Effects of shade and thickness on the translucency parameter of anatomical-contour zirconia, transmitted light intensity, and the degree of conversion of the resin cement

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ABSTRACT

Statement of problem. Anatomic-contour zirconia prostheses are usually cemented with resin cement. However, information regarding the effects of the zirconia shade and thicknesses on the translucency of the prosthesis, the intensity of the transmitted light beneath the prosthesis, and the subsequent degree of conversion in the resin cement is sparse.

Purpose. The purpose of this in vitro study was to investigate the translucency parameter in 3 anatomic-contour zirconia specimens of 2 shades at 5 different thicknesses and to investigate the transmitted light intensity and degree of conversion of the resin cement beneath the ceramic specimens by using a traditional zirconia and a lithium disilicate glass ceramic as controls.

Material and m**ethods**. Ceramic specimens from 1 anatomic-contour zirconia in a generic shade (CAP FZ) and 2 anatomic-contour zirconias in A2 shade (Zirlux and Luxisse) were used. Lithium disilicate in HT A2 shade (IPS e.max CAD) and traditional zirconia in a generic shade (CAP QZ) were used as controls. A total of 125 ceramic specimens, (n=25) were fabricated to a final specimen dimension of 12×12 mm and in thicknesses of 1.0, 1.25, 1.5, 1.75, and 2.0 mm according to the manufacturers' recommendations. The CIELab color space for all specimens placed against a white and black ground was measured with a spectrophotometer (CM-2600D), and the translucency parameters were calculated for the materials at various thicknesses. A light-polymerizing unit (DEMI LED) was used to polymerize the resin cement (Variolink II; Ivoclar Vivadent AG) placed beneath the ceramic specimens. Transmitted light intensity from the polymerization unit beneath the ceramic specimens was measured by using a spectrophotometer (MARC Resin Calibrator), and the transmittance of each specimen was calculated. The coefficient of absorption of each material was calculated from the regression analysis between the natural log of transmittance and specimen thickness. The degree of conversion of resin cement was measured by using a Fourier transformation infrared (FTIR) spectrophotometer. The results were analyzed by using 2-way ANOVA (α=.05). The relationship between the transmittance and the translucency parameter was evaluated by plotting the transmittance against the translucency parameter value of each specimen.

Results. The translucency parameter decreased with increasing thickness in all 5 material groups. All anatomic-contour zirconia had lower translucency parameters than e-max CAD (*P*<.001). The same results were found for the intensity of the transmitted light (*P*<.001). Both A2 shade anatomic-contour zirconia (Zirlux and Luxisse) showed significantly lower light transmittance compared with a generic shade anatomic-contour zirconia (CAP FZ) (*P*<.001). The coefficients of absorption were found to range from 0.63 to 1.72 mm^{-1} and reflectance from 0.10 to 0.25. The results from the degree of conversion of resin cement after polymerization through 1 to 2 mm of specimens showed a significantly higher degree of conversion in the E.max group compared with all other groups (*P*<.001). The correlation between translucency parameter and the intensity of the transmitted light suggested that the relationship was shade dependent.

Conclusions. The translucency parameter and the transmitted light intensity of ceramic material were influenced by the type of ceramic and the shade and thickness of the ceramic. The combined effects of layer thickness and the intensity of the transmitted light in A2 shade anatomic-contour zirconia (Zirlux and Luxisse) resulted in a lower degree of conversion in resin cement when compared with a generic shade anatomic-contour zirconia (CAP FZ) at layer thicknesses of 1.75 and 2 mm.

CLINICAL IMPLICATIONS

The combined effects of thickness and translucency in anatomic-contour zirconia should be systematically evaluated to ensure an adequate degree of conversion of the resin cement.

