Heliyon 10 (2024) e32557

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Flexural strength and degree of conversion of universal single shade resin-based composites

Ghada Alharbi [a,b,*], Hend NA Al Nahedh [a], Loulwa M. Al-Saud [a], Nourah Shono [a], Ahmed Maawadh [a]

[a] *Department of Restorative Dental Science, College of Dentistry, King Saud University. P.O. Box 60169, Riyadh 11545, Saudi Arabia*

[b] *Department of Clinical Dental Sciences, College of Dentistry, Princess Nourah Bint Abdulrahman University. PO Box 84428, Riyadh 11671, Saudi Arabia*

ARTICLE INFO

Keywords:
Universal single-shade RBCs
Flexural strength
Degree of conversion
Three-point bending test
Universal test machine
FTIR spectrometer

ABSTRACT

Background/purpose: Recently, a group of universal single-shade resin-based composites (RBCs) has been developed to simplify the process of shade selection. Excellent mechanical and physical properties are crucial for the ultimate success and clinical longevity of restorations. Therefore, evaluating the properties of the single-shaded RBCs is imperative. This study aimed to determine the flexural strength (FS) and degree of conversion (DC) of universal single-shade RBCs.

Materials and methods: In this study, four commercial RBCs were used; three universal single-shade RBCs; Omnichroma (OC), Charisma® Diamond ONE (CD), and Vittra APS Unique (VU), and a conventional nanohybrid composite Filtek™ Z250 XT (FT) which was used as a control. Sixty composite beams and 40 composite discs were used for FS and DC, respectively. A universal test machine with a three-point bending test was used to measure the FS, whereas the DC was measured using a Fourier-transform infrared spectrometer (FTIR). Three fractured specimens from each resin composite group were qualitatively analyzed using scanning electron microscopy.

Results: ANOVA was used to compare the mean values of FS and DC among the four RBCs (OC, CD, VU, and FT). Highly significant differences were observed in the mean FS and DC values ($F = 673.043$, $p < 0.001$ and F ($=782.4$, $p < 0.0001$), respectively. The highest FS was observed in the CD group, followed by FT and VU groups; the lowest value was observed in the OC group. In addition, a statistically significant difference was identified in DC values. The highest DC value was observed in VU, followed by OC and CD, and the lowest DC value was observed in FT.

Conclusion: Universal single-shade RBCs demonstrated a good FS, except for OC, which exhibited a significantly low FS. The DC of the universal single-shade RBCs was higher than that of the conventional nanohybrid composite restorative material.

1. Introduction

Resin-based composites (RBCs) are frequently used in daily dental practice because of their esthetic appearance and good mechanical properties [1]. Advances in restorative dentistry have enabled composites to maintain the functionality and esthetics of

---

* Corresponding author. Department of Restorative Dental Science, College of Dentistry, King Saud University, P.O. Box 60169, Riyadh, 11545, Saudi Arabia.

E-mail addresses: dr-ghadaalharbi@hotmail.com, gsalharbi@pnu.edu.sa (G. Alharbi).

https://doi.org/10.1016/j.heliyon.2024.e32557

Received 9 December 2023; Received in revised form 13 May 2024; Accepted 5 June 2024

natural tooth structures [2]. A comprehensive understanding of RBCs' different characteristics will help with the appropriate selection of restorative materials and, consequently, optimal clinical outcomes [3]. Flexural strength (FS) is the maximum stress that a material can withstand before it fails under flexural loading and it is an important property of RBCs specifically when the restorative material is used in areas subjected to heavy masticatory forces notably in posterior regions [4,5]. One of the most significant and common techniques for determining the mechanical behavior of dental materials is the three-point bending test [6].

Another crucial feature of resin-based composites (RBCs) is the degree of conversion (DC), which directly impacts their mechanical and physical attributes, ultimately affecting the longevity of the restoration [7]. Several intrinsic factors, such as the chemical structure of the dimethacrylate monomer and the concentration of the photoinitiator, as well as extrinsic factors, such as polymerization conditions, play an important role in determining the final DC [8]. Notably, the FS increases with an increase in DC [9]. Thus, the higher the conversion of double bonds, the greater the mechanical strength of RBCs [10].

Shade matching of resin composite restorations is challenging and is considered a crucial factor for patient satisfaction with dental treatments [11,12]. Color matching techniques involving shade selection and multilayer filling approaches require considerable professional skill and more clinical time to perform [13]. The blending effect is a term that describes the ability of a material to display a color similar to that of the surrounding tooth structure [14]. Therefore, this characteristic has enabled the innovation of new dental resin-based composites to facilitate clinical techniques, reduce treatment time, and increase the efficiency of the color selection process [15]. Recently, a new concept emerged "single shade" where resin-based composites are designed to mimic all shades aesthetically using just one shade [16,17]. Commercially available universal single-shade RBCs include Omnichroma (OC) (Tokuyama Dental, Tokyo, Japan) [18], Charisma ® Diamond ONE (CD) (Kulzer GmbH, Hanau, Germany) [19], and Vittra APS Unique (VU) (FGM, Joinville, SC, Brazil) [20] which have recently been introduced into the market. Several studies have investigated the color matching of universal single-shade RBCs, they demonstrated acceptable and positive results [21–28].

The ultimate success and clinical longevity of restorations are greatly reliant on the mechanical and physical properties of the restorative material. Compared to conventional composites, universal single-shade RBCs are relatively new; therefore, there is insufficient information about their properties. Consequently, further research is required to gain a deeper insight into the properties of these novel restorative materials, the most significant of which are their DC and FS. Therefore, the purpose of this study was to determine the FS and DC of universal single-shade RBCs. The null hypotheses were as follows: 1- There would be no statistically significant difference in the FS between the universal single-shade RBCs and a conventional nanohybrid composite. 2- There would be no significant difference in the DC between universal single-shade RBCs and a conventional nanohybrid composite. 3- There would be no significant correlation between FS and DC of the universal single-shade RBCs and a conventional nanohybrid composite.

2. Materials and Methods

Four RBCs available in the market were the main materials chosen for this study (Table 1) [29]. The universal single shade RBCs were OC (Tokuyama Dental, Tokyo, Japan) [18], CD (Kulzer GmbH, Hanau, Germany) [19], and VU (FGM, Joinville, SC, Brazil) [20] and the conventional resin composite Filtek ™ Z250 XT (FT) (3 M ESPE, St. Paul, MN, US) [30] was used as a control. A total of 100 specimens were used: 60 beams (n = 15) were used to test the FS, and 40 discs (n = 10) were used to evaluate the DC.

- Sample Size Determination

Table 1
List of resin-based composites (RBCs) used in this study.

