Journal of
Composites Science

MDPI

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Effect of Shade and Light-Curing Intensity on Bulk-Fill Composite: Heat Generation and Chemo-Mechanical Properties (In Vitro Study)

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Abstract: The aim of this study is to assess the effect of shade and light-curing intensity on the heat generation and degree of conversion of bulk-fill composite. A commercially available bulk-fill composite resin was used in this study. A total of 250 cylindrical specimens of each composite shade (n = 25/group) were prepared (125 for testing heat generation and 125 for testing degree of conversion, then cured using a monowave light-curing unit (LCU) with a single light intensity of 1470 mW/cm^2 and a polywave LCU with three different light intensities (1200, 2000, and 3000 mW/cm^2). Heat generation during polymerization was measured by five K-type thermocouples placed in each 1 mm layer from top to bottom. FTIR was used for evaluating the degree of conversion. Regarding heat generation, significant differences were seen in layers 4 and 5. Curing types and times also showed significant impacts on heat generation and the degree of conversion. Heat generation relates more to curing time than light intensity. Darker shades generate and retain more heat. Lighter shades exhibit higher degrees of conversion with longer curing.

Keywords: degree of conversion; thermocouple; FTIR

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Citation: Hussein, H.A.; Saeed, H.M.M. Effect of Shade and Light-Curing Intensity on Bulk-Fill Composite: Heat Generation and Chemo-Mechanical Properties (In Vitro Study). *J. Compos. Sci.* **2024**, *8*, 237. https://doi.org/10.3390/jcs8070237

Academic Editor: Francesco Tornabene

Received: 16 May 2024
Revised: 10 June 2024
Accepted: 20 June 2024
Published: 24 June 2024

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1. Introduction

To satisfy the rising esthetic demands of patients and professionals, light-curing dental composite resins are available in various hues that closely resemble the color of natural teeth. The optical properties of the composite resins are altered using pigments in combination with the yellow photoinitiator camphor quinone to control the hues. The light will be reflected by the dispersed filler particles and pigments and absorbed by the photoinitiators and pigments after exposure to blue curing light. This means that as light travels through the composite resin, the intensity of the light is diminished, reducing irradiance and the effectiveness of the curing process [1–4].

It is widely known that effective composite dental restorations require materials with sufficient mechanical qualities to withstand the constant stresses of chewing and the erosive oral environment [5]. The degree of conversion (DoC) through photo-activation via light curing is a significant component that influences these attributes [5,6]. Since they allow for the bulk implantation of dental fillings in thick increments (instead of the multi-layer applications used for conventional composites), bulk-fill composite resins (BCRs) are growing in popularity in restorative dentistry. BCRs also exhibit a high degree of conversion, which enhances both long-term clinical durability and mechanical qualities like hardness [7–9]. Any composite restoration that has undergone insufficient resin polymerization and curing can have a lower surface hardness, which increases the likelihood that the final restoration will deform and wear out prematurely, or fail due to secondary caries [7].

Dentists typically cure BCRs with high-intensity light to achieve effective polymerization of thick layers. According to recent research, there may be relationships between light intensity, degree of conversion, and surface hardness [5,6,8]. As a result, appropriate

resin polymerization and acceptable mechanical qualities are made possible by high light intensity (radiance emittance) at the effective wavelength [10]. These latest studies all imply that there is a beneficial correlation between mechanical strength and enhanced light-curing intensity [9]. However, several studies have found contradictory outcomes. Shimokawa et al. [7], for instance, looked into high-intensity light curing units and reported that they can result in greater polymerization stress due to quicker polymerization rates. Additionally, extremely intense light produces more radicals more quickly, which leads to early bi-radical termination and reduces the degree of BCR conversion [11].

Many manufacturers are now working to enhance the qualities of light-emitting diode (LED) light-curing units (LCU). Recent innovations include broad-spectrum polywave technology. Especially in BCRs that integrate co-initiators, which require shorter wavelengths to trigger the polymerization process, this is used to improve photoactivation and the corresponding degree of polymerization [12,13]. However, according to recent research, multiple-wavelength outputs increased the irradiance's inhomogeneity, which caused the composite to cure unevenly and have fewer overall mechanical qualities [13–15].