INTRODUCTION

Zirconia has become popular as a dental restorative material because of its high toughness and is processed by computer-aided design and computer-aided manufacturing (CAD-CAM) from a porous block which is milled to the designed shape, followed by sintering. The zirconia core is traditionally veneered with a more translucent ceramic to provide an esthetic restoration. However, chipping of the veneer is a common mode of failure in these restorations.[1-4]

Zirconia materials have been developed with higher translucency to be without veneering, with acceptable esthetic and mechanical properties. The optical quality is enhanced by processing methods such as the use of a titanium oxide additive, hot-isostatic pressing (HIP), high-pressure spark plasma sintering (SPS), and the addition of nanoparticles.[5-8] These procedures change the particle size and porosity of the material, changing translucency.[5,6,8,9]

The optical properties of anatomic-contour zirconia play a significant role in the success of the restoration, with translucency being affected by the light wavelength, material thickness, type of material, and surface roughness. Light of a higher wavelength has been reported to lead to a higher translucency value.[10-12] Furthermore, opacifiers such as barium, tin, titanium, zirconium, aluminum, and magnesium oxides added to the ceramic material have been reported to increase scattering and decrease translucency.[10] The translucency parameter calculated from the color difference of a restorative material placed against white and black backgrounds has been used to quantify the translucency of restorative material,[13,14] with increased material thickness reducing the translucency parameter.[10,11,15,16]

Similarly, light transmittance of a restorative material has been reported to be affected by different physical properties.[17] Transmitted light intensity can have a strong effect on the degree of conversion of resin luting cement used for crown cementing and is reported to be correlated to the mechanical and biological properties in such a way that the higher degree of conversion resulted in better mechanical properties.[18]

Although the color of anatomic-contour zirconia has been evaluated, information is sparse on the effect of its shade and thickness on the translucency of the prosthesis, transmitted light intensity beneath the prosthesis,[19] and subsequent degree of conversion in the resin cement.[14,19,20] The objective of this in vitro study was to investigate the effects of shades and thicknesses on the translucency parameter of 3 anatomic-contour zirconia. The effects of shades and thicknesses on the intensity of the transmitted light and the degree of conversion of the resin cement underneath the ceramic specimens were also investigated. A traditional zirconia and a lithium disilicate glass ceramic were used as controls. The null hypotheses were that the material group and the specimen thickness would not affect the translucency parameter, the transmitted light intensity, or the degree of conversion in resin cement beneath the specimens.

MATERIAL AND METHODS

Ceramic specimens from 1 anatomic-contour zirconia in a generic shade (CAP FZ; Custom Automated Prosthetics) and 2 anatomic-contour zirconia in A2 shade (Zirlux; Ardent, Inc, Luxisse; Heany Industries) were tested. Lithium disilicate in HT A2 shade (IPS e.max CAD; Ivoclar Vivadent AG) and a traditional zirconia in a generic shade (CAP QZ; Custom Automated Prosthetics) were used as controls (Table 1). Variolink II (Ivoclar Vivadent AG) without a catalyst paste was used as the resin cement in the degree of conversion study.

A total of 125 square-shaped ceramic specimens were prepared from CAD-CAM material blocks using a cutting machine (Isomet 1000; Buehler). For e.max CAD, block ingots in HT A2 shade were cut in the dimension of 12×12 mm and polished into thicknesses of 1, 1.25, 1.50, 1.75, and 2 mm. The traditional and anatomic-contour zirconia was cut to a larger dimension according to the shrinkage factors supplied by the manufactures, sintered, and polished to achieve the final specimen dimensions as described. Five specimens in each thickness were used for each type of ceramic. The specimens were finished with 400- and 600-grit silicon carbide abrasive papers (EXAKT Technologies) with 10 strokes in each direction on both sides by using finger pressure under water lubrication. The thickness of the specimens was measured with calipers with a digital readout (Mitutoyo Corp). The e.max CAD specimens were sintered in a furnace (Programat CS; Ivoclar Vivadent AG), and all zirconia specimens were sintered in a high-temperature furnace (Blue M; SPX Corp) according to the manufacturer's recommendations. After sintering, specimen thickness was confirmed with digital calipers (Mitutoyo Corp) at the center of each specimen. All specimens were polished with 600- to 1200-grit abrasive papers (EXAKT Technologies) under water lubrication with 10 finger strokes on both sides before testing. No glazing was used to simulate the condition of the prosthesis after occlusal adjustment and polishing.