Material	Composition	Filler Type (wt/vol)	Lot.no	Manufacturer
OMNICHROMA (OC) [18] (One Shade)	**Filler:** Uniform-sized supra-nano spherical filler (SiO2–ZrO2 260 nm), round-shaped composite filler (containing 260 nm spherical SiO2–ZrO2). **Base resin:** UDMA, TEGDMA	Supra-Nanofilled. (79 wt%, 68 vol%)	(030E81)	Tokuyama Dental, Tokyo, Japan
Charisma® Diamond ONE (CD) [19] (One Shade)	**Filler:** Barium Aluminium Boro Fluor Silicate Glass (contains approximately 64 % filer by volume, its filler particle size is 5 nm–20 μm). **Base resin:** TCD-Urethaneacrylate, Silica, UDMA, TEGDMA. Titanium Dioxide, Fluorescent Pigments, Metallic oxide Pigments, Organic Pigments, Aminobenzoic acid-ester, BHT, Camphorquinone. Bisphenol A (BPA) free products	Nanohybrid (81 wt % 64 vol%)	(K010022)	Kulzer GmbH, Hanau, Germany
Vittra APS UNIQUE (VU) [20] (One Shade)	**Filler:** boron-aluminum-silicate glass. **Base resin:** A mixture of methacrylate monomers, a Photoinitiator with an advanced polymerization system (APS), co-initiators, stabilizers, and silane. Bisphenol A (BPA) free products	Nanohybrid (72–80 wt %, 52–60 vol%)	(230,921)	FGM Joinville, SC Brazil
Filtek™ Z250 XT (FT) [30] (Shade A2)	**Filler:** Silica particle 20 nm and Zirconia/Silica particle. **Base resin:** BIS-GMA, UDMA, BIS-EMA, TEGDMA and PEGDMA	Nanohybrid (82 wt % 68 vol%)	(NE58072)	3 M Dental Products ESPE, St. Paul, Minnesota, United States

Abbreviations: Bis-GMA = Bisphenol A diglycidyl dimethacrylate; UDMA=Urethane dimethacrylate; TEGDMA = Triethylene glycol dimethacrylate; Bis-EMA = Bisphenol A ethoxylated dimethacrylate; PEGDMA=Polyethylene glycol dimethacrylate; HEMA, = 2-hydroxyethyl methacrylate. TCD, tricyclodecane; BHT, butylhydroxytoluene [29].

The sample size was determined using G Power v3.1.9.4 software (Düsseldorf, Germany).

According to Cohen's guidelines [31], the required sample size to achieve 85 % power for detecting a medium effect at a significance criterion of $\alpha = 0.05$ was $N = 60$ (15 per group for the FS) and $N = 40$ (10 per group for the DC) for analysis of variance (ANOVA) test. Therefore, the sample sizes obtained, 60 for FS and 40 for DC, were adequate to test the study hypotheses.

- Measurement of Flexural Strength

Fifteen specimens of each type of RBC were prepared, totaling 60 beams used to measure the FS using a three-point bending test. Following the ISO 4049 specifications, a transparent polymer matrix tape was placed on a glass slide, and a stainless-steel split mold (25 mm × 2 mm × 2 mm) was positioned on it. The resin composite was then inserted into a mold and covered with matrix tape. The pressure was manually applied to the composites using another glass plate. The specimen was irradiated at a distance of 1 mm from the top of the RBCs in three overlapping steps of 20 s each using a blue phase light curing unit (LCU) with a tip diameter of 10 mm and an irradiance of 1200 mW/cm^2 (Ivoclar Vivadent, Schaan, Liechtenstein, Switzerland). The polymerized specimen was removed from the mold, all sides were polished using 1200-grit SiC paper. Additionally, the dimensions of the specimens were reevaluated to ensure compliance with ISO standards. The prepared specimens were stored in distilled water at 37 °C in the dark for 48 h.

The specimens were subjected to a three-point bending test (span length = 20 mm) using a universal testing machine (Instron, model 5965, Instron Corp., Canton, USA) at a load of 5 kN and a crosshead speed of 1.0 mm/min until the breaking point. The FS was measured using a computer-controlled universal testing machine and calculated using the following formula [32]:

$$F = \frac{3LS}{2WH^2}$$

Where F is the FS, L is the maximum load, S is the span, and W is the specimen width.

and H = height.

- Scanning Electron Microscopy (SEM) Observation

Following the three-point bending test, three specimens from each RBC group were selected (highest, median, and lowest FS values). The representative fractured surface of each specimen was sputter-coated with gold (JEOL ION SPUTTER JFC-1100; JEOL, Tokyo, Japan) for 5 min at a current of 10 mA. Each specimen was scanned using an SEM (JEOL JSM-6360LV; JEOL, Tokyo, Japan) at an accelerating voltage of 15 kV. Representative photomicrographs for each sample were taken at × 50 to × 2000 magnification [33].

- Measurement of Degree of Conversion

Forty discs (10 mm diameter and 2.0 mm depth) were used to measure the DC. Ten specimens of each RBC were prepared using a customized split stainless-steel mold for the DC samples. First, the RBCs were inserted into the molds. Next, a clear Mylar strip (Mylar Uni-strip, Caulk/Dentsply, Milford, Delaware, United States) and a 1-mm thick glass plate were fixed atop every mold in order to flatten the surface and eliminate extra material extruded.

The mold was positioned on a dark non-reflective surface for bottom measurements both before and after polymerization. The reflectance of a Fourier-transform infrared (FTIR) spectrometer (Thermo Scientific, NICOLET iS10, US) was implemented to acquire absorbance and transmission peaks. The uncured composite spectra were recorded as references. The absorbance and transmission peaks were obtained using the reflectance mode. DC (%) was calculated as the ratio of the absorbance intensities of the aliphatic C═C peak relative to the internal reference aromatic C═C peak. For FT, the aliphatic C═C peak was observed at 1638 cm-1 and the internal reference aromatic C═C peak was detected at 1608 cm-1. For OC, CD, and VU, the aliphatic C═C peak was observed at 1637 cm-1 and the internal reference aromatic C═C peak was noted at 1531 cm-1. The DC was determined using the following equation [34,35]:

$$DC(\%) = 100\left[1 - \left(\frac{\frac{\textit{Aliphatic peak height}}{\textit{Aromatic peak height}}\ \textit{after polymerziation}}{\frac{\textit{Aliphatic peak height}}{\textit{Aromatic peak height}}\ \textit{before polymerziation}}\right)\right]$$

- Statistical Analysis

The data were analyzed using IBM SPSS Statistics version 26.0 for Windows (IBM, Inc., Chicago, USA). Descriptive statistics, including mean and standard deviation (SD), were employed to summarize the quantitative outcome variables. The results were initially tested for normality using the Shapiro–Wilk test. The assumption of homogeneity of variances was assessed using Levene's test for equality of variances. One-way ANOVA was performed to compare the mean values of FS and DC among the study materials. Post hoc multiple comparison tests were used to compare the mean values of FS and DC in each pair of study materials. A p-value of $\leq .05$ was used to report the statistical significance. As the distribution of both variables (FS and DC) departed from normality, as indicated by the Shapiro–Wilk test ($p < .01$). A Spearman's correlation test, a non-parametric method, was utilized to assess the correlation between FS and DC for each of the four materials tested.

3. Results

- **Flexural Strength**

The Welch's ANOVA was utilized due to the violation of the assumption of homogeneity of variances for the FS values as judged by Levene's test for equality of variances ($p = .009$). Welch's ANOVA demonstrated a significant difference in FS among the four tested materials (Welch's F (3, 29.67) = 673.043, $p < 0.001$). Games-Howell post hoc analysis revealed that the highest mean FS was identified in CD (M = 194, SD = 7.82) followed by FT (M = 172, SD = 3.79), VU (M=170, SD = 8.54), and the lowest mean value was observed in OC (M = 102, SD = 5.45).

Multiple comparisons of the FS values (Table 2) revealed statistically significant mean differences among all the tested RBCs ($p < 0.0001$), except between VU and FT ($p < 0.868$).

- SEM Observation

Representative SEM images of the fractured surfaces of each resin composite after the three-point bending test are displayed in Figures [1 (a-d) and 2 (a-d)]. The features of the fractured composite surfaces were generally similar to those of ceramics (fracture origin, radial marks, and compression curl). SEM micrographs of OC, CD, VU, and FT exhibited typical macroscopic fracture patterns such as fracture origin (asterisk), radial marks (dotted arrows), and compression curl (solid white arrows). The SEM images of the OC displayed a slightly smooth fracture surface with radial marks and a compression curl (Fig. 1 [a and b]). SEM images of CD demonstrated a rough fracture surface with cracks and cleavage facets, radial marks, and compression curl (Fig. 1 [c and d]). The SEM images of VU exhibited a rough fracture surface with multiple radial marks, fracture origins, compression curls, and crack lines (Fig. 2 [a and b]). The SEM images of FT displayed a rough fracture surface with multiple radial marks, crack lines, and a compression curl (Fig. 2 (c and d]).

