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## RESEARCH ARTICLE OPEN ACCESS

# The Effect of Cement Shade on the Optical Properties of Additively Manufactured Permanent Crown Materials

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## ABSTRACT

**Objectives:** To investigate the effect of cement shade and printing parameters on the optical properties of additively manufactured (AM) permanent crown materials.

**Methods:** Two AM crown materials (Bego VarseoSmile Crown Plus and Formlabs Permanent Crown) and one conventional milled material were tested ( $n = 560$ ). Dimensions for each specimen measured  $10 \times 10$  mm and were categorized by thickness (1 and 2 mm). AM materials were additively manufactured (3D-printed) at three orientations:  $0^\circ$ ,  $45^\circ$  and  $90^\circ$ . Specimens were cemented with four shades of dual-cure cement: light, neutral, warm, and translucent. Color change ( $\Delta E$ ) and translucency parameter (TP) measurements were calculated utilizing a spectrophotometer, VITA EasyShade V. Data was analyzed with a two-way ANOVA and Tukey's post hoc tests.

**Results:** Neutral cement shade exhibited the lowest  $\Delta E$  overall ( $2.30 \pm 0.43$ ). Translucent cement shade exhibited the least color difference between materials. Milled materials generally exhibited higher  $\Delta E$  ( $5.57 \pm 0.26$ – $7.17 \pm 0.33$ ) than AM materials. Material thickness significantly affected the  $\Delta E$  across all shades of cement ( $p < 0.05$ ).  $45^\circ$  print orientation for 2 mm thick specimens exhibited the greatest clinically acceptable  $\Delta E$ .

**Conclusion:** Cement shade may cause clinically unacceptable color changes based on material choice and 3D-printing parameters. Clinicians providing permanent AM crowns must consider the impact of cement shade and printing parameters on aesthetic outcomes.

## 1 | Introduction

Indirect dental restorations are presently manufactured through various techniques, however, a shift of focus from traditional workflows to digital technologies has seen rapid development in the past 20 years [1, 2]. Digital technologies largely utilize computer-aided manufacturing (CAM), which can be further divided into subtractive manufacturing (SM) and additive manufacturing (AM) [3]. AM is becoming the fast-growing alternative for the more common SM in dentistry, due to its increased benefits including reduced material wastage, low

manufacturing costs, and faster production times. AM can also produce complex geometries with higher precision compared to SM technology, whilst maintaining the ability to produce same-day dental prostheses [3–6]. The concurrent advancement of AM resin materials has emphasized transitioning from temporary, or interim resin, to permanent resin materials with adequate mechanical properties to withstand the oral environment [2, 5]. Permanent crowns which are manufactured through AM technologies, are clinically accepted in practice, however, are largely under-studied due to their recent development, meaning they are often not the first choice for indirect restorations [1, 5].

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For the few *in vitro* studies that have been conducted on permanent resin crown materials, the main areas of investigation are assessments of mechanical properties, including flexural and compressive strength, accuracy, precision and biocompatibility [5, 7, 8]. While mechanical properties are important for the longevity of the restoration, even fewer studies have investigated factors that may influence optical properties [9, 10]. Optical properties in *in vivo* and *in vitro* dental studies commonly reference the investigation of color difference and translucency [11]. As reported in SM dental restorations, aesthetics and optical properties may be compromised or enhanced by various factors including, but not limited to, tooth/substrate color, design parameters, and more recently, the choice of cement shade [12].

Dental cement is a necessary material for bonding an indirect restoration to the underlying natural tooth structure [13]. There are a range of dental cements on the market for clinicians to use when cementing fixed prostheses [13]. The increasing aesthetic expectation from patients is one of the major challenges that modern dentistry must adapt to [9, 12]. This can be especially difficult to satisfy, as slight differences in color, translucency or texture are extremely perceptible to the human eye. To further enhance and match an indirect restoration to the natural dentition, a range of opaque and translucent resin cements with different degrees of chroma have been developed [13]. Opaque cements are intended to mask an unfavorable, underlying tooth or substructure appearance by lightening or darkening the final restorative color, to more closely match the adjacent dentition [14]. This contrasts the purpose of translucent or neutral cements which are designed to preserve favorable tooth color by allowing greater light transmission through the material to the underlying tooth [14]. Recent studies on SM materials have suggested that the choice of cement shade can have a significant impact on the final restorative color [8, 15]. It was also noted that the parameters of the indirect restoration can affect the degree of influence from the shade of cement. While companies have provided broad indications for the use of different shades of cement, there is currently no guideline as to when each cement shade should be implemented, relative to the choice of restorative material or design parameters. This can create difficulties for clinicians to achieve the best aesthetic outcome for the patient.