For translucency parameter measurement, the CIELab color space of all specimens was first measured with a spectrophotometer (CM-2600D; Konica Minolta Sensing Americas, Inc). The device was set at a 10% observer angle by using standard illuminant of D65 with wavelength output between 300 to 780 nm. Ceramic specimens of 1-, 1.25-, 1.5-, 1.75-, and 2-mm thicknesses were placed underneath a spectrophotometer device on either a white or black background. The translucency parameter of each specimen was calculated according to the following equation[13,14]: $TP=[(L^*_B - L^*_W)^2 + (a^*_B - a^*_W)^2 + (b^*_B - b^*_W)^2]^{½}$, where L* refers to the brightness, a* represents redness to greenness, and b* is yellowness to blueness. The subscript B refers to the color coordination on the black background and W to those on the white background.[13,14]

A light-emitting diode (LED) unit (DEMI LED; Kerr Corp) was used as the polymerization light source. A spectrophotometer (MARC Resin Calibrator; BlueLight Analytics, Inc) was used to measure the light transmittance. The average irradiance and the peak wavelength for the light-polymerization unit were determined to be 1071 mW/cm^2 and 450 nm, respectively. The intensity of the transmitted light beneath the ceramic specimens was characterized by inserting ceramic specimens from each material group between the light-polymerization tip and the spectrophotometer sensor, and the light intensity beneath each specimen was measured. Transmittance (T) of each specimen was calculated by dividing the transmitted light intensity beneath each specimen by the intensity of the polymerization light of 1071 mW/cm^2. The relationship between the transmittance and the translucency parameter was evaluated by plotting the transmittance against the translucency parameter value of each specimen.

To obtain the absorption coefficient and reflectance of each material, the natural log of T from each specimen was plotted against the thickness of each specimen, and a linear regression equation was derived from the curve. The absorption coefficient and reflectance of each material were calculated by using the following equation[21]: $\ln(T) = -\alpha t + \ln(1-R)^2$, where T is the transmittance, α is the absorption coefficient, t is the specimen thickness, and R is the reflectance.

For degree of conversion of the resin cement (Variolink II; Ivoclar Vivadent AG), the base paste of resin cement was used without the catalyst paste. The degree of conversion was determined by using a Fourier transformation infrared (FTIR) spectrophotometer (ATR-MIRacle; Pike technologies).[22] First, a small quantity of unpolymerized resin cement was placed directly on the diamond crystal plate of the FTIR machine, which had been calibrated yearly to ensure validity and repeatability. The FTIR spectra were collected from 4000 cm^{-1} to 1500 cm^{-1} with 64 scans per spectrum at a resolution of 4 cm^{-1}. For the polymerized resin cement, the resin cement was placed between 2 Mylar strips, with a glass slab beneath and ceramic specimen on the top to avoid air entrapment. The film thickness was controlled by the matte-plastic mold that was 191-µm thick as confirmed with digital calipers (Mitutoyo Corp). The tip of the polymerization unit (DEMI LED; Kerr Corp) was placed directly against the ceramic specimens. The cement was then polymerized through the different thicknesses of ceramic specimens for 40 seconds by using the light-polymerization unit (Fig. 1). After polymerization, the resin cement strips were removed from under the ceramic specimens and were immediately placed in a standard FTIR holder. FTIR spectra were collected in the same manner as for the unpolymerized resin cement. Two scans from different areas of the surface (right and left) for each slice of resin were performed, and the relevant peak areas were averaged. Measurement of the degree of conversion was conducted at room temperature (22 °C). The area under the peak at 1638 cm^{-1} represented the vinyl C=C groups of the composite resin, while the area under the peak at 1608 cm^{-1} represented the aromatic C=C and served as the internal standard. The degree of conversion was then determined according to the formula[22]:

$$888\text{Degree of Conversion} = 1 - \left(\frac{\text{Area}_{1638}/\text{Area}_{1608}\ \text{polymerized}}{\text{Area}_{1638}/\text{Area}_{1608}\ \text{unpolymerized}}\right)$$

The statistical power of the experimental design was analyzed. With a sample size of 5 specimens from each material × thickness combination, the study was designed to have 80% power to detect a translucency difference of 1.6 between any 2 groups, assuming 2-sided tests, a nonsignificant interaction between group and thickness, and a within-group standard deviation of 2.0 based on pilot data (α=.05). Normality was checked using stem-and-leaf plots of the residuals. Translucency and degree of conversion were compared using 2-way ANOVA with the group, thickness, and interaction as factors in the models (α=.05).