A connection between heat production and light-curing intensity has also been proposed [16]. However, there has been little research examining the impact of heat generation associated with light intensity during curing on BCRs' hardness. There is a gap in the literature regarding the best curing light intensity, which produces the least amount of heat to protect the pulp while giving the BCRs the greatest mechanical properties. Scientific research on this will inform physicians of the most efficient method to treat BCRs by providing patients with dental fillings with the optimum mechanical characteristics while minimizing clinical time and expense.

Therefore, the purpose of our study was to investigate the effects of shade, light-curing intensity, and wavelength spectrum on the heat generation of five different shades of BCRs, and their influences on hardness and degree of conversion when cured with two different types of LCUs (monowave and polywave). The null hypotheses were:

1. There are no differences in the amount of heat generation between various shades of the bulk-fill composite after using different light-curing intensities.
2. There are no differences regarding chemo-mechanical properties between various shades of bulk-fill composite when different light cures are used.

2. Material and Methods

2.1. Study Design

Design and configuration of the samples in this in vitro study showed in (Figure 1).

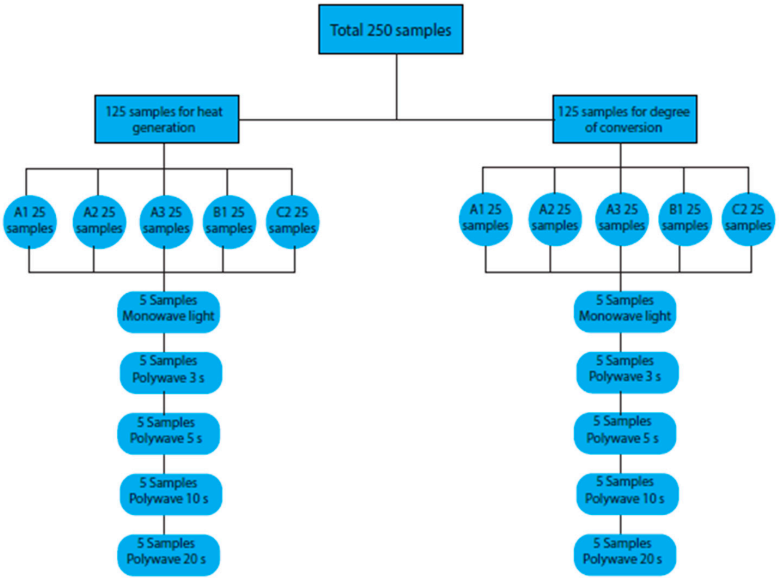


Figure 1. Showing study design and configuration of the samples for each test and shade.

2.2. Specimen Preparation and Curiing

The present study was approved by the Ethics Committee of the College of Dentistry at the University of Sulaimani (no. 23/173 on 3 May 2023). A commercially available bulk-fill composite resin, 3M™ Filtek™ One Bulk Fill Restorative (St. Paul, MN, USA) with five different shades (A1, A2, A3, B1, and C2) was used in this study, as presented in Table 1. A sample size calculation was performed by using the software G.power v3.0.10 (Heinrich-Heine University Dusseldorf). The calculation showed that 25 specimens per group were required. Hence, a total of 125 molds were produced for the composite specimens and they were randomly divided into five groups: 25 for each group according to the different shades. Molds were created by using tooth-colored resin (Free print Temp 3D print resin) through 3D printing device (Sprintray pro 95, Los Angeles, CA, USA) at 4 mm diameter and 5 mm depth, then small cavities were created at each 1 mm at the sides of the molds to allow the placement of thermocouple wires (Figure 2). The BCRs were packed in a 5 mm increment after the placement of thermocouples at the bottom of each increment. The BCRs were injected and packed in 1 mm increments after the placement of thermocouples on the top of each increment. The final BCR increment was then immediately light-cured 1 mm away from the restorative surface using the monowave LCU (Elipar Deep Cure-L LED Curing Light, (3 M, St. Paul, MN, USA); a single light intensity of 1470 mW/cm^2 with a curing time of 20 s) and a polywave LCU (Woodpecker O-Star Wide-Spectrum Curing Light, Guilin, China) providing three different light intensities of 1200, 2000, and 3000 mW/cm^2 with curing times of 3, 5, 10 and 20 s, respectively. The LCUs were held in position using a clamp to enable consistent distribution of light during the polymerization process; the application of the composite into the molds and curing with the LCUs was handled by a single-blinded operator for consistent data collection. Light intensity (radian emittance) was measured (n = 10 per group/curing modes) using a dental radiometer (O-Star curing light radiometer, Guilin, China) to confirm the intensity/emittance claimed by the manufacturer.