- **Degree of Conversion**

Homogeneity of variances was observed as assessed using Levene's test for equality of variances ($p = 0.827$). One-way ANOVA demonstrated a significant difference in DC among the four tested materials (F (3,36) = 782.4, $p < 0.0001$). Tukey post hoc analysis revealed that the highest DC was obtained in VU (M = 69.4, SD = 1.26) followed by OC (M = 59.7, SD = 1.42), CD (M = 53.30, SD = 1.16), and the lowest value was obtained in FT (M = 43.00, SD = 1.15).

Multiple comparisons of the DC values (Table 3) revealed statistically significant mean differences between all the tested RBCs ($p < 0.0001$).

- **Correlation Between FS and DC**

Both variables (FS and DC) were not normally distributed, as indicated by the Shapiro–Wilk test ($p < .01$); therefore, a non-parametric Spearman's correlation test was selected.

Multiple Spearman's correlation tests were performed to determine whether any statistically significant correlation was present between FS and DC among the tested resin composites. No statistically significant correlation was observed between the FS and DC among the tested materials. However, a moderately positive correlation was identified in FT, r_s (13) = 0.623, $p = .0549$ (Fig. 3[A-D]).

Table 2
The flexural strength mean, standard deviation values, and multiple comparisons of mean values across pairs of the tested resin-based composites.

Resin Composite Material (n = 15)		Mean and Standard Deviation	Mean difference	*p*-value	95 % Confidence Interval	
					Lower bound	Upper bound
OMNICHROMA (OC)	CD	102 ± 5.45	−91.98	<0.001	−98.44	−85.53
	VU		−67.69	<0.001	−74.15	−61.24
	FT		−69.56	<0.001	−76.02	−63.11
Charisma® Diamond ONE (CD)	OC	194 ± 7.82	91.98	<0.001	85.53	98.44
	VU		24.29	<0.001	17.84	30.75
	FT		22.42	<0.001	15.96	28.87
Vittra APS UNIQUE (VU)	OC	170 ± 8.54	67.69	<0.001	61.24	74.15
	CD		−24.29	<0.001	−30.75	−17.84
	FT		−1.87	0.868	−8.33	4.58
Filtek™ Z250 XT (FT)	OC	172 ± 3.79	69.56	<0.001	63.11	76.02
	CD		−22.42	<0.001	−28.88	−15.96
	VU		1.87	0.868	−4.58	8.33

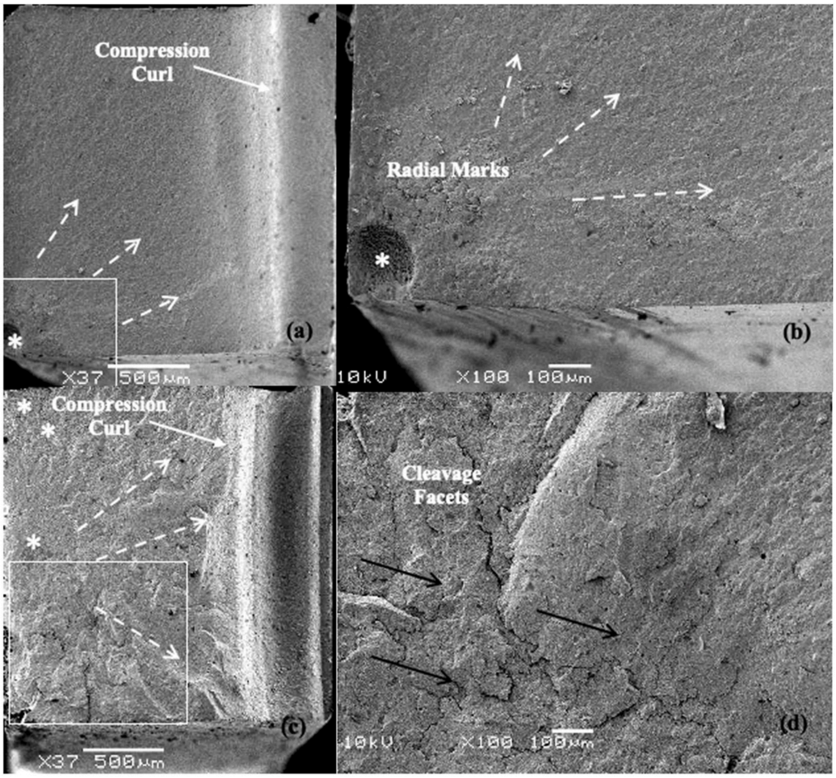

Fig. 1. Scanning electron microscopy (SEM) micrographs of the fractured surfaces. (a) SEM image of Omnichroma displays fracture origin (asterisk), radial marks (dotted arrows), and compression curl (solid white arrows). (b) SEM images at a high magnification demonstrate a slightly smooth fracture surface with multiple radial marks. (c) SEM image of Charisma® Diamond ONE displays fracture origin (asterisk), radial marks (dotted arrows), and compression curl (solid white arrows). (d) SEM images at high magnification exhibit a rough fracture surface with cracks and cleavage facets (solid black arrows).

4. Discussion

This in vitro study determined the FS and DC of three universal single-shade RBCs. OC (Tokuyama Dental) is the first supra-nano-filled single-shade RBC with novel technology and contains no pigments. The optical features of OC depend on structural color, a “smart chromatic technology” wherein the RBC precisely reflects a particular wavelength within the tooth color space in response to light waves of a given frequency [21]. Also, CD (Kulzer) is a nanohybrid single-shade universal RBC with the concept of “adaptive light matching” which involves absorbing wavelengths reflected from the surrounding tooth shade in order to create the restoration shade [25]. In addition, VU (FGM) is another nanohybrid single-shade RBC featuring an exclusive Advanced Polymerization System (APS) technology. This technology incorporates a blending effect that mirrors the shade of the tooth substrate during polymerization. According to the manufacturer, APS technology enhances the curing effectiveness of the LCU by utilizing a range of photoinitiators that interact synergistically. Consequently, APS facilitates strong polymerization, leading to high conversion rates and improved mechanical properties [36].

FS indicates a material’s capability to withstand fracture under stress. The results of FS testing help ascertain the suitability and longevity of the material for application [4]. The simplicity of sample preparation and testing is an advantage of the flexural test. The fact that the results of this testing method are sensitive to the specimen, loading geometry, and strain rate all are drawbacks of this test. The flexural test resulted in compressive stress on the force application side and tensile stress on the opposite side of the material. This created an area of shear along the midline. This complex stress distribution is similar to that observed in clinical conditions. Various methods, such as uniaxial and biaxial flexural tests, can be used to test the FS of dental materials. Uniaxial flexure tests were conducted in the form of three- and four-point bends [37]. Generally, the literature suggests that the strength may be higher when tested in a three-point as opposed to a four-point bending test [38]. Other than that, the two tests could be carried out in the same way and on specimens with identical dimensions [39]. The biaxial flexure test is typically used for brittle materials, such as ceramics, and has only infrequently been used for dental composites [40]. Therefore, the three-point bending test is one of the most important and widely used methods for characterizing the mechanical behavior of RBCs [6].