RESULTS

The ANOVA table for all analysis is provided in Table 2. In specimens of all thicknesses, the translucency parameter values followed a trend of e.max CAD > Luxisse > Zirlux > CAP FZ > CAP QZ. The translucency parameter decreased with increasing thickness in all 5 material groups. All anatomic-contour zirconia had lower translucency parameters than e.max CAD (P<.001) (Table 3). In transmitted light intensity, the trend showed e.max CAD > CAP FZ > CAP QZ > Zirlux and Luxisse. Transmitted light intensity decreased with increasing thickness in all 5 material groups. All anatomic-contour zirconia had lower transmitted light intensity than e.max CAD (P<.001) (Table 4). Transmittance (T) of all specimens followed the same trend as transmitted light intensity (Table 5). Significant differences were found in the transmittance among the 3 anatomic-contour zirconias, with the generic shade CAP FZ showing a transmittance more than twice the values for the A2 shade Zirlux and Lusisse. The traditional zirconia (CAP QZ) showed a higher transmittance compared with the 2 anatomic-contour zirconias (Zirlux and Luxisse) (P<.001). The regression analysis of transmittance and specimen thickness showed a linear relation between ln(T) and specimen thickness (Fig. 2).

The derived absorption coefficient and the calculated reflectance of each material are shown in Table 6. The absorption coefficient of e.max CAD was similar to the data reported by Pereira et al.[23] Plotting the transmittance against the translucency parameter demonstrated a linear relationship between the 2 parameters (Fig. 3). The data were found to separate into 2 groups. All A2 shade specimens (e.max CAD, Zirlux, and Luxisse) were approximately on the same line, while the 2 generic shade zirconia (CAP FZ and CAP QZ) plotted on another line. The results from the degree of conversion of resin cement after polymerization through 1- to 2-mm thick specimens showed a significantly higher degree of conversion in the e.max group compared with all other groups ($P<.001$) (Table 7).

DISCUSSION

Based on the results of the study, the null hypothesis was rejected. The translucency parameters of anatomic-contour zirconia were significantly lower than that of e.max CAD. The translucency parameter values for e.max CAD in this study was about 12.44 at 1-mm ceramic thickness, similar to the results reported by Oh et al.[24] The results confirmed that the translucency parameter of e.max CAD is closer to that of the natural tooth[25] compared with the traditional zirconia (CAP QZ) and similar to the finding reported by Haffernan et al.[14] In the present study, the anatomic-contour zirconias (CAP FZ, Zirlux, and Luxisse) had higher translucency parameter values than the traditional zirconia (CAP QZ). The difference was assumed to be the result of the varying amounts of crystal, the size of particles, and the porosity of these materials.

In the present study, e.max CAD had a transmittance of 37.9% at 1-mm thickness and 20.4% at 2-mm thickness, similar to previous studies.[26-28] An increase in thickness has been reported to lead to an exponential decrease in the transmitted light intensity and transmittance beneath ceramic specimens.[29] The exponential decrease was also demonstrated in the present study, and a classical transmittance-thickness equation was further used to derive the absorption coefficient and the reflectance of the materials.[21]

Significant differences were found in the transmittance among the 3 anatomic-contour zirconias (Table 5). A potential reason for the differences was because of the material shades. Comparing CAP FZ to Zirlux and Luxisse, a dramatic decrease in transmitted light intensity was seen in the A2 shade of Zirlux and Luxisse, although these 2 materials show the same range of translucency parameters compared with generic shade CAP FZ (Fig. 3). The results indicated that the material shade might explain the low transmission in Zirlux and Luxisse anatomic-contour zirconias. Comparing e.max CAD to CAP FZ, while e.max CAD showed a much higher translucency parameter, both materials had a similar level of transmittance. The results suggested that, though both materials allowed a similar level of light transmission to polymerize the resin cement, CAP FZ provided more masking of the underlying abutment or tooth structure because of its low translucency parameter. Additionally, e.max CAD allowed more color from underneath the material to show through.