The manufacturing process between AM and SM is vastly different. Even between AM technologies, such as stereolithography (SLA) and digital light processing (DLP), the curing process between the layers of the final build differs [3]. No studies are available on the effect of cement shade on AM materials, highlighting a potentially substantial undocumented effect that

needs to be recognized before implementing AM in clinical dentistry. Furthermore, AM requires consideration for additional printing parameters, which do not apply to SM. These include print orientation or angle, support structures and print layer thickness. AM is noted to display anisotropy of a material's mechanical properties, depending on the material composition and design parameters utilized [16]. The effect of this anisotropy may extend also to optical properties, where differences in the multi-layer build orientation may affect the light transmission through an AM material [17]. This can affect the perceived appearance of the restoration to the adjacent dentition [11]. The most external layer of the human tooth, enamel, is naturally semitranslucent and similarly, to AM, multilayered and orientated in such a way that allows for light transmission [9]. Selecting a biomimetic AM print orientation to better match the natural translucency of the adjacent dentition could result in better aesthetic outcomes for the patient [9]. Clinicians should be aware of the effect of print orientation on both mechanical and optical properties to provide clinically appropriate treatment.

An investigation into the effect of cement shade on the optical properties of AM permanent dental materials has yet to be conducted. As the benefits of AM continue to outweigh those of SM the future of AM is fast approaching, and further investigation is required to ensure the uptake of this technology [3–6]. Therefore, this study aimed to measure the effect of cement shade on the optical properties of AM permanent crown materials in terms of color change and translucency. The hypothesis was that there will be a significant difference in the optical properties between crown materials when cemented with different shades. The specified printing parameters will also significantly affect the measured optical properties.

## 2 | Materials and Methods

### 2.1 | Materials Investigated

Two permanent resin crown materials were additively manufactured utilizing different AM technologies. This included the Asiga 3D printer using Digital Light Processing (DLP) technology and FormLabs 3D printer using Stereolithography (SLA) technology. The two permanent crown materials, Bego VarseoSmile Crown Plus and FormLabs Permanent Crown were compared to the subtractive manufactured control Ivoclar PM7 (milled crown materials). Details of the materials used is listed in Table 1. Four different shades of dual-cure resin cement were used, these were Light, Neutral and Warm from Ivoclar:

**TABLE 1** | CAM crown materials investigated.

Manufacturing method	Product name	Composition
Subtractive manufacturing (milling)	Ivotion PMMA (HT) Ivoclar PM7 A2	Polymethylmethacrylate
Additive manufacturing (SLA)	Formlab (FL) Permanent Crown A2	Diphenyl (2,4,6 – trimethylbenzoyl) phosphine oxide))
Additive manufacturing (DLP)	Bego Varseo Smile Crown Plus A2 (BG)	Esterification products of 4,4; isopropylidenediphenol, ethoxylated and 2- methylprop—2- enoic acid

Variolink Aesthetic and Translucent from Pulpdent ACTIVA. The selected shade for all crown materials was A2 Dentin according to the VITA classical shade system for standardization. AM materials had a controlled print layer thickness of 50µm.

## 2.2 | Specimen Groups

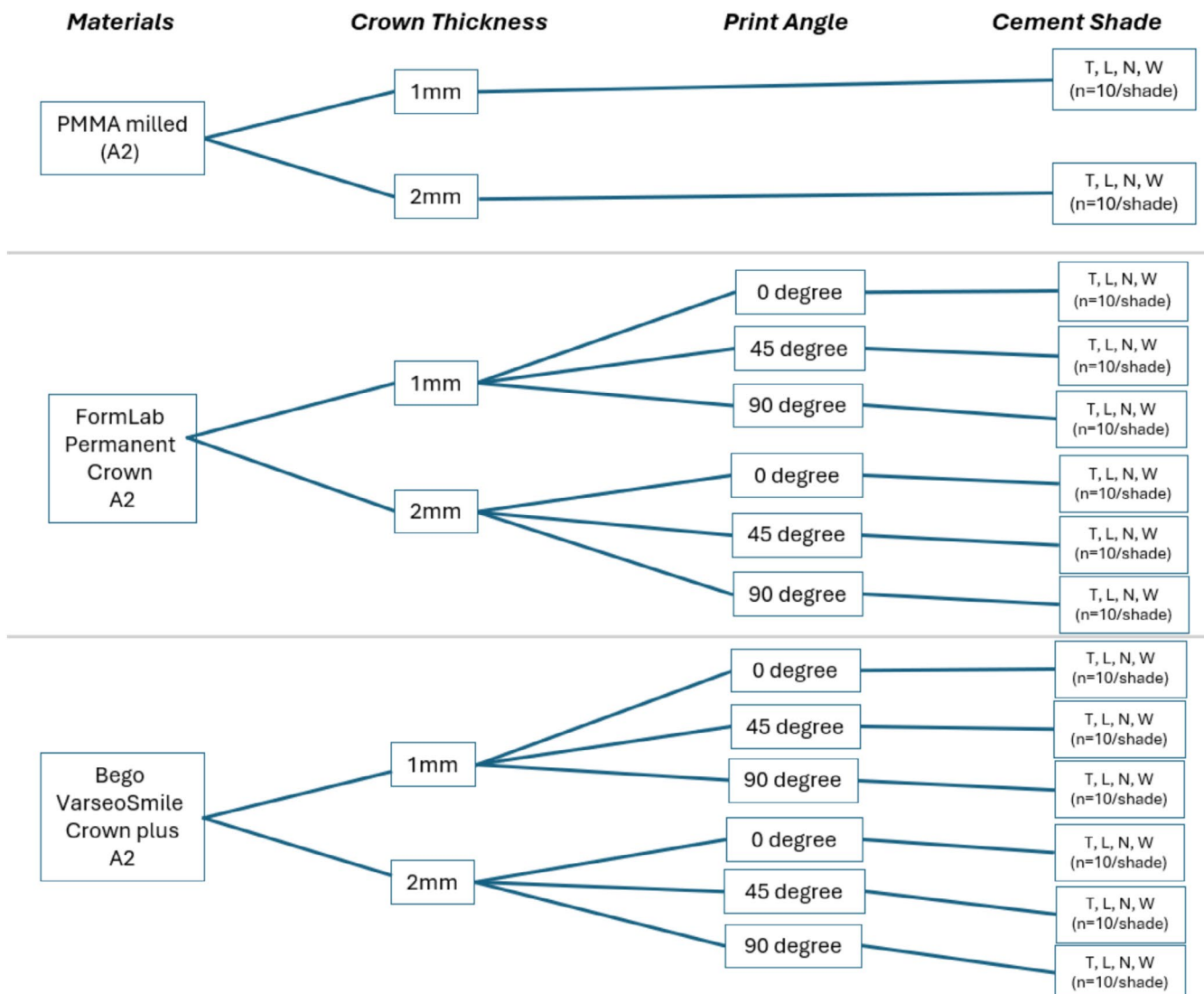
A sample size calculation was performed based on previous experiments of similar nature and outcomes using the software G\*power v3.0.10 (Heinrich-Heine-Universität Düsseldorf). The effect size ( $d_z = 4.9706$ ) and the required sample size were calculated for  $\alpha = 0.05$  and a power of 0.95 ( $1 - \beta$  err prob), assuming a normal distribution. The calculation showed that a minimum of 8 specimens per group was required. The current study had 10 specimens per group ( $n = 10/\text{cement shade}$ ) to ensure the statistical significance of the results. A total of  $n = 560$  specimens were investigated in this study. Specimens were divided by material, crown thickness, print angle and cement shade (Figure 1). Specimen dimensions were  $10 \times 10$  mm to ensure an adequate surface area for testing. Two groups of thickness were