Table 1. Composition of the materials tested as provided by the manufacturer.

Material	Manufacturer Increment Thickness (mm)	Matrix	Filler	Filler % (wt)
FiltekVR One Bulk Fill (3M ESPE)	5	AFM AUDMA UDMA 1,12-docecane-DMA	Non-agglomerated 20 nm silica Non-agglomerated 4–11 nm zirconia Aggregated zirconia/silica cluster filler Ytterbium trifluoride filler	76.5

Note: AUDMA—aromatic urethane dimethacrylate; UDMA—urethane dimethacrylate.

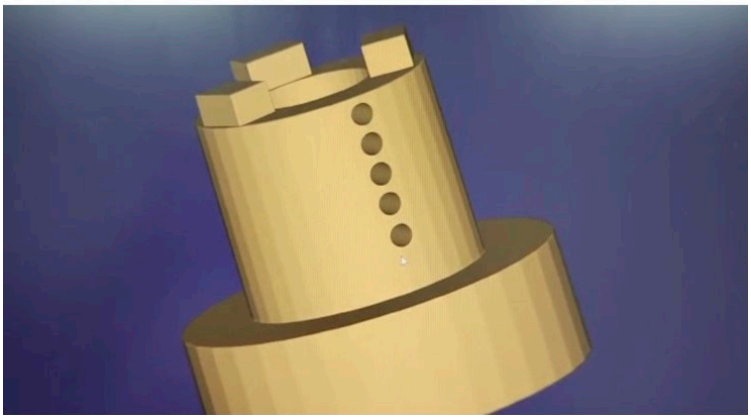


Figure 2. Shows the design and dimensions of the 3D-printed resin mold.

Next, for the second part of the study, a sample size calculation was performed by using the software G.power v3.0.10 (Heinrich-Heine University Dusseldorf). The calculation showed that 25 specimens per group were required; hence, a total of 125 cylindrical specimens (4 mm in diameter × 5 mm deep), 25 for each tested material, were prepared in

a resin mold. They were randomly divided into five groups. A mylar strip was placed on a 10 mm thick glass plate and the resin mold was placed over it. For each of the bulk-fill composites, the material was packed in bulk inside the mold until it was slightly overfilled. A second mylar strip was placed over the composite resin and another glass slide, 1 mm thick, was slightly compressed to extrude excess material. Photoactivation was performed by positioning the light guide tip to be in contact with the glass slide on the top surface of the specimen. Each specimen was irradiated according to the same protocol followed for the first test.

The output power of the curing unit was verified regularly every five exposures using a light radiometer. Standardization of the distance between the light source and specimen was obtained by the thickness of the glass slide and mylar strips, which provided smooth surfaces for the specimens After photo-activation, the specimens were stored dry in a dark container at room temperature for 24 h before testing. Twenty-five specimens of each composite material were used for conducting the DC test (n = 25).

2.3. Temperature Measurement

A total of five (k-type) thermocouples were connected and subsequently used in the experiment to measure real-time temperature changes. After packing 5 mm of BCR into the mold in one increment, five (k-type) thermocouples were inserted into the center of the mold through the holes created earlier in the mold. This setup enabled real-time temperature change at each millimetre using a data logger (Huato, Shenzhen, China). Each data logger was pre-setup to start at the same time and accurate to milliseconds to enable simultaneous temperature measurements from each layer. The data loggers started to record real-time temperature changes at the beginning of the light curing and stopped after two minutes of cooling time. The starting time was recorded in milliseconds and the finishing time was calculated accurately to milliseconds using the following formula: starting time + curing time + 2 s.

This procedure was repeated five times for each group, after which the measured data were converted and transferred into Microsoft Excel using EasyLog USB software (version 7.7). The means and standard deviations were calculated.