The results of the present study demonstrated a linear correlation between the translucency parameter and transmittance, 2 different parameters. The translucency parameter is related to the differences in the reflectance of light through the medium lying against white and black backgrounds. Transmittance is related to the attenuation of light after it passes through and exits the medium, a process that involves reflectance, internal scattering, and absorption. The strongly shade-dependent relationship was demonstrated in this study by using 2 classes of entirely different material of A2 shade e.max CAD and the A2 shade anatomic-contour zirconias of Zirlux and Luxisse. The trend lines of CAP QZ and CAP FZ in a generic shade were different than those from the A2 shade materials. This relationship will be further investigated with materials of wider range of shade.

The polymerization in the present study was conducted by using 1071 mW/cm^2 for 40 seconds, and only the photopolymerizable portion of the resin cement was investigated. The main purpose of only using the photopolymerizable portion was to demonstrate the effects of the translucency parameter and transmittance to the degree of conversion without the influences of setting time and the effect of a catalyst. The degree of conversion for e.max CAD was similar to that reported by Flury et al.[26] The combined effects of layer thickness and transmitted light intensity in A2 shade anatomic-contour zirconia (Zirlux and Luxisse) resulted in a lower degree of conversion in resin cement when compared with a generic shade anatomic-contour zirconia (CAP FZ) at layer thicknesses of 1.75 and 2 mm.

Limitations of the present study included that only 2 shades were studied. Whether the findings apply to other shades will be investigated in the future.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The type of ceramic, shade of the ceramic, and its thickness affected the translucency parameter and the transmitted light intensity of the ceramic material investigated.
2. The combined effects of layer thickness and the intensity of the transmitted light in A2 shade anatomic-contour zirconia (Zirlux and Luxisse) resulted in a lower degree of conversion in resin cement when compared with a generic shade anatomic-contour zirconia (CAP FZ) at layer thicknesses of 1.75 and 2 mm.
3. An equation based on the natural log of transmittance and specimen thickness was

introduced in this project to derive the absorption coefficient and reflectance of the CAD-CAM ceramic materials. The plot between the translucency parameter and transmittance demonstrated that anatomic-contour zirconia materials have similar translucency parameter value yet are significantly different in their transmittance.

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TABLES

Table 1. Material used in study

Brands (Manufacturers)	Group	Shade
IPS e.max CAD (Ivoclar Vivadent AG)	Lithium Disilicate	HT A2
CAP QZ (Custom Automated Prosthetics)	Traditional Zirconia	Generic shade
CAP FZ (Custom Automated Prosthetics)	Anatomical-contour zirconia	Generic shade
Zirlux (Ardent Inc)	Anatomical-contour zirconia	U3 (A2)
Luxisse (Heany Industries)	Anatomical-contour zirconia	A2

Table 2. ANOVA tables for degree of conversion, translucency parameter, and transmitted light intensity

	Effect	Num. df	Den. df	F Statistic	*P*
Degree of Conversion	Material	5	120	1354	<.001
	Thickness	4	120	2996	<.001
	Material×Thickness	20	120	3477	<.001
Translucency Parameter	Material	5	120	5733	<.001
	Thickness	4	120	372	<.001
	Material×Thickness	20	120	123	<.001
Transmitted Light Intensity	Material	5	108	5121	<.001
	Thickness	4	108	1364	<.001
	Material×Thickness	17	108	82	<.001

Den. df=Denominator degrees of freedom; Num. df, Numerator degrees of freedom.

Table 3. Translucency parameter of each material at different thicknesses (mean ±standard deviation)

Thickness (mm)	1	1.25	1.5	1.75	2
e.max CAD	12.44 ±0.06 ^{a,A}	11.24 ±0.53 ^{a,B}	9.72 ±0.08 ^{a,C}	8.67 ±0.02 ^{a,D}	7.85 ±0.26 ^{a,E}
CAP QZ	0.86 ±0.05 ^{e,A}	0.65 ±0.03 ^{e,B}	0.45 ±0.02 ^{e,C}	0.42 ±0.05 ^{e,C}	0.29 ±0.05 ^{e,D}
CAP FZ	4.14 ±0.30 ^{d,A}	3.54 ±0.24 ^{d,A}	2.24 ±0.10 ^{d,B}	1.78 ±0.13 ^{d,C}	1.44 ±0.07 ^{d,D}
Zirlux	5.37 ±0.87 ^{c,A}	4.37 ±0.35 ^{c,B}	3.06 ±0.53 ^{c,C}	2.75 ±0.76 ^{c,C}	2.03 ±0.32 ^{c,D}
Luxisse	5.84 ±0.09 ^{b,A}	4.98 ±0.06 ^{b,B}	3.90 ±0.06 ^{b,C}	3.58 ±0.14 ^{b,D}	2.62 ±0.02 ^{b,E}

Similar superscript letters indicate no statistically significant difference ($P>.05$); lowercase letters for within same thickness group comparison and uppercase letters for within same material group comparison.