investigated, 1 and 2 mm. Additively manufactured materials were produced at three print orientations: 0 degrees, 45 degrees and 90 degrees.

For this study, groups have been abbreviated to IM (Ivotion milled specimens), FL (FormLab specimens), and BG (Bego specimens). FL and BG will be further defined by print orientation (build angle) as, FL 0°, FL 45°, FL 90°, BG 0°, BG 45°, and BG 90°.

## 2.3 | Specimen Preparation

After specimens were manufactured according to the prior dimensions stated, they were processed post-printing according to manufacturer guidelines. For both materials (FL and BG), this involves post-process washing in an ethanol solution (95%) for 5 min and then post-cured to remove residual monomers and promote polymerization. The specimens were post-cured under vacuum and nitrogen to avoid oxygen inhibition layer forming. All specimens were sequentially polished with



**FIGURE 1** | A flowchart showing the different experiment groups divided by crown material, crown thickness, print angle/orientation and cement shade.

500 and 1200-grit silicon carbide paper (Struers, Denmark) and with the consistent amount of water and pressure. This was to mimic clinical finishing and polishing and to provide an adequate flat surface area for testing the optical properties later. Accepted thickness parameters post-polishing were  $1 \pm 0.04$  mm and  $2 \pm 0.04$  mm. All specimens were measured with a digital caliper and any specimens with the thickness outside the acceptable threshold were not included in the study.