2.4. Evaluation of the Degree of Conversion

Fourier transform infrared (FTIR) spectroscopy (Waltham, MA, USA) (Figure 3) was used to evaluate the degree of conversion. Each of the polymerized specimens (n = 25) of each composite was milled into fine powder with a mortar and pestle. Fifty micrograms of the powder was mixed with 5 mg of potassium bromide powder and pressed to produce a thin disc, which was placed in a specimen holder and transferred to the spectrophotometer. The absorbance peaks were recorded using the diffuse reflectance mode of FTIR under the following conditions: 32 scans, over a wavelength of 400–4000 cm^{-1} and a resolution of 4 cm^{-1}. Unpolymerized specimens (n = 5) of each composite resin were smeared onto thin potassium bromide discs and placed into a cell holder in a spectrophotometer, and then a spectrum was obtained with the same parameters as for the polymerized specimens.



Figure 3. FTIR device for measuring the degree of conversion of BCRs.

The number of double-carbon bonds that were converted into single bonds would provide the DC of the BCRs. The DC would be determined according to the following Equation:

$$DC\ \% \ = \ 1 - \left[\frac{\frac{\text{Aliphatic}}{\text{Aromatic}}}{\frac{\text{Aliphatic}}{\text{Aromatic}}} \frac{\text{area cured}}{\text{area uncured}} \right] \times 100$$

2.5. Statistical Analysis

Data were analyzed using the Statistical Package for Social Sciences (SPSS, version 26). The normality of data was checked using the Shapiro–Wilk test; accordingly, non-parametric tests were used when indicated. One-way analysis of variance (ANOVA) was used to compare the means of five groups, and a post-hoc test (LSD) was used to compare each two means. When the data were not normally distributed, the Kruscal–Wallis test was used to compare the mean ranks of the five study groups, and a post-hoc test (Bonferroni) was used to compare each two groups. A p-value of $\leq$0.05 was considered statistically significant.

3. Results

3.1. Heat Generation

First, each LCU and each of the curing modes employed in this study had their real polymerization light-curing intensity (mW/cm^2, radiant emittance) analyzed and compared with the claims made by the manufacturers. The real mean light intensities measured for the polywave and monowave LCUs were less than those claimed by the manufacturers in Table 2. The polywave LCU had a higher standard deviation in the light intensity measured by the radiometer, compared to that of the monowave LCU.

Table 2. Light intensity characterization (mW/cm^2) of used light-curing units (LCUs), depending on curing mode, measured by a radiometer (n = 10).

	Monowave 20 s	**Polywave 3 s**	**Polywave 5 s**	**Polywave 10 s**	**Polywave 20 s**
Light-curing intensity (mW/cm^2) claimed by the manufacturer	1470	3000	2000	1200	1200
Actual mean light intensity (mW/cm^2)	881 ± 43.93	2716 ± 190.61	1666 ± 214.24	1092 ± 91.26	1131 ± 37.31

Generally speaking, there was a consistent decrease in heat generation while using the monowave light-curing unit, starting from 42.5 °C in layer 1 (top layer), progressing to 40.9 °C in layer 2, 39.3 °C in layer 3, 37.9 °C in layer 4, and ending with 35.9 °C in layer 5 (bottom layer). Regarding the association between heat generation and shades, no significant association was detected when measured in layer 1 (p = 0.574), layer 2 (p = 0.162), or layer 3 (p = 0.144), while in layer 4 significant associations (p = 0.035) were evident from Table 1, showing that the heat of C2 (38.8 °C) was higher than that of A1 (37.6 °C), A2 (37.6 °C), and B1 (37.3 °C), and the differences were significant (p = 0.033, p = 0.024, and p = 0.004, respectively). The difference between the shades was also significant in layer 5 (p = 0.004) where it is evident from Table 2 that the highest area of heat generation was C2 (36.5 °C). More details are presented in Table 3.

In general, the heat generated by polywave light-curing (for 3 s) was less than that generated by monowave. Table 2 shows that the heat generated in layer 1 (35.9 °C) decreased consistently to 35.5 °C in layer 2, 34.7 °C in layer 3, 34.0 °C in layer 4, and 32.8 °C in layer 5. No significant association was detected between heat generation and the shades in layer 1 (p = 0.507), layer 2 (p = 0.355), layer 3 (p = 0.412), and layer 4 (p = 0.111), while there was significant association in layer 5 (p = 0.012), where it is evident from the table that the highest mean of heat was in C2 (33.1 °C) and the lowest was in A3 (32.4 °C), as presented in Table 4.