Table 4. Transmitted light intensity (mW/cm^2) in each material at different thicknesses (mean ±standard deviation)

Thickness (mm)	1	1.25	1.5	1.75	2
E.max CAD	405.9 ±6.9 ^{a,A}	351.8 ±3.4 ^{a,B}	292.4 ±2.6 ^{a,C}	266.3 ±5.2 ^{a,D}	218.3 ±5.0 ^{a,E}
CAP QZ	189.8 ±5.8 ^{c,A}	156.7 ±3.8 ^{c,B}	111.0 ±3.5 ^{c,C}	92.1 ±2.3 ^{c,D}	64.6 ±1.6 ^{c,E}
CAP FZ	363.8 ±7.2 ^{b,A}	312.5 ±1.1 ^{b,B}	240.0 ±6.4 ^{b,C}	194.4 ±2.6 ^{b,D}	160.9 ±3.4 ^{b,E}
Zirlux	146.4 ±2.6 ^{d,A}	93.8 ±2.0 ^{d,B}	60.8 ±1.1 ^{d,C}	43.6 ±1.2 ^{d,D}	26.6 ±0.5 ^{d,E}
Luxisse	137.9 ±3.0 ^{e,A}	93.3 ±0.6 ^{d,B}	64.1 ±1.5 ^{d,C}	46.0 ±0.5 ^{d,D}	28.0 ±0.7 ^{d,E}

Similar superscript letters indicate no statistically significant difference ($P>.05$); lowercase letters for within same thickness group comparison and uppercase letters for within same material group comparison.

Table 5. Transmittance (%) in each material at different thicknesses (mean ±standard deviation)

Thickness (mm)	1	1.25	1.5	1.75	2
E.max CAD	37.9 ±1.4 ^{a,A}	32.8 ±0.7 ^{a,B}	27.3 ±0.5 ^{a,C}	24.9 ±1.1 ^{a,D}	20.4 ±1.0 ^{a,E}
CAP QZ	17.7 ±1.2 ^{c,A}	14.6 ±0.8 ^{c,B}	10.4 ±0.7 ^{c,C}	8.6 ±0.5 ^{c,D}	6.0 ±0.3 ^{c,E}
CAP FZ	34.0 ±1.5 ^{b,A}	29.2 ±0.2 ^{b,B}	22.6 ±1.5 ^{b,C}	18.8 ±1.5 ^{b,D}	15.0 ±0.7 ^{b,E}
Zirlux	13.7 ±0.6 ^{d,A}	8.8 ±0.4 ^{d,B}	5.7 ±0.2 ^{d,C}	4.1 ±0.3 ^{d,D}	2.5 ±0.1 ^{d,E}
Luxisse	12.9 ±0.6 ^{e,A}	8.8 ±0.1 ^{d,B}	6.0 ±0.3 ^{d,C}	4.3 ±0.1 ^{d,D}	2.6 ±0.1 ^{d,E}

Similar superscript letters indicate no statistically significant difference ($P>.05$); lowercase letters for within same thickness group comparison and uppercase letters for within same material group comparison.

Table 6. Coefficient of absorption and reflectance for each material

	Coefficient of Absorption (mm^{-1})	Reflectance
e.max CAD	0.63	0.15
CAP QZ	1.04	0.29
CAP FZ	0.85	0.11
Zirlux	1.60	0.18
Luxisse	1.55	0.22

Table 7. Degree of conversion (%) of each material at different thicknesses. (mean ±standard deviation)