The FS of resin-based composite materials must be at least 80 MPa, according to the ISO standards [32,41]. Based on the results of this study, the FS values were higher than 80 MPa for all tested materials, and significant differences in FS were identified among the four tested RBC materials. Thus, the first null hypothesis was rejected. The highest FS was observed in CD, which is likely due to the

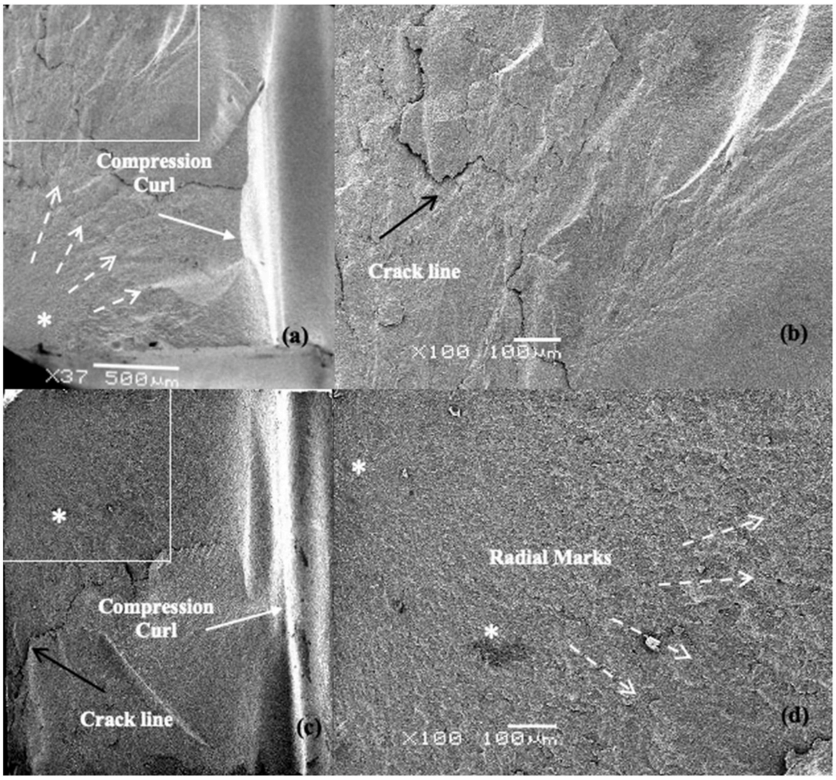

Fig. 2. Scanning electron microscopy (SEM) micrographs of the fractured surfaces. (a) SEM image of Vittra APS Unique displays fracture origin (asterisk), radial marks (dotted arrows), compression curl (solid white arrows), and crack line (solid black arrows). (b) SEM image at high magnification exhibits a rough fracture surface. (c) SEM image of Filtek™ Z250 XT demonstrates a void (asterisk), compression curl (solid white arrows), and crack line (solid black arrows) (X40). (d) SEM image at high magnification displays a slightly rough fracture surface with multiple radial marks.

tricyclodecane-urethane-based matrix. This unique matrix forms a robust three-dimensional network, contributing to high strength and favorable mechanical properties [42–44]. OC presented significantly lower FS values than those of the other tested materials, despite having a high filler content. This could be due to the composition of the OC, which is known to consist of uniformly sized spherical fillers with constant interparticle spacing. Therefore, crack propagation in OC tends to be easy, leading to low fracture resistance and low FS [45]. VU and FT were not significantly different in FS, which could be a result of the filler size or matrix composition, which was not disclosed by the manufacturer. The findings of this study are consistent with those of previous studies that investigated the FS of universal single-shade RBCs [45–47]. Consequently, CD, VU, and OC achieved the ISO standards requirements for dental resin-based composite and demonstrated FS values comparable to those of conventional nanohybrid composites.

Polymers may exhibit brittle behavior that is not greatly affected by the strain rate. Flexural testing demonstrated the polymers' susceptibility to brittle fracture and cracking. This susceptibility could be attributed to any local inhomogeneity in the specimen that causes local tensile stress, which can initiate brittle failure [48]. Fractography enables precise examination of the microscopic characteristics of fractured surfaces, indicating the precise direction of the fracture origin site. In the current study, the microscopic surface and subsurface fracture characteristics that pinpoint the location of the crack origin and propagation direction inside each composite resin material were detailed employing qualitative fractography [49]. The investigated composite resin materials exhibited several composite resin fracture pattern characteristics, including fracture origins, radial lines, and compression curls. When the specimens were loaded for flexural testing, a crack was formed and propagated perpendicular to the tensile surface, indicating the origin of the crack. Radial marks are lines on the fracture surface formed by the junction of brittle fractures that propagate at different levels and radiate outward from their origins. As the crack progressed closer to the compression side of the sample, it slowed down forming a compression curl that indicated the fracture's termination at the compression side of the beam. The presence of compression curl is a significant characteristic as it shows that the sample will bend when loaded. The fracture origin is frequently located on the opposite side of the compression curl [50–52].

The DC is the percentage of polymerizable double bonds converted to single bonds and is considered a critical factor for the success of RBCs [53]. The ultimate degree of conversion (DC) in present-day dental composites typically falls within the range of 50 %–80 %, indicating that a notable proportion of double bonds remain [7]. A low polymer conversion rate has a significant effect on the RBCs' properties resulting in reduced mechanical properties, poor color stability, and biocompatibility [8]. Various methods are available for measuring the DC of resin-based composites, including the halogenation of residual carbon double bonds, differential scanning

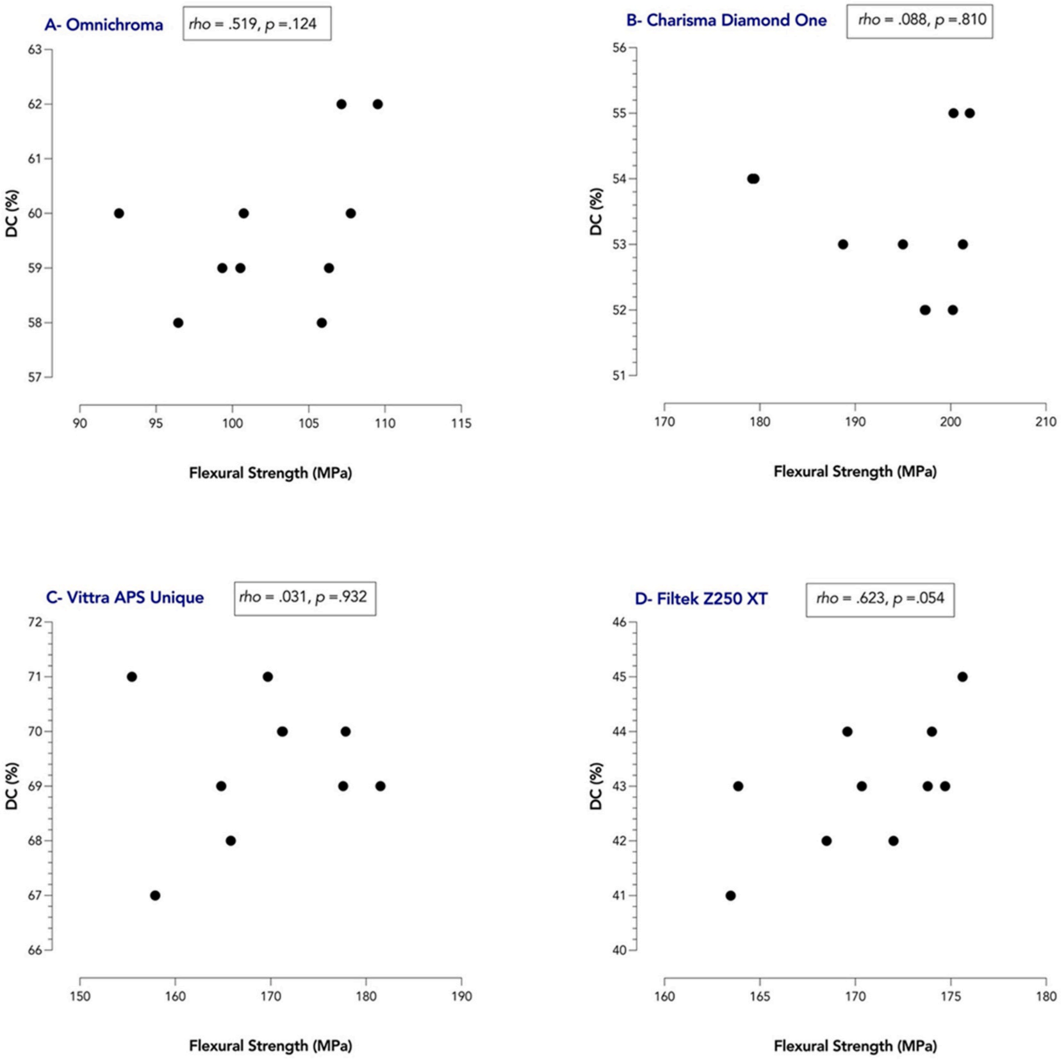

Fig. 3. Scatter plots of Spearman's correlations between flexural strength and degree of conversion for each tested resin composite material.