Table 3. Temperature data measurements at each layer for all five shades of BCRs cured by a monowave light-curing unit.

Shades	Mean	SD	Min.	Max.	*p* *	Groups	*p* **	Group	*p* **
L1 (top)									
A1	41.1	7.0	33.5	58.9					
A2	42.5	9.1	31.7	69.5					
A3	43.0	8.4	33.4	70.0	0.574 †				
B1	42.7	9.3	32.6	65.8					
C2	43.1	8.3	33.3	65.9					
Total	42.5	8.5	31.7	70.0					
L2									
A1	39.9	5.0	33.7	51.7					
A2	41.0	6.6	32.0	57.7					
A3	41.8	6.2	33.5	57.6	0.162 †				
B1	40.0	6.0	32.8	55.3					
C2	41.8	6.4	33.8	58.3					
Total	40.9	6.1	32.0	58.3					
L3									
A1	38.7	3.6	33.3	47.0					
A2	38.7	4.1	32.1	48.8					
A3	40.0	4.4	33.3	49.7	0.144 †				
B1	38.9	4.3	32.9	49.4					
C2	40.0	4.2	34.2	50.1					
Total	39.3	4.2	32.1	50.1					
L4									
A1	37.6	2.7	32.6	42.5		A1 × A2	0.898	A2 × B1	0.557
A2	37.6	3.0	32.8	44.3		A1 × A3	0.262	A2 × C2	0.024
A3	38.2	3.1	31.7	44.7	0.035	A1 × B1	0.475	A3 × B1	0.066
B1	37.3	3.0	32.0	43.0		A1 × C2	0.033	A3 × C2	0.313
C2	38.8	3.2	33.5	45.0		A2 × A3	0.212	B1 × C2	0.004
Total	37.9	3.0	31.7	45.0					
L5 (bottom)									
A1	35.4	1.7	30.9	38.1		A1 × A2	0.721	A2 × B1	0.911
A2	35.6	2.1	31.9	40.2		A1 × A3	0.019	A2 × C2	0.008
A3	36.3	2.2	30.8	40.7	0.004	A1 × B1	0.807	A3 × B1	0.036
B1	35.5	2.0	30.7	39.4		A1 × C2	0.002	A3 × C2	0.495
C2	36.5	2.0	31.4	39.8		A2 × A3	0.047	B1 × C2	0.005
Total	35.9	2.1	30.7	40.7					

* By Kruskal–Wallis test. ** By post-hoc test (Bonferroni). † Post-hoc test was not conducted because the difference was not significant.

A consistent decrease in heat was also observed in Table 5 (curing by polywave for 5 s) where the mean was 36.9 °C in layer 1, which decreased consistently to reach 33.3 °C in layer 5. No significant association was detected between heat generation and the shades, whether measured in layer 1 ($p = 0.084$), layer 2 ($p = 0.102$), or layer 3 ($p = 0.0610$). In layer 4, the differences were significant ($p = 0.038$), and the highest mean of heat (34.9 °C) was in shades A3 and C2. The difference was also significant ($p < 0.001$) in layer 5, where it is evident that the highest mean of heat (34.0 °C) was in C2. All the differences between C2 and the other shades were significant ($p < 0.05$), as presented in Table 5.

Table 4. Temperature data measurements at each layer in all five shades of BCRs cured by a polywave (3 s) light-curing unit.