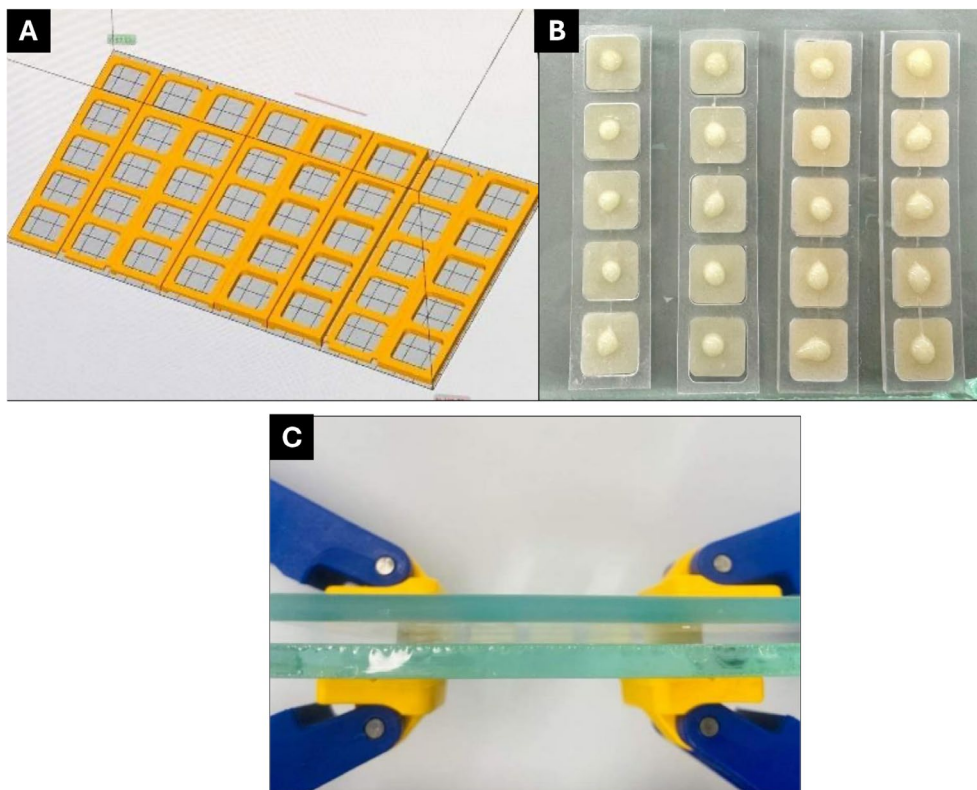
## 2.4 | Cementation of Specimens

Prepared specimens were randomly selected  $n=6$ /group for initial reference measurements on white and black backgrounds for later comparison. These were measured by placing two prepared specimens on top of each other so that there were three reference specimens per group.  $L^* a^* b^*$  coordinates were measured using a spectrophotometer (Spectrophotometer Easyshade V, VITA Zahnfabrik, BadSackingen, Germany). Each reference group was measured three times, for accuracy and all values were averaged. The spectrophotometer was calibrated before each measurement. Specimens were cemented with four different dual cure resin cement shades (Light, Neutral, Warm and Translucent) ( $n=10$ /group). The cement layer thickness was standardized to  $100 \mu\text{m}$  (0.1 mm) with clear customized designed jigs (Figure 2). Jigs were first placed on a glass slide. Control SMed and AMed specimens were fitted within the hollow structure of the jigs measuring  $10 \times 10$  mm. Dual-cured resin cement was placed directly onto the specimens. Another glass slide was placed on top of the jigs and both slides were brought together

with clamps to ensure the specimens lie flush to the height of the jig (Figure 2). Cement was able to flow into the  $100 \mu\text{m}$  space provided by the design thickness of the jigs (1.1 and 2.1 mm). The Bluephase PowerCure curing light (Ivoclar Vivadent, Germany) was used for 40 s to cure the cement through the crown material. Specimens were then stored away from direct light and were measured 24h later for color change and translucency.

## 2.5 | Measurement of Color Change and Translucency Parameter

The color and translucency of each specimen were determined with the spectrophotometer (Spectrophotometer Easyshade V, VITA Zahnfabrik, BadSackingen, Germany) according to the Commission Internationale de l'Eclairage (CIE)  $L^* a^* b^*$  system. Variables measured were  $L^* a^* b^*$  values, where  $L^*$  = brightness,  $a^*$  = chroma along the red-green axis and  $b^*$  = chroma along the yellow- blue axis [18]. These values were recorded to measure color difference using the CIELab formula and translucency using the translucency parameter formula [19]. The color change was calculated between reference measurements taken prior to cementation and specimens 24 h post-cementation. Translucency was directly compared between specimen groups 24 h post-cementation. For all color and translucency readouts, test specimens were blotted dry with absorbent paper and placed on a standard white background and black background (Leneta Form 2A), in accordance with the ISO/TR Z8642:Z016(E). The spectrophotometer was calibrated before each measurement according to the manufacturer's instructions. All measurements were repeated three



**FIGURE 2** | Images showing the design of jigs (A); CAM specimens placed within jig with consistent amount of cement placed (B); Clamps are used to ensure the standardized thickness of cement by ensuring specimens and cement are flush with the height of the jig (C).

times on each specimen and results were averaged. The light condition was standardized by measuring all specimens in a lightbox that shields the contact cap of the spectrophotometer from external light sources. Color change ( $\Delta E_{ab}$ ) was calculated using the following formula:

Equation (1) CIELab formula [18].

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

Where  $\Delta L^* = L \times \text{final} - L \times \text{initial}$ ,  $\Delta a^* = a \times \text{final} - a \times \text{initial}$  and  $\Delta b^* = b \times \text{final} - b \times \text{initial}$ . Initial variable measurements were derived from reference specimens measured on a white background. Final variable measurements were derived from cemented specimens post 24h on a white background. Values of  $\Delta E \leq 2.7$  were considered clinically unacceptable [18].

Translucency was calculated using the following formula:

Equation (2) Translucency Parameter Formula [19].

$$TP = \sqrt{\left[ (L_B^* - L_w^*)^2 + (a_B^* - a_w^*)^2 + (b_B^* - b_w^*)^2 \right]} \quad (2)$$

Where subscript “w” refers to the  $L^*$ ,  $a^*$  and  $b^*$  values for the specimen over the white background. Subscript “B” refers to the  $L^*$ ,  $a^*$  and  $b^*$  values for the same specimen over the black background. Translucency parameter was directly compared between groups based on cement shade, material thickness and print orientation angle.

## 2.6 | Statistical Analysis

A statistical software program (PRISM Version 10 GraphPad) was used. All data was statistically analyzed with a two-way analysis of variance (ANOVA) and Tukey’s Post hoc test. The significance level was set at  $p < 0.05$ .