Table 3
The degree of conversion mean and standard deviation values and multiple comparisons of mean values across pairs of the tested resin-based composites.

Resin Composite Material (n = 10)		Mean and Standard Deviation	Mean difference	*p*-value	95 % Confidence Interval	
					Lower bound	Upper bound
OMNICHROMA (OC)	CD	59.7 ± 1.42	6.4	<0.001	4.88	7.91
	VU		−9.7	<0.001	−11.21	−8.18
	FT		16.7	<0.001	15.18	18.21
Charisma® Diamond ONE (CD)	OC	53.3 ± 1.16	−6.4	<0.001	−7.91	−4.88
	VU		−16.1	<0.001	−17.61	−14.58
	FT		10.3	<0.001	8.78	11.81
Vittra APS UNIQUE (VU)	OC	69.4 ± 1.26	9.7	<0.001	8.18	11.21
	CD		16.1	<0.001	14.58	17.61
	FT		26.4	<0.001	24.88	27.91
Filtek™ Z250 XT (FT)	OC	43.0 ± 1.15	−16.7	<0.001	−18.21	−15.18
	CD		−10.3	<0.001	−11.81	−8.78
	VU		−26.4	<0.001	−27.91	−24.88

calorimetry, differential thermal analysis, and infrared spectroscopy, which is the most commonly used method, and more specifically, FTIR spectroscopy [54,55]. Moreover, indirect methods such as surface micro-hardness are also available for the analysis of DC [56–58]. FTIR spectrometer is a non-destructive test with a wide range of applications and offers several advantages such as high scan speed, high resolution, and high sensitivity [54,55].

The materials tested in this study demonstrated significant differences among the four tested RBC materials; hence, the second null hypothesis was rejected. These findings are consistent with those of a previous study that investigated the DC of universal single-shade RBCs [46]. The highest DC was obtained with VU, which was probably due to the combination of different photoinitiators that resulted in an advantageous polymerization system which led to the high performance of the polymeric matrix formation and consequently resulted in the highest DC value [36,59].

Generally, the universal single-shade composites exhibited higher DC than that displayed by the conventional RBC, which could be due to the matrix structure of FT containing bisphenol A diglycidyl dimethacrylate, a monomer with low mobility and reactivity, which may have caused the low conversion rates [60,61]. On the other hand, urethane dimethacrylate (UDMA) and triethylene glycol dimethacrylate (TEGDMA) monomers were included in the matrix structure of both VU and OC; CD monomer comprises UDMA, TEGDMA, and a special low shrinkage monomer TCDI-HEA, which promotes the reactivity of urethane groups [62]. This may have increased polymer crosslinking, and therefore, increased the DC values [63]. Interestingly, VU and FT demonstrated vastly different DC values, but their FSs were comparable. FT had a high filler content, which may have improved the FS and compensated for the superior DC of VU.

The concentration and type of photoinitiator can affect DC and the polymerization of RBCs. Evidence exists that increased concentrations of photoinitiators improve the DC and mechanical properties of the RBCs [7,64,65]. Unfortunately, no benefits are observed above a certain threshold, which may affect esthetics owing to the yellow color of camphorquinone (CQ) [66,67]. Although yellowing might be reduced during the photoactivation process, some photoinitiators may remain unreacted owing to insufficient irradiation [68]. Moreover, the existence of unconverted carbon double bonds can render the material more prone to degradation, potentially resulting in color instability and the release of substances that could be toxic [69]. Therefore, adequate photoactivation is required for resin composites to achieve the desired esthetic, biological, and mechanical properties [57,58].

The most commonly used photoinitiator is CQ, which is associated with tertiary amine [70]. CQ is a solid yellow diketone compound that leads to unfavorable yellow discoloration of the light-cured restoration [71]. Other photoinitiators such as phenyl-propanedione (PPD), diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide (TPO), and phenylbis (2,4,6-trimethylbenzoyl) phosphine oxide have been suggested as alternatives to CQ in dental resin-based composites to improve esthetic appearance by reducing CQ and its yellowing effect, especially for bleach shades [72].

Additionally, OC contains CQ as a photoinitiator [18], while CD contains, CQ, PPD, and TPO as photoinitiators [19]. Several studies have discovered that composites containing TPO have a higher DC and better polymerization efficiency than those containing CQ [73–76]. VU contains a small amount of CQ that is used only to initiate the polymerization reaction and has an APS that contains other initiators that are not disclosed by the manufacturer [20]. The exact type and concentration of photoinitiators in most of the tested materials are unknown; therefore, deriving a conclusion on the effect of photoinitiators on the polymerization of these materials is difficult.

The color stability of RBCs is strongly associated with their DC [68]. Low conversion rates and the presence of degradable unreacted residual monomers diminish the mechanical properties and promote staining resulting in a considerable color shift [77,78]. Although single-shade RBCs demonstrated a high DC in the present study, several studies that evaluated the color stability of single-shade RBCs have shown that these composites had more color change than other materials [79–82]. Further studies are required to examine the behavior of these materials and evaluate the correlation between color stability and DC.

The findings revealed that there was no statistically significant correlation between the FS and DC among the four tested resin-based composites (RBCs). Our results contradict those of previous studies, which reported that mechanical strength increases with more conversion of double bonds of RBCs [10,83,84]. This may be due to the implementation of different methodologies and the selection of RBCs with varying compositions.

5. Conclusion

Given the limitations of this study, the following conclusions can be made.

- The universal single-shade RBCs demonstrated good FS and DC compared to the conventional nanohybrid composite restorative material.
- The highest FS was obtained in CD, and the highest DC was obtained in VU followed by OC. No statistically significant correlation was detected between the FS and DC among the tested materials.
- Universal single-shade RBCs meet the ISO requirements for dental resin composites. They can be a viable option to restore teeth with simplified shade selection, making the process less time-consuming while providing restorations with good esthetic and mechanical properties.

Availability of data and materials

Data will be made available on request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

CRediT authorship contribution statement

Ghada Alharbi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hend NA. Al Nahedh:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Loulwa M. Al-Saud:** Writing – review & editing, Supervision, Software, Resources, Formal analysis, Data curation. **Nourah Shono:** Writing – review & editing, Supervision. **Ahmed Maawadh:** Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Ghada Alharbi reports financial support was provided by Saudi National Institute of Health (Saudi NIH). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the support and funding provided by the Deanship of Scientific Research at King Saud University and the Saudi National Institute of Health (Saudi NIH), Riyadh, Saudi Arabia, which facilitated the completion of this study. The study was registered and approved by the College of Dentistry Research Center with registration number PR 0130. This manuscript constitutes part of a dissertation for the Doctor of Science in Dentistry (DScD) degree.