Thickness (mm)	1	1.25	1.5	1.75	2
e.max CAD	60.95 ±0.20 ^{a,A}	59.99 ±0.23 ^{a,B}	58.21 ±0.16 ^{a,C}	57.30 ±0.31 ^{a,D}	55.12 ±0.26 ^{a,E}
CAP QZ	52.74 ±0.33 ^{d,A,B}	53.11 ±0.12 ^{d,A}	52.05 ±0.31 ^{d,B,C}	51.48 ±0.25 ^{d,C,D}	51.10 ±0.24 ^{e,D}
CAP FZ	59.20 ±0.06 ^{b,A}	57.59 ±0.42 ^{bc,B}	56.68 ±0.27 ^{b,B,C}	56.30 ±0.08 ^{b,C}	56.55 ±0.29 ^{b,C}
Zirlux	57.95 ±0.39 ^{c,A}	56.82 ±0.16 ^{c,B}	56.90 ±0.24 ^{b,B}	51.94 ±0.34 ^{d,C}	52.23 ±0.14 ^{d,C}
Luxisse	58.85 ±0.18 ^{b,A}	57.26 ±0.07 ^{b,B}	56.58 ±0.11 ^{b,C}	54.93 ±0.08 ^{c,D}	53.90 ±0.04 ^{c,E}

Similar superscript letters indicate no statistically significant difference ($P>.05$); lowercase letters for within same thickness group comparison and uppercase letters for within same material group comparison.

FIGURES

Figure 1. Experimental design.

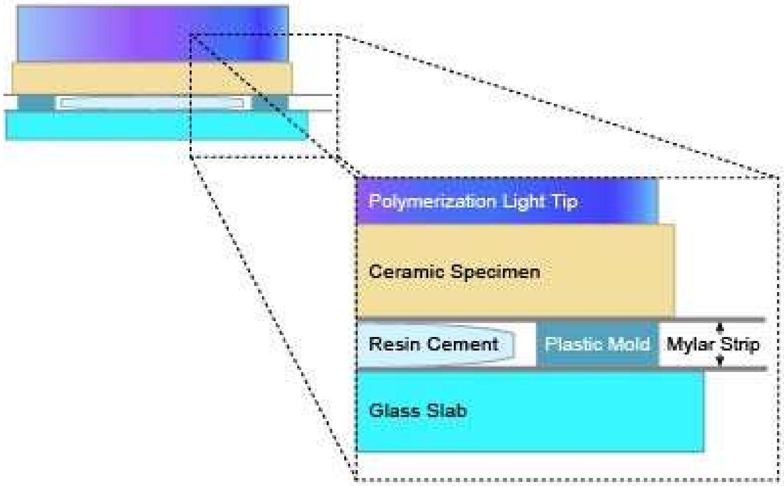

Figure 2. ln(T) of each material at each thickness.

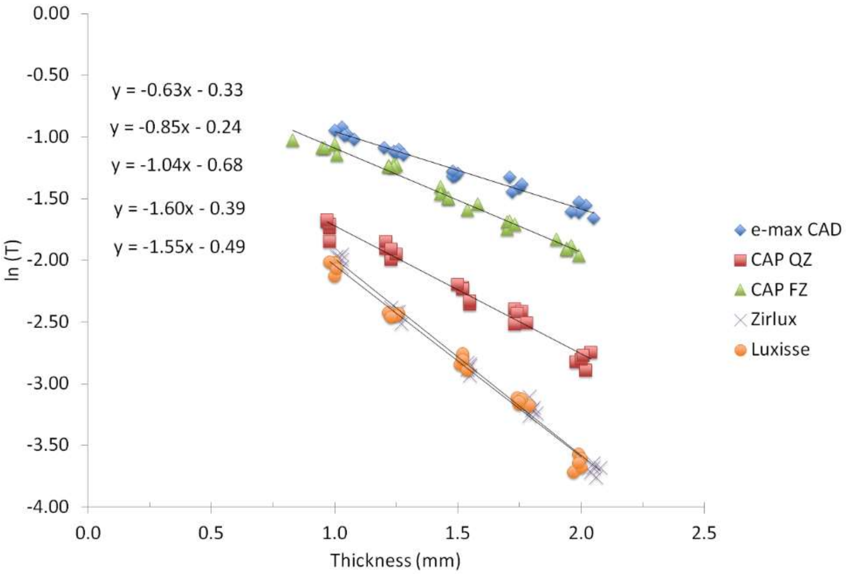

Figure 3. Relationship between translucency parameter and transmittance.