	Mean	SD	Min.	Max.	*p* *	Groups	*p* **	Group	*p* **
L1 (top)									
A1	35.4	3.9	31.1	50.7					
A2	36.1	5.2	30.8	53.0					
A3	35.5	4.5	30.7	47.8	0.507 †				
B1	35.8	4.3	30.8	50.2					
C2	36.4	4.6	31.3	51.0					
Total	35.9	4.5	30.7	53.0					
L2									
A1	35.1	2.9	31.4	42.7					
A2	35.3	3.7	30.8	45.0					
A3	35.5	3.9	30.5	45.5	0.355 †				
B1	35.6	3.4	31.4	44.4					
C2	36.1	3.3	31.6	44.1					
Total	35.5	3.4	30.5	45.5					
L3									
A1	34.7	2.1	31.7	39.4					
A2	34.5	2.5	30.9	40.3					
A3	34.6	2.6	30.2	40.3	0.412 †				
B1	34.9	2.2	31.7	39.8					
C2	35.1	2.1	31.8	40.0					
Total	34.7	2.3	30.2	40.3					
L4									
A1	33.9	1.5	31.6	37.5					
A2	33.8	1.7	30.9	37.1					
A3	33.7	2.3	29.7	40.8	0.111 †				
B1	34.0	1.6	31.3	37.8					
C2	34.4	1.4	31.9	37.3					
Total	34.0	1.7	29.7	40.8					
L5 (bottom)									
A1	33.0	1.0	31.1	34.6		A1 × A2	0.204	A2 × B1	0.634
A2	32.7	1.2	30.6	35.0		A1 × A3	0.007	A2 × C2	0.057
A3	32.4	1.5	29.0	35.5	0.012	A1 × B1	0.427	A3 × B1	0.059
B1	32.9	0.9	31.0	34.5		A1 × C2	0.525	A3 × C2	0.001
C2	33.1	0.9	31.0	34.7		A2 × A3	0.158	B1 × C2	0.153
Total	32.8	1.1	29.0	35.5					

* By Kruskal–Wallis test. ** By post-hoc test (Bonferroni). † Post-hoc test was not conducted because the difference was not significant.

Nearly the same pattern as in the previous tables can be observed in Table 6 (10 s curing time), where the mean temperature decreased consistently from 37.3 °C in layer 1 to 33.7 °C in layer 5. No significant association was detected between heat generation and shades in layer 1 ($p = 0.658$), layer 2 ($p = 0.427$), or layer 3 ($p = 0.550$). In layer 4, the difference between the shades was significant ($p = 0.001$). The highest mean of heat (35.4 °C) was in C2, and the lowest (34.1 °C) was in A3. The same pattern can be observed in layer 5 ($p < 0.001$), where the highest mean of heat generation (34.4 °C) was in C2, and the lowest (32.5 °C) was in A3. More details are presented in Table 6.

Table 5. Temperature data measurements at each layer in all five shades of BCRs cured by a polywave (5 s) light-curing unit.

	Mean	SD	Min.	Max.	*p* *	Groups	*p* **	Group	*p* **
L1 (top)									
A1	36.1	5.7	29.0	55.7					
A2	36.9	5.3	30.8	52.0					
A3	37.0	5.1	31.5	51.1	0.084 †				
B1	36.5	5.5	31.2	55.0					
C2	38.0	5.6	32.4	53.1					
Total	36.9	5.5	29.0	55.7					
L2									
A1	35.6	4.6	29.1	48.5					
A2	35.9	4.0	31.0	46.0					
A3	36.5	4.0	31.8	48.1	0.102 †				
B1	35.7	3.8	31.3	48.1					
C2	36.9	3.7	32.7	47.6					
Total	36.1	4.0	29.1	48.5					
L3									
A1	34.6	3.0	29.3	40.9					
A2	35.2	3.0	31.1	44.2					
A3	35.6	2.7	31.6	41.3	0.061 †				
B1	35.4	2.8	31.4	43.4					
C2	36.0	2.5	32.4	41.3					
Total	35.4	2.8	29.3	44.2					
L4									
A1	33.9	2.4	29.1	38.3		A1 × A2	0.406	A2 × B1	0.962
A2	34.3	2.0	31.0	39.0		A1 × A3	0.017	A2 × C2	0.074
A3	34.9	2.0	31.5	39.5	0.038	A1 × B1	0.434	A3 × B1	0.110
B1	34.3	1.8	31.1	37.8		A1 × C2	0.009	A3 × C2	0.811
C2	34.9	1.6	32.1	38.4		A2 × A3	0.121	B1 × C2	0.066
Total	34.5	2.0	29.1	39.5					
L5 (bottom)									
A1	32.5	1.7	28.9	36.2		A1 × A2	0.018	A2 × B1	0.989
A2	33.2	1.3	30.9	35.7		A1 × A3	0.001	A2 × C2	0.002
A3	33.5	1.2	30.7	35.5	<0.001	A1 × B1	0.019	A3 × B1	0.265
B1	33.2	1.1	31.1	35.3		A1 × C2	<0.001	A3 × C2	0.042
C2	34.0	1.1	31.4	35.8		A2 × A3	0.271	B1 × C2	0.002
Total	33.3	1.4	28.9	36.2					

* By Kruskal–Wallis test. ** By post-hoc test (Bonferroni). † Post-hoc test was not conducted because the difference was not significant.