References

[1] N.J. Opdam, J.J. Roeters, T.C. Peters, R.C. Burgersdijk, R.H. Kuijs, Consistency of resin composites for posterior use, Dent. Mater. 12 (6) (1996) 350–354, https://doi.org/10.1016/s0109-5641(96)80045-5.

[2] J.L. Ferracane, Resin composite–state of the art, Dent. Mater. 27 (1) (2011) 29–38, https://doi.org/10.1016/j.dental.2010.10.020.

[3] S.D. Heintze, N. Ilie, R. Hickel, A. Reis, A. Loguercio, V. Rousson, Laboratory mechanical parameters of composite resins and their relation to fractures and wear in clinical trials-A systematic review, Dent. Mater. 33 (3) (2017) e101–e114, https://doi.org/10.1016/j.dental.2016.11.013.

[4] P. Lambrechts, M. Braem, G. Vanherle, Buonocore memorial lecture. Evaluation of clinical performance for posterior composite resins and dentin adhesives, Operat. Dent. 12 (2) (1987) 53–78.

[5] J. Manhart, K.H. Kunzelmann, H.Y. Chen, R. Hickel, Mechanical properties and wear behavior of light-cured packable composite resins, Dent. Mater. 16 (1) (2000) 33–40, https://doi.org/10.1016/s0109-5641(99)00082-2.

[6] N. Ilie, T.J. Hilton, S.D. Heintze, R. Hickel, D.C. Watts, N. Silikas, J.W. Stansbury, M. Cadenaro, J.L. Ferracane, Academy of Dental Materials guidance-Resin composites: Part I-Mechanical properties, Dent. Mater. 33 (8) (2017) 880–894, https://doi.org/10.1016/j.dental.2017.04.013.

[7] J.G. Leprince, W.M. Palin, M.A. Hadis, J. Devaux, G. Leloup, Progress in dimethacrylate-based dental composite technology and curing efficiency, Dent. Mater. 29 (2) (2013) 139–156, https://doi.org/10.1016/j.dental.2012.11.005.

[8] M. Par, O. Gamulin, D. Marovic, E. Klaric, Z. Tarle, Raman spectroscopic assessment of degree of conversion of bulk-fill resin composites–changes at 24 hours post cure, Operat. Dent. 40 (3) (2015) E92–E101, https://doi.org/10.2341/14-091-l.

[9] L.G. Lovell, H. Lu, J.E. Elliott, J.W. Stansbury, C.N. Bowman, The effect of cure rate on the mechanical properties of dental resins, Dent. Mater. 17 (6) (2001) 504–511, https://doi.org/10.1016/s0109-5641(01)00010-0.

[10] L.G. Lovell, S.M. Newman, M.M. Donaldson, C.N. Bowman, The effect of light intensity on double bond conversion and flexural strength of a model, unfilled dental resin, Dent. Mater. 19 (6) (2003) 458–465, https://doi.org/10.1016/s0109-5641(02)00090-8.

[11] J. da Costa, P. Fox, J. Ferracane, Comparison of various resin composite shades and layering technique with a shade guide, J. Esthetic Restor. Dent. 22 (2) (2010) 114–124, https://doi.org/10.1111/j.1708-8240.2010.00322.x.

[12] D. Dietschi, N. Fahl Jr., Shading concepts and layering techniques to master direct anterior composite restorations: an update, Br. Dent. J. 221 (12) (2016) 765–771, https://doi.org/10.1038/sj.bdj.2016.944.

[13] R.D. Paravina, S. Westland, W.M. Johnston, J.M. Powers, Color adjustment potential of resin composites, J. Dent. Res. 87 (5) (2008) 499–503, https://doi.org/10.1177/154405910808700515.

[14] R.D. Paravina, S. Westland, F.H. Imai, M. Kimura, J.M. Powers, Evaluation of blending effect of composites related to restoration size, Dent. Mater. 22 (4) (2006) 299–307, https://doi.org/10.1016/j.dental.2005.04.022.

[15] R.D. Paravina, S. Westland, M. Kimura, J.M. Powers, F.H. Imai, Color interaction of dental materials: blending effect of layered composites, Dent. Mater. 22 (10) (2006) 903–908, https://doi.org/10.1016/j.dental.2005.11.018.

[16] R.S. Iyer, V.R. Babani, P. Yaman, J. Dennison, Color match using instrumental and visual methods for single, group, and multi-shade composite resins, J. Esthetic Restor. Dent. 33 (2) (2021) 394–400, https://doi.org/10.1111/jerd.12621.

[17] B. Trifkovic, J.M. Powers, R.D. Paravina, Color adjustment potential of resin composites, Clin. Oral Invest. 22 (3) (2018) 1601–1607, https://doi.org/10.1007/s00784-017-2260-6.

[18] Tokuyama, Omnichroma Product Information, 2019 9 June 2023. Available from: https://www.tokuyama-us.com/omnichroma-dental-composite/.

[19] Kulzer, Charisma Diamond One Product Information, 2020 9 June 2023. Available from: https://www.kulzer.com/int2/en/products/2020-charisma-diamond-one-shade.html.

[20] FGM, Vittra APS Unique Product Information, 2021 9 June 2023. Available from: https://fgmus.com/product/vittra-aps-unique/.

[21] N. Pereira Sanchez, J.M. Powers, R.D. Paravina, Instrumental and visual evaluation of the color adjustment potential of resin composites, J. Esthetic Restor. Dent. 31 (5) (2019) 465–470, https://doi.org/10.1111/jerd.12488.

[22] M. Saegusa, H. Kurokawa, N. Takahashi, T. Takamizawa, R. Ishii, K. Shiratsuchi, M. Miyazaki, Evaluation of color-matching ability of a structural colored resin composite, Operat. Dent. 46 (3) (2021) 306–315, https://doi.org/10.2341/20-002-l.

[23] M. Oivanen, F. Keulemans, S. Garoushi, P.K. Vallittu, L. Lassila, The effect of refractive index of fillers and polymer matrix on translucency and color matching of dental resin composite, Biomater Investig Dent 8 (1) (2021) 48–53, https://doi.org/10.1080/26415275.2021.1906879.

[24] L.B. Durand, J. Ruiz-López, B.G. Perez, A.M. Ionescu, F. Carrillo-Pérez, R. Ghinea, M.M. Pérez, Color, lightness, chroma, hue, and translucency adjustment potential of resin composites using CIEDE2000 color difference formula, J. Esthetic Restor. Dent. 33 (6) (2021) 836–843, https://doi.org/10.1111/jerd.12689.

[25] C. Lucena, J. Ruiz-López, R. Pulgar, A. Della Bona, M.M. Pérez, Optical behavior of one-shaded resin-based composites, Dent. Mater. 37 (5) (2021) 840–848, https://doi.org/10.1016/j.dental.2021.02.011.

[26] S. Kobayashi, M. Nakajima, K. Furusawa, A. Tichy, K. Hosaka, J. Tagami, Color adjustment potential of single-shade resin composite to various-shade human teeth: effect of structural color phenomenon, Dent. Mater. J. 40 (4) (2021) 1033–1040, https://doi.org/10.4012/dmj.2020-364.

[27] E.T. Cruz da Silva, C.F. Charamba Leal, S.B. Miranda, M. Evangelista Santos, S. Saeger Meireles, A.K. Maciel de Andrade, M.A. Japiassú Resende Montes, Evaluation of single-shade composite resin color matching on extracted human teeth, Sci. World J. 2023 (2023) 4376545, https://doi.org/10.1155/2023/4376545.

[28] H. Altınışık, E. Özyurt, Instrumental and visual evaluation of the color adjustment potential of different single-shade resin composites to human teeth of various shades, Clin. Oral Invest. 27 (2) (2023) 889–896, https://doi.org/10.1007/s00784-022-04737-x.