## 3 | Results

### 3.1 | Color Difference ( $\Delta E$ )

A summary of the mean  $\Delta E$  and standard deviation and mean TP for 1mm specimens and 2mm specimens is given in Tables 2 and 3, respectively. Values of  $\Delta E > 2.7$  were considered clinically unacceptable. Overall, statistically significant color differences were found between conventionally milled and both AM materials ( $p < 0.05$ ). Milled specimens exhibited greater color changes than AM materials across all shades of cement, with some exceptions when specimens were 1 mm thick.

With increasing thickness of the specimen materials from 1 to 2 mm, the  $\Delta E$  measured was generally reduced as shown in Figure 3. When comparing  $\Delta E$  between 1 and 2 mm thick SM materials, those cemented with translucent, neutral and warm were not statistically significant ( $p > 0.05$ ). Only the light cement shade had a statistically significant effect between the different thicknesses for SM  $\Delta E$  measurements,  $\Delta E$

TABLE 2 | Mean ( $\pm$  Standard Deviation) of color difference  $\Delta E$  and mean of translucency parameter (TP) in 1 mm thick specimens.

	IM		FL0		FL45		FL90		BG0		BG45		BG90	
	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP
Translucent	5.73 $\pm$ 0.35	21.20	4.88 $\pm$ 0.78	16.07	5.5 $\pm$ 1.26	18.21	5.46 $\pm$ 0.52	17.96	6.21 $\pm$ 0.71	18.61	4.29 $\pm$ 0.67	17.63	4.33 $\pm$ 1.92	16.56
Light	7.17 $\pm$ 0.33	22.18	3.83 $\pm$ 2.19	17.05	4.49 $\pm$ 1.21	17.05	6.06 $\pm$ 1.07	18.04	5.92 $\pm$ 0.33	19.77	5.25 $\pm$ 0.70	17.85	5.64 $\pm$ 2.07	17.56
Neutral	6.41 $\pm$ 0.24	21.72	4.72 $\pm$ 1.30	16.87	4.12 $\pm$ 0.89	17.52	4.64 $\pm$ 0.87	17.98	5.05 $\pm$ 0.95	19.51	4.7 $\pm$ 0.98	18.08	3.16 $\pm$ 1.79	17.10
Warm	5.93 $\pm$ 0.24	22.46	4.8 $\pm$ 0.80	16.69	4.57 $\pm$ 0.81	17.25	6.21 $\pm$ 0.71	18.29	5.07 $\pm$ 0.61	19.43	4.52 $\pm$ 0.86	17.50	3.64 $\pm$ 0.90	16.73

**TABLE 3** | Mean ( $\pm$  Standard Deviation) of color difference  $\Delta E$  and mean of translucency parameter (TP) in 2mm thick specimens.

	IIM		FL 0		FL 45		FL 90		BG 0		BG 45		BG 90	
	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP	$\Delta E$	TP
Translucent	6.13 $\pm$ 0.34	12.56	2.94 $\pm$ 0.98	7.48	2.86 $\pm$ 0.51	7.69	2.35 $\pm$ 0.49	7.61	3.09 $\pm$ 0.51	8.43	2.88 $\pm$ 0.45	8.50	3.92 $\pm$ 1.4	7.20
Light	5.95 $\pm$ 0.24	12.15	3.23 $\pm$ 0.86	7.10	2.64 $\pm$ 0.54	7.38	3.25 $\pm$ 0.60	7.54	2.84 $\pm$ 0.41	8.29	2.54 $\pm$ 0.48	7.99	4.85 $\pm$ 1.22	7.39
Neutral	5.94 $\pm$ 0.29	12.45	3.08 $\pm$ 0.96	7.11	2.71 $\pm$ 0.89	7.67	2.30 $\pm$ 0.43	7.63	2.34 $\pm$ 0.38	8.29	2.34 $\pm$ 0.42	8.37	3.54 $\pm$ 1.36	7.49
Warm	5.57 $\pm$ 0.26	11.93	3.25 $\pm$ 0.44	7.15	2.68 $\pm$ 0.51	7.42	3.50 $\pm$ 0.55	7.74	3.34 $\pm$ 0.59	8.20	2.45 $\pm$ 0.44	8.29	4.43 $\pm$ 1.01	7.27

at 1 mm =  $7.17 \pm 0.33$ ,  $\Delta E$  at 2 mm =  $5.95 \pm 0.24$  ( $p < 0.05$ ). For AM materials when comparing 1 and 2 mm thickness at the same print orientation all measurements of  $\Delta E$  were statistically significant ( $p < 0.05$ ) except for the following outliers: BG 90° (translucent cement), FL 0° (light cement) and BG 90° (neutral cement) ( $p > 0.05$ ).