It is evident from Table 7 (20 s light-curing time) that, in general, the mean of heat generation was higher than in the previous three tables, with means of heat generation of 41.3 °C in layer 1, 40.2 °C in layer 2, 38.8 °C in layer 3, 37.3 °C in layer 4, and 35.5 °C in layer 5. No significant differences were detected between the heat generation and the shades in layer 1 ($p = 0.156$), layer 2 ($p = 0.331$), or layer 3 ($p = 0.197$), but there were significant differences in layer 4 ($p = 0.002$) and layer 5 ($p < 0.001$). In layer 4, the highest mean of heat generation was in C2 (38.4 °C) and the lowest (36.4 °C) was in B1. In layer 5, the highest

and lowest means were also in C2 (36.7 °C) and B1 (34.5 °C). Other details are presented in Table 7.

Table 6. Temperature data measurements at each layer in all five shades of BCRs cured by a polywave (10 s) light-curing unit.

	Mean	SD	Min.	Max.	*p* *	Groups	*p* **	Group	*p* **
L1 (top)									
A1	37.3	5.3	31.7	55.3					
A2	37.2	5.6	31.2	52.9					
A3	36.9	5.7	31.0	54.3	0.658 †				
B1	37.7	5.5	31.0	53.1					
C2	37.4	5.0	31.6	53.0					
Total	37.3	5.4	31.0	55.3					
L2									
A1	36.8	3.9	32.0	47.5					
A2	36.5	4.3	31.4	48.4					
A3	36.3	4.6	31.1	47.9	0.427 †				
B1	36.4	3.8	30.7	47.8					
C2	37.1	4.0	31.8	48.6					
Total	36.6	4.1	30.7	48.6					
L3									
A1	36.3	2.9	32.4	42.5					
A2	36.1	3.5	31.5	47.0					
A3	35.7	3.4	31.1	43.0	0.550 †				
B1	35.8	2.9	30.5	43.2					
C2	36.3	2.8	31.7	43.7					
Total	36.1	3.1	30.5	47.0					
L4									
A1	35.6	2.1	32.3	40.4		A1 × A2	0.143	A2 × B1	0.676
A2	35.0	2.1	31.5	39.1		A1 × A3	<0.001	A2 × C2	0.265
A3	34.1	2.0	31.0	38.0	0.001	A1 × B1	0.060	A3 × B1	0.055
B1	34.8	1.9	31.0	38.0		A1 × C2	0.727	A3 × C2	0.001
C2	35.4	2.1	32.0	40.3		A2 × A3	0.019	B1 × C2	0.125
Total	35.0	2.1	31.0	40.4					
L5 (bottom)									
A1	33.9	1.1	31.6	35.7		A1 × A2	0.623	A2 × B1	0.386
A2	33.9	1.6	31.0	37.1		A1 × A3	<0.001	A2 × C2	0.032
A3	32.5	1.2	30.1	34.9	<0.001	A1 × B1	0.174	A3 × B1	<0.001
B1	33.6	1.2	30.9	35.4		A1 × C2	0.099	A3 × C2	<0.001
C2	34.4	1.3	32.0	37.0		A2 × A3	<0.001	B1 × C2	0.003
Total	33.7	1.4	30.1	37.1					

* By Kruskal–Wallis test. ** By post-hoc test (Bonferroni). † Post-hoc test was not conducted because the difference was not significant.