[29] G. Alharbi, H.N. Al Nahedh, L.M. Al-Saud, N. Shono, A. Maawadh, Effect of different finishing and polishing systems on surface properties of universal single shade resin-based composites, BMC Oral Health 24 (1) (2024) 197, https://doi.org/10.1186/s12903-024-03958-8.

[30] 3M, Filtek Z250 XT Product Information, 2011 9 June 2023. Available from: https://www.3m.com/3M/en_LB/p/d/b5005188044/.

[31] Cohen, Statistical Power Analysis for the Behavioral Sciences, Routledge Academic, New York, NY, 1988.

[32] ISO 4049, Dentistry — Polymer-Based Restorative Materials, International Organization for Standardization, 2019, p. 29. ISO 4049, 2019.

[33] J. Syed, Scanning electron microscopy in oral research, Journal of Pakistan Dental Association 26 (2017) 189–195, https://doi.org/10.25301/JPDA.264.195.

[34] P. Yu, A. Yap, X.Y. Wang, Degree of conversion and polymerization shrinkage of bulk-fill resin-based composites, Operat. Dent. 42 (1) (2017) 82–89, https://doi.org/10.2341/16-027-l.

[35] M. Aldhafyan, N. Silikas, D.C. Watts, Influence of curing modes on conversion and shrinkage of dual-cure resin-cements, Dent. Mater. 38 (1) (2022) 194–203, https://doi.org/10.1016/j.dental.2021.12.004.

[36] M. Basílio, R. Gregorio, J.V. Câmara, L. Serrano, P.R. Campos, J.J. Pierote, S. Groisman, G. Pereira, S. Barreto, Influence of different photoinitiators on the resistance of union in bovine dentin: experimental and microscopic study, J Clin Exp Dent 13 (2) (2021) e132–e139, https://doi.org/10.4317/jced.57756.

[37] N. Kumar, Inconsistency in the strength testing of dental resin-based composites among researchers, Pakistan J. Med. Sci. 29 (1) (2013) 205–210, https://doi.org/10.12669/pjms.291.2922.

[38] W.M. Palin, G.J. Fleming, F.J. Burke, P.M. Marquis, R.C. Randall, The reliability in flexural strength testing of a novel dental composite, J. Dent. 31 (8) (2003) 549–557, https://doi.org/10.1016/s0300-5712(03)00110-6.

[39] P. Chitchumnong, S.C. Brooks, G.D. Stafford, Comparison of three- and four-point flexural strength testing of denture-base polymers, Dent. Mater. 5 (1) (1989) 2–5, https://doi.org/10.1016/0109-5641(89)90082-1.

[40] W.M. Palin, G.J. Fleming, P.M. Marquis, The reliability of standardized flexure strength testing procedures for a light-activated resin-based composite, Dent. Mater. 21 (10) (2005) 911–919, https://doi.org/10.1016/j.dental.2005.01.005.

[41] S.A. Rodrigues Jr., J.L. Ferracane, A. Della Bona, Flexural strength and Weibull analysis of a microhybrid and a nanofill composite evaluated by 3- and 4-point bending tests, Dent. Mater. 24 (3) (2008) 426–431, https://doi.org/10.1016/j.dental.2007.05.013.

[42] H. Takahashi, W.J. Finger, T. Endo, M. Kanehira, N. Koottathape, M. Komatsu, M. Balkenhol, Comparative evaluation of mechanical characteristics of nanofiller containing resin composites, Am. J. Dent. 24 (5) (2011) 264–270.

[43] K.E. Frauscher, N. Ilie, Depth of cure and mechanical properties of nano-hybrid resin-based composites with novel and conventional matrix formulation, Clin. Oral Invest. 16 (5) (2012) 1425–1434, https://doi.org/10.1007/s00784-011-0647-3.

[44] C. Schmidt, N. Ilie, The mechanical stability of nano-hybrid composites with new methacrylate monomers for matrix compositions, Dent. Mater. 28 (2) (2012) 152–159, https://doi.org/10.1016/j.dental.2011.11.007.

[45] K. Mizutani, T. Takamizawa, R. Ishii, S. Shibasaki, H. Kurokawa, M. Suzuki, A. Tsujimoto, M. Miyazaki, Flexural properties and polished surface characteristics of a structural colored resin composite, Operat. Dent. 46 (3) (2021) E117–e131, https://doi.org/10.2341/20-154-l.

[46] P. Yılmaz Atalı, B. Doğu Kaya, A. Manav Özen, B. Tarçın, A.A. Şenol, E. Tüter Bayraktar, B. Korkut, G. Bilgin Göçmen, D. Tağtekin, C. Türkmen, Assessment of micro-hardness, degree of conversion, and flexural strength for single-shade universal resin composites, Polymers 14 (22) (2022), https://doi.org/10.3390/polym14224987.

[47] F.A. Hasanain, Flexural strength and depth of cure of single shade dental composites, JPRI 33 (49A) (2021) 110–118, https://doi.org/10.9734/jpri/2021/v33i49A33310.

[48] F. Keulemans, P. Palav, M.M. Aboushelib, A. van Dalen, C.J. Kleverlaan, A.J. Feilzer, Fracture strength and fatigue resistance of dental resin-based composites, Dent. Mater. 25 (11) (2009) 1433–1441, https://doi.org/10.1016/j.dental.2009.06.013.

[49] J.B. Quinn, G.D. Quinn, Material properties and fractography of an indirect dental resin composite, Dent. Mater. 26 (6) (2010) 589–599, https://doi.org/10.1016/j.dental.2010.02.008.

[50] D.M. Davis, N.E. Waters, Fractography of a bis-GMA resin, J. Dent. Res. 68 (7) (1989) 1194–1198, https://doi.org/10.1177/00220345890680071001.

[51] B.W.L. S, Fracture Appearance and Mechanisms of Deformation and Fracture, ASM International, Materials Park, OH, 2002, pp. 559–586.

[52] C.W.R. Dg, Materials Science and Engineering, John Wiley & Sons., New York, NY, 2011.

[53] J.W. Stansbury, Dimethacrylate network formation and polymer property evolution as determined by the selection of monomers and curing conditions, Dent. Mater. 28 (1) (2012) 13–22, https://doi.org/10.1016/j.dental.2011.09.005.

[54] T.H. Yoon, Y.K. Lee, B.S. Lim, C.W. Kim, Degree of polymerization of resin composites by different light sources, J. Oral Rehabil. 29 (12) (2002) 1165–1173.

[55] M. Du, Y. Zheng, Degree of conversion and mechanical properties studies of UDMA based materials for producing dental posts, Polym. Compos. 29 (6) (2008) 623–630.

[56] R.B. Price, J. Whalen, T.B. Price, C.M. Felix, J. Fahey, The effect of specimen temperature on the polymerization of a resin-composite, Dent. Mater. 27 (10) (2011) 983–989.

[57] S. Flury, S. Hayoz, A. Peutzfeldt, J. Hüsler, A. Lussi, Depth of cure of resin composites: is the ISO 4049 method suitable for bulk fill materials? Dent. Mater. 28 (5) (2012) 521–528, https://doi.org/10.1016/j.dental.2012.02.002.

[58] R.B. Price, J.L. Ferracane, A.C. Shortall, Light-curing units: a review of what we need to know, J. Dent. Res. 94 (9) (2015) 1179–1186, https://doi.org/10.1177/0022034515594786.

[59] G. de Fátima Alves da Costa, A. Melo, I.V. de Assunção, B.C.D. Borges, Impact of additional polishing method on physical, micromorphological, and microtopographical properties of conventional composites and bulk fill, Microsc. Res. Tech. 83 (3) (2020) 211–222, https://doi.org/10.1002/jemt.23404.