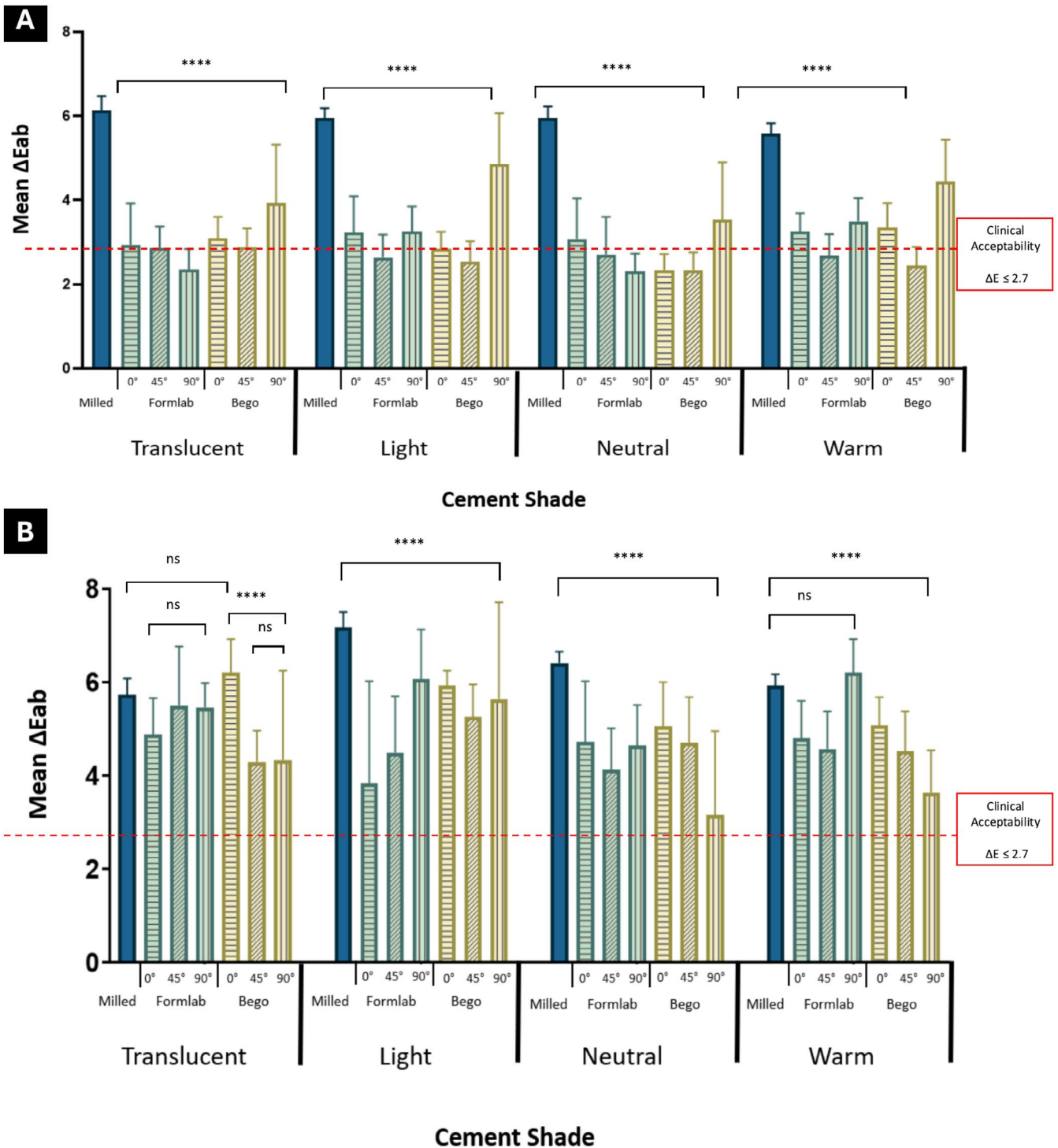
Translucent cement showed the least color change between all material groups at both thicknesses (Tables 2 and 3). At 1 mm thick, when cemented with a translucent shade, milled specimens had no significant color difference compared with FL 45°, FL 90° and BG 0° ( $p > 0.05$ ). There was only a weak significance when the milled translucent group was compared with FL 0° ( $p = 0.03$ ). This contrasts all other groups based on cement shade, where statistical significance was exhibited between AM and SM across light, neutral and warm cement shades ( $p < 0.001$ ). Only one outlier exists where SM versus FL 90° cemented with warm shade was not statistically significant ( $p > 0.05$ ). Comparing the shades of cement for 2 mm thick specimens, the least color difference between all AM specimens was observed in the translucent and neutral cement shades. Warm cement shade had the greatest difference of  $\Delta E$  values between AM materials at 2 mm thickness.

Statistically significant color differences were generally noted for the opposing print orientations (0 vs. 90 degrees) for both Formlab and Bego material at 1 and 2 mm thickness ( $p < 0.05$ ). For 1 mm specimens, this significance was noted in translucent cement shade between BG 0° versus 90°, light cement shade between FL 0° versus 90°, neutral cement shade between BG 0° versus 90°, and warm cement shade between FL 0° versus 90° and BG 0° versus 90° ( $p < 0.05$ ). For 2 mm thick specimens, this difference was noted between translucent cement shade, both FL and BG 0° versus 90°. Light cement shade BG 0° versus 90°, neutral cement shade, both FL and BG 0° versus 90°, and warm cement shade BG 0° versus 90°.

