for any ceramic, a thickness of 1.0 mm produced acceptable results for the HT ceramic with one substrate and the LT ceramic with four substrates, one of which was even below the perceptibility threshold. The findings of the present study are consistent with those of earlier investigations concerning the impact of translucency.[39,67,68,71,73,74,76] Skyllouriotis et al. determined the translucency of six materials used for veneer restorations. They assessed the materials' translucency parameters, contrast ratios, and potential to mask dark tooth colors.[76] The investigation revealed that lithium disilicate materials exhibiting low translucency possessed a higher degree of opacity compared to the other ceramic specimens examined. This characteristic renders them more effective in masking properties.[76]

6. Conclusions

Within the limitations of the *in vitro* studies underlying the present dissertation, the following conclusions were established:

a/1) The reflection of the examined polymer-infiltrated ceramic-network material is distinguished by both diffuse and specular characteristics.

a/2) The color reproduction ability of polymer-infiltrated ceramic-network materials is significantly affected by the layer thickness. It demonstrates an exponential increase with increasing layer thickness, according to a constant multiplier, which is a characteristic of the material.

a/3) A comprehensive examination of nine distinct substrate materials revealed that, in the case of high translucent polymer-infiltrated ceramic-network material, five substrate materials (ND3, ND6, ND7, ND8, ND9) exert a significant influence on the color reproduction ability of the ceramics, while in the case of translucent material, three substrate materials (ND4, ND6, ND9) exert a significant influence on this ability.

a/4) The color reproduction abilities of translucent and high translucent polymer-infiltrated ceramic-network materials are significantly different.

b/1) The color reproduction ability of lithium disilicate glass-ceramics is significantly affected by the layer thickness. It demonstrates an exponential increase with increasing layer thickness, according to a constant multiplier, which is a characteristic of the material.

b/2) A comprehensive examination of nine distinct substrate materials revealed that, in the case of high and low translucency lithium disilicate glass-ceramics, seven substrate materials (in the same order: ND3, ND4, ND5, ND6, ND7, ND8, ND9 and ND2, ND3, ND4, ND5, ND6, ND8, ND9) exert a significant influence on the color reproduction ability of the ceramics.

b/3) The color reproduction abilities of high and low translucency lithium disilicate glass-ceramics are significantly different.

7. Summary

Recent decades have witnessed a substantial development in the field of esthetic dentistry, largely attributable to the integration of digital technologies and the advent of advanced ceramic materials. The widespread use of intraoral and laboratory scanners and the rise of CAD/CAM technology are defining elements of today's dentistry. The expectations of esthetic results are constantly increasing from both patients and dentists. Consequently, it is an unavoidable and very important task to examine the optical properties of the ceramic materials used. In the case of all-ceramic systems, such as polymer-infiltrated ceramic-network materials and lithium disilicate glass-ceramics, the esthetics of the final restoration are also influenced by additional factors such as the substrate, the thickness and translucency of the ceramic. Although the literature has shown increased interest in the topic in recent years, there is a lack of numerical data available to draw appropriate conclusions.

Spectrophotometers are the most widely used color measuring devices. In order to obtain scientifically unquestionable data, the research that formed the basis of the dissertation was also conducted using a laboratory spectrophotometric method. The two types of ceramic materials were investigated in two translucencies and five layer thicknesses on nine types of substrate materials to obtain a comprehensive picture of the materials' color reproducing ability.

The research highlighted that the translucency of the ceramic, its layer thickness and, in many cases, the color of the substrate material also significantly influence the color reproducing ability of the ceramics.

Overall, the results of our studies are in accordance with previous research results discussing PICN and LDGC materials and contain new findings that carry important information for clinical practice and can provide guidelines for choosing the right material with the appropriate translucency and layer thickness.

It is imperative to underscore that the outcomes stem from an *in vitro* investigation, which necessitates circumspect interpretation when extrapolated to external environments. While the utilized method is deemed adequate for the examination of factors influencing the optical properties of PICN and LDGC materials, the perfect simulation of *in vivo* conditions (convex and wet surfaces, natural tooth tissues, etc.) remains unresolved.

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9. List of figures and tables

The author's own, previously unpublished figures and tables:

- Figure 2, 3, 4, 5, 10, 14, 15
- Table 1

10. Bibliography of the candidate's publications

10.1. Publications related to the dissertation

- **Saláta J**, Szabó F, Csuti P, Antal M, Márton P, Hermann P, Borbély J, Ábrám E. Quantitative examination of factors influencing the colour reproduction ability of lithium disilicate glass-ceramics. *BMC Oral Health*. 2024 Jun 5;24(1):660. doi: 10.1186/s12903-024-04429-w (**IF: 2,6**)
- **Saláta J**, Szabó F, Csuti P, Antal M, Márton P, Hermann P, Borbély J, Ábrám E. Effect of thickness, translucency, and substrates on the masking ability of a polymer-infiltrated ceramic-network material. *J Esthet Restor Dent*. 2023 Sep;35(6):886-895. doi: 10.1111/jerd.13071 (**IF: 3,2**)
- **Saláta J**, Fehér D, Lenk S, Ujhelyi F, Borbély J, Hermann P, Ábrám E. Monolitikus cirkónium-dioxid fogpótlások anyagának spektrofotometriai vizsgálata. *Fogorvosi Szemle*. 2023;116(1):2-8. doi: 10.33891/FSZ.116.1.2-8
- **Saláta J**. A fogászati kerámiaanyagok fejlődésének történeti áttekintése. *Kaleidoscope: Művelődés- Tudomány- és Orvostörténeti Folyóirat*. 2021;2021/2022:284-293. doi: 10.17107/KH.2021.22.284-293
- Ábrám E, Gajdátsy G, Fehér D, **Saláta J**, Beleznai S, Hermann P, Borbély J, Shen ZJ. Spectrophotometric examination of the optical effects of monolithic multilayered zirconia with different substrates. *Advances in Applied Ceramics*. 2020;119(5-6):261-266. doi: 10.1080/17436753.2019.1707412 (**IF: 2,088**)

10.2. Other publications not related to the dissertation

- Török G, **Saláta J**, Ábrám E, Nemes B, Hermann P, Rózsa N, Kispélyi B. Prosthetic rehabilitation of a patient with ectrodactyly-ectodermal dysplasia-cleft lip/palate syndrome through a hybrid workflow: A case report with 2-year follow-up. *Spec Care Dentist*. 2024 Jan-Feb;44(1):96-102. doi: 10.1111/scd.12826 (**IF: 0,9**)
- **Saláta J**, Hermann P, Ábrám E. Króm- és nikkelallergiás páciens komplex protetikai ellátása. *Fogorvosi Szemle*. 2023;116(2):81-89. doi: 10.33891/FSZ.116.2.81-89

- Ábrám E, **Saláta J**. II.3. Részleges rögzített fogpótlások. In Hermann Péter, Kispélyi Barbara (szerk.): *Fogpótlástan*. Semmelweis Kiadó, Budapest, 2022, 289-301.

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