[60] C. Sarosi, M. Moldovan, A. Soanca, A. Roman, T. Gherman, A. Trifoi, A.M. Chisnoiu, S. Cuc, M. Filip, G.F. Gheorghe, R.M. Chisnoiu, Effects of monomer composition of urethane methacrylate based resins on the C=C degree of conversion, residual monomer content and mechanical properties, Polymers 13 (24) (2021), https://doi.org/10.3390/polym13244415.

[61] A. Szczesio-Wlodarczyk, M. Domarecka, K. Kopacz, J. Sokolowski, K. Bociong, An evaluation of the properties of urethane dimethacrylate-based dental resins, Materials 14 (11) (2021), https://doi.org/10.3390/ma14112727.

[62] K.K. Roy, K.P. Kumar, G. John, S.G. Sooraparaju, S.K. Nujella, K. Sowmya, A comparative evaluation of effect of modern-curing lights and curing modes on conventional and novel-resin monomers, J. Conserv. Dent. 21 (1) (2018) 68–73, https://doi.org/10.4103/jcd.Jcd_71_17.

[63] N. Graf, N. Ilie, Long-term mechanical stability and light transmission characteristics of one shade resin-based composites, J. Dent. 116 (2022) 103915, https://doi.org/10.1016/j.jdent.2021.103915.

[64] M.G. Neumann, W.G. Miranda Jr., C.C. Schmitt, F.A. Rueggeberg, I.C. Correa, Molar extinction coefficients and the photon absorption efficiency of dental photoinitiators and light curing units, J. Dent. 33 (6) (2005) 525–532, https://doi.org/10.1016/j.jdent.2004.11.013.

[65] W.F. Schroeder, C.I. Vallo, Effect of different photoinitiator systems on conversion profiles of a model unfilled light-cured resin, Dent. Mater. 23 (10) (2007) 1313–1321, https://doi.org/10.1016/j.dental.2006.11.010.

[66] R. Janda, J.F. Roulet, M. Latta, M. Kaminsky, S. Rüttermann, Effect of exponential polymerization on color stability of resin-based filling materials, Dent. Mater. 23 (6) (2007) 696–704, https://doi.org/10.1016/j.dental.2006.06.009.

[67] N.B. Cramer, J.W. Stansbury, C.N. Bowman, Recent advances and developments in composite dental restorative materials, J. Dent. Res. 90 (4) (2011) 402–416, https://doi.org/10.1177/0022034510381263.

[68] L.F. Schneider, C.S. Pfeifer, S. Consani, S.A. Prahl, J.L. Ferracane, Influence of photoinitiator type on the rate of polymerization, degree of conversion, hardness and yellowing of dental resin composites, Dent. Mater. 24 (9) (2008) 1169–1177, https://doi.org/10.1016/j.dental.2008.01.007.

[69] J. Durner, J. Obermaier, M. Draenert, N. Ilie, Correlation of the degree of conversion with the amount of elutable substances in nano-hybrid dental composites, Dent. Mater. 28 (11) (2012) 1146–1153, https://doi.org/10.1016/j.dental.2012.08.006.

[70] P.P. Albuquerque, A.D. Moreira, R.R. Moraes, L.M. Cavalcante, L.F. Schneider, Color stability, conversion, water sorption and solubility of dental composites formulated with different photoinitiator systems, J. Dent. 41 (Suppl 3) (2013) e67–e72, https://doi.org/10.1016/j.jdent.2012.11.020.

[71] H.C. Georg, K. Coutinho, S. Canuto, Solvent effects on the UV-visible absorption spectrum of benzophenone in water: a combined Monte Carlo quantum mechanics study including solute polarization, J. Chem. Phys. 126 (3) (2007) 034507, https://doi.org/10.1063/1.2426346.

[72] D.C. de Oliveira, M.G. Rocha, A. Gatti, A.B. Correr, J.L. Ferracane, M.A. Sinhoret, Effect of different photoinitiators and reducing agents on cure efficiency and color stability of resin-based composites using different LED wavelengths, J. Dent. 43 (12) (2015) 1565–1572, https://doi.org/10.1016/j.jdent.2015.08.015.

[73] L.F. Schneider, L.M. Cavalcante, S.A. Prahl, C.S. Pfeifer, J.L. Ferracane, Curing efficiency of dental resin composites formulated with camphorquinone or trimethylbenzoyl-diphenyl-phosphine oxide, Dent. Mater. 28 (4) (2012) 392–397, https://doi.org/10.1016/j.dental.2011.11.014.

[74] V.E. Salgado, M.M. Borba, L.M. Cavalcante, R.R. Moraes, L.F. Schneider, Effect of photoinitiator combinations on hardness, depth of cure, and color of model resin composites, J. Esthetic Restor. Dent. 27 (Suppl 1) (2015) S41–S48, https://doi.org/10.1111/jerd.12146.

[75] G. Conte, M. Panetta, M. Mancini, A. Fabianelli, A. Brotzu, R. Sorge, L. Cianconi, Curing effectiveness of single-peak and multi-peak led light curing units on tpo-containing resin composites with different chromatic characteristics, Oral Implant. 10 (2) (2017) 140–150, https://doi.org/10.11138/orl/2017.10.2.140.

[76] M. Popal, J. Volk, G. Leyhausen, W. Geurtsen, Cytotoxic and genotoxic potential of the type I photoinitiators BAPO and TPO on human oral keratinocytes and V79 fibroblasts, Dent. Mater. 34 (12) (2018) 1783–1796, https://doi.org/10.1016/j.dental.2018.09.015.

[77] A.P. Samra, S.K. Pereira, L.C. Delgado, C.P. Borges, Color stability evaluation of aesthetic restorative materials, Braz. Oral Res. 22 (3) (2008) 205–210, https://doi.org/10.1590/s1806-83242008000300003.

[78] E.M. da Silva, J. Dória, J. da Silva Jde, G.V. Santos, J.G. Guimarães, L.T. Poskus, Longitudinal evaluation of simulated toothbrushing on the roughness and optical stability of microfilled, microhybrid and nanofilled resin-based composites, J. Dent. 41 (11) (2013) 1081–1090, https://doi.org/10.1016/j.jdent.2013.08.013.

[79] N. Aydın, S. Karaoglanoglu, E. Oktay, B. Ersöz, Investigation of single shade composite resin surface roughness and color stability, Atatürk Üniversitesi Diş Hekimliği Fakültesi Dergisi (2021) 1, https://doi.org/10.17567/ataunidfd.895734, 1.

[80] B. Ersöz, S. Karaoğlanoğlu, E.A. Oktay, N. Aydin, Resistance of single-shade composites to discoloration, Operat. Dent. 47 (6) (2022) 686–692, https://doi.org/10.2341/21-156-l.

[81] W. Gamal, A. Safwat, A. Abdou, Effect of coloring beverages on color stability of single shade restorative material: an in vitro study, Open Access Macedonian Journal of Medical Sciences 10 (2022) 28–32, https://doi.org/10.3889/oamjms.2022.7679.

[82] S. Rohym, H.E.M. Tawfeek, R. Kamh, Effect of coffee on color stability and surface roughness of newly introduced single shade resin composite materials, BMC Oral Health 23 (1) (2023) 236, https://doi.org/10.1186/s12903-023-02942-y.

[83] W.M. Palin, G.J. Fleming, F.J. Burke, P.M. Marquis, R.C. Randall, Monomer conversion versus flexure strength of a novel dental composite, J. Dent. 31 (5) (2003) 341–351, https://doi.org/10.1016/s0300-5712(03)00050-2.

[84] V.E. Gajewski, C.S. Pfeifer, N.R. Fróes-Salgado, L.C. Boaro, R.R. Braga, Monomers used in resin composites: degree of conversion, mechanical properties and water sorption/solubility, Braz. Dent. J. 23 (5) (2012) 508–514, https://doi.org/10.1590/s0103-64402012000500007.