The group with the greatest overall color difference was the milled 1 mm thick specimens cemented with light shade ( $\Delta E = 7.17$ ). The least color change ( $\Delta E = 2.30$ ) was found in the 2 mm thick 90-degree FormLabs group cemented with a neutral shade. According to the clinical acceptability threshold ( $\Delta E \leq 2.7$ ), all 1 mm thick specimens displayed clinically unacceptable color differences. A summary of the groups at 2 mm thickness that were considered to have clinically acceptable  $\Delta E$  is provided in Table 4. Due to the nature of acceptability thresholds, 'borderline' clinical acceptability was considered and is defined as  $\Delta E \leq 2.9$  within this study. Overall, across the thickness, print orientation and material, the highest to lowest  $\Delta E$  values were found in, light > warm > translucent > neutral.

### 3.2 | Translucency Parameter

The mean and standard deviation of TP for each group are presented in Tables 2 and 3. Overall, there were no statistically significant differences in TP measured between all materials, print orientations and cement shades ( $p > 0.05$ ). 1mm thick specimens exhibit higher, but not significant, values of translucency than 2 mm thick specimens ( $p > 0.05$ ). Translucency was notably higher in SM specimens across all cement shades at both



**FIGURE 3** | The mean color difference of all specimens in this study with clinically acceptable threshold and level of significance (A) 1 mm specimen group; (B) 2 mm specimen group.

thicknesses however was statistically significant in difference. For 1 mm thick specimens, when comparing print orientation for AM materials, BG 0° material displayed greater but not significantly, higher TP than BG 45° and BG 90°. This contrasts the Formlabs materials, as FL 90° displayed greater but not significantly, higher TP than FL 0° and FL 45°. For 2 mm thick specimens, when comparing print orientation for AM materials, both BG and FL more often had greater TP values for materials printed at 45° however, was not statistically greater compared to other print orientations.

#### 4 | Discussion

Optical properties of dental materials are important for consideration when matching an indirect restoration to the adjacent dentition. Slight differences in color and translucency may be perceptible to the patient, affecting acceptance and therefore, success of the restorative treatment [12]. This study assessed the effect of cement shade on the optical properties of AM permanent crown materials compared to SM materials, depending on thickness and print orientation. According to the results of

**TABLE 4** | Summary of 2 mm specimen groups that showed clinically acceptable  $\Delta E$  (✓ indicates clinical acceptance).

<b>Materials</b>							
<b>cement shade</b>	<b>IM</b>	<b>FL 0</b>	<b>FL 45</b>	<b>FL 90</b>	<b>BG 0</b>	<b>BG 45</b>	<b>BG 90</b>
Translucent	Not acceptable	Not acceptable	Borderline	✓	Not acceptable	Borderline	Not acceptable
Light	Not acceptable	Not acceptable	✓	Not acceptable	Borderline	✓	Not acceptable
Neutral	Not acceptable	Not acceptable	Borderline	✓	✓	✓	Not acceptable
Warm	Not acceptable	Not acceptable	✓	Not acceptable	Not acceptable	✓	Not acceptable

this study, the initial hypothesis, that there will be a significant difference in the optical properties, color difference and translucency, between crown materials when cemented with different shades and when manufactured at different printing parameters, was partially accepted. While statistically significant findings for color difference were influenced by cement shade and manufacturing parameters, the translucency parameter was not significantly influenced by the investigated variables. These findings reinforce the importance of providing clinicians, who wish to use AM technology, insight into how color difference and translucency of AM materials may differ from SM materials.

The results noted between SM and AM materials, indicate that AM may be more favorable in terms of aesthetics compared to conventional SM materials. SM materials had significantly greater  $\Delta E$  than AM materials at both thicknesses across light, neutral and warm cement shades.  $\Delta E$  of all SM materials were clinically unacceptable however, non-significant results between SM and AM materials were noted when cemented with the translucent shade. This suggests that translucent cement may be applied to various material types with minimal color difference between them. Yu et al. (2009) reported that the TP of enamel and dentine respectively is 18.7 and 16.4 [20]. In this study, it was noted that similar TP between enamel, dentine and 1mm AM materials indicating that AM materials may have better biomimetic properties than SM. These differences may be attributed to the variances in composition, as reported in other resin-based dental restorative materials, and the difference in manufacturing technique [17, 21, 22]. Where AM materials are manufactured in a homogenous, multilayer direction, SM materials are produced by removing material from a preformed block. The milling process is thought to remove up to 90% of the initial material [23]. The abrasive effect of this process on the surface topography of the final restoration may result in micro-changes, ultimately affecting the transmittance of light through the material [24, 25]. Whereas the multilayer design of AM materials may result in different transmittance, scattering, reflectance and absorption patterns of light between each print layer [17]. Due to limited information, further investigation should be conducted on the effects of the multilayer design of AM materials, the effect of polishing on the surface roughness, and the interaction of light influencing optical properties, as there is yet to be a clear consensus [25].

The clinical acceptability threshold for the color difference was set to  $\Delta E \leq 2.7$  as recommended when interpreting tooth-colored materials [26]. As a threshold only provides an indication of a mismatch of  $\Delta E$ , considerations were made for specimens that were

on the borderline for clinical acceptability, these were defined as  $\Delta E \leq 2.9$ . All 1 mm specimens in this study displayed clinically unacceptable  $\Delta E$  regardless of cement shade, and material. Previous studies that have investigated the effect of cement shade consistently highlight that there is increased light transmission through thinner materials, which may produce greater color differences, due to increased reflectance of the cement shade [27, 28]. This effect becomes inversely proportional, where an increased thickness of material results in reduced influence of cement shade on color difference. This is due to reduced translucency through the thicker material, thus resulting in a greater masking ability [27, 28]. This was consistent with our results on 2mm thick specimens, where color differences of  $\Delta E \leq 2.7$  were noted and measurements of TP decreased with increasing specimen thickness. Within 2mm thick specimens, only AM materials at certain print orientations displayed clinically acceptable  $\Delta E$  and was found to differ between cement shades. Clinically acceptable  $\Delta E$  was most often measured in specimens printed at 45° for both SLA and DLP technology and neutral cement shade exhibited the lowest differences of  $\Delta E$ . However, as reported in the results there were statistically significant color differences, often noted between a print orientation of 0° and 90°, for both SLA and DLP specimens. In SLA using the Formlabs material, clinically acceptable  $\Delta E$  was reported at 90° but not 0°. In contrast, for DLP using Bego material, clinical acceptability was reported at 0° but not 90°. These differences in  $\Delta E$  between print orientations could be attributed to multiple factors, such as the degree of conversion during the AM process, and surface roughness. The different printers, SLA and DLP employ different methods of curing [3]. A study to assess the degree of conversion across specimens printed at 0°, 45° and 90° using SLA found that greater polymerization occurring closer to the printing platform was higher than at the base [29]. This suggests that different degrees of polymerization may occur between different build orientations, where 0° specimens have a greater surface area on the building platform base and therefore may have a higher degree of conversion on the surface used for measuring TP and  $\Delta E$  in comparison to 45° and 90° in SLA [17, 29]. Surface roughness from polishing in specimen preparation may also cause differences in light and material interaction [25]. Specimens at 0° and 90° often required more polishing than 45° to remove excess resin which can affect the surface microstructure. The exact effect of the degree of conversion and surface roughness from polishing is unknown but may be the cause of the discrepancy between SLA and DLP  $\Delta E$  and TP. Further investigation is required before this can be concluded.

There were various strengths and limitations of this study. Some limitations of this study include a limited choice of materials.

Only one AM material was selected for each type of technology available (SLA and DLP printing). These materials were chosen for their similarity in composition but should not be considered a representative range of the available permanent resin materials. This also extends to the choice of cement shade, the effect of light+, warm+ and white opaque from the Variolink Aesthetic range could not be investigated due to limitations on time and resources. Furthermore, only two thicknesses were investigated, the inclusion of an in-between thickness of, 1.5 mm, would provide further information on how optical properties may be influenced by cement shade at different design parameters of AM materials [10, 17]. Another clinical limitation to consider was the dimensions in which each specimen was manufactured. Definitive prostheses would not be a square geometric shape but rather would be rounded according to the tooth morphology trying to be recreated. This could change the behavior of color difference and translucency when applied clinically [17]. Despite these limitations, to the authors' knowledge, this is the first available study on the effect of cement shade on AM permanent dental resins. This study highlights the importance of consideration for cement shade selection, print orientation, and thickness of material for clinicians wishing to provide additively manufactured permanent fixed prostheses, using these permanent resin materials. Statistically significant differences in color and differences in translucency suggest that these choices may have a large impact on the overall aesthetic quality of an AM restoration. Based on the results of this study the clinical recommendation of cement shade depends on the technology that is being utilized in practice. During this transitional period of interchange from SM to AM, it can be expected that practices may begin to provide restorations produced from both technologies. In this case, a translucent cement shade, when the tooth color is favorable, would provide reduced variation of  $\Delta E$  across the different materials. When only AM is utilized in practice, the neutral cement shade will result in the lowest  $\Delta E$  values. If tooth color is unfavorable, a thicker restoration (2 mm) would reduce translucency and therefore  $\Delta E$ . Similarly, if the ideal cement shade is not available for color matching a thicker restoration would mask the color of the cement. When deciding on print orientation, a 45° orientation regardless of AM technology may result in reduced  $\Delta E$  for all cement shades, but for Formlabs and Bego, a 90° and 0° restoration, respectively, could also be considered. The present, in vitro study measured the color difference and translucency, of additively manufactured permanent resin crown materials when different shades of dual-cure cement were applied. Further investigation on a wider range of cement shades and masking ability of these would be beneficial.

## 5 | Conclusion

Within the limits of this study, it can be concluded that

1. Cement shade may cause clinically unacceptable color changes depending on material choice, thickness of the material and print orientation.
2. No significant differences in translucency parameter are noted between milled specimens and additively manufactured specimens of different print orientations across all shades of cement.

3. Neutral and translucent cement shade exhibited lower values for color difference compared to light and warm.
4. A 45° print orientation for 2 mm thick specimens exhibited the greatest clinically acceptable color differences.

Therefore, clinicians providing permanent AM crowns must consider the impact of cement shade and design parameters on restorative aesthetic outcomes as these may result in clinically unacceptable changes. These aspects should be considered when printing dental restorations depending on the desired location of the restoration and underlying tooth color.

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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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