Tables 3–7 display the temperature profiles, which include the peak temperature increases during polymerization with various LCU types (polywave vs. monowave), light intensity, and BCR materials. The monowave LCU (Elipa DeepCure-L) results revealed that the peak (highest) temperatures during polymerization ranged from 30.7 to 70.0 °C. This included the temperature rise brought on by the curing light's irradiance as well as the reaction's exotherm. The top layer of the A3 shade BCR material had the highest peak tem-

perature (70 °C), whereas the bottom layers—especially those from the B1 shade—showed the lowest peak temperature (30.7 °C). When the Woodpecker O-Star Wide-Spectrum Curing Light (Polywave LCU) was applied, the peak temperature dropped and ranged from 28.9 to 63.6 °C. The top layer of the C2 shade BCR had the highest peak temperature (63.6 °C) after curing in normal mode for 20 s at an intensity of 1200 mW/cm^2. When the A1 shade BCR was polymerized for 5 s at 2000 mW/cm^2, the bottom layer displayed the lowest peak temperature of 28.9 °C.

Table 7. Temperature data measurements at each layer in all five shades of BCRs cured by a polywave (20 s) light-curing unit.

	Mean	SD	Min.	Max.	*p* *	Groups	*p* **	Group	*p* **
L1 (top)									
A1	41.4	7.5	32.7	60.0					
A2	41.7	7.7	31.4	58.8					
A3	41.2	7.3	31.7	59.6	0.156 †				
B1	39.6	6.7	31.0	55.2					
C2	42.6	8.4	33.2	63.6					
Total	41.3	7.5	31.0	63.6					
L2									
A1	40.1	5.4	32.8	53.0					
A2	40.8	6.1	32.7	53.9					
A3	40.7	6.2	32.0	55.7	0.331 †				
B1	39.0	5.4	30.7	50.7					
C2	40.6	5.4	33.6	54.1					
Total	40.2	5.7	30.7	55.7					
L3									
A1	38.6	3.8	32.8	48.1					
A2	38.6	4.1	32.5	47.9					
A3	38.4	4.1	32.0	47.9	0.197 †				
B1	38.4	4.3	31.5	47.6					
C2	39.8	4.1	34.1	48.6					
Total	38.8	4.1	31.5	48.6					
L4									
A1	37.7	2.9	32.8	43.3		A1 × A2	0.480	A2 × B1	0.079
A2	37.4	3.0	31.3	42.6		A1 × A3	0.072	A2 × C2	0.052
A3	36.8	3.0	31.3	42.3	0.002	A1 × B1	0.014	A3 × B1	0.505
B1	36.4	2.8	31.1	41.3		A1 × C2	0.216	A3 × C2	0.002
C2	38.4	2.8	33.7	44.1		A2 × A3	0.275	B1 × C2	<0.001
Total	37.3	3.0	31.1	44.1					
L5 (bottom)									
A1	35.4	1.8	32.2	39.2		A1 × A2	0.824	A2 × B1	0.013
A2	35.5	2.2	30.2	39.8		A1 × A3	0.805	A2 × C2	0.002
A3	35.5	2.2	31.3	40.0	<0.001	A1 × B1	0.024	A3 × B1	0.012
B1	34.5	1.9	30.2	37.6		A1 × C2	0.001	A3 × C2	0.002
C2	36.7	2.0	32.4	40.0		A2 × A3	0.980	B1 × C2	<0.001
Total	35.5	2.1	30.2	40.0					

* By Kruskal–Wallis test. ** By post-hoc test (Bonferroni). † Post-hoc test was not conducted because the difference was not significant.

3.2. Degree of Conversion

When using monowave light curing, there was a significant association between the mean degree of conversion (DC) with shades (p = 0.015), but this association was not consistent, as the lowest DC mean was of A3 (94.1%), which was significantly lower than the means of A1 (p = 0.006), A2 (p = 0.007), and C2 (p = 0.003), as presented in Table 8.

Table 8. Degree of conversion (%) by shades in each different category of light-curing intensity and time.

Shades	Mean	SD	Min.	Max.	p *	Groups	p **	Groups	p **
Monowave									
A1	96.8	1.3	95.4	98.5		A1 × A2	0.962	A2 × B1	0.167
A2	96.7	1.7	95.6	99.6		A1 × A3	0.006	A2 × C2	0.698
A3	94.1	1.7	92.3	95.9	F(4,20) = 4.036 0.015	A1 × B1	0.154	A3 × B1	0.131
B1	95.5	1.2	93.8	97.0		A1 × C2	0.733	A3 × C2	0.003
C2	97.1	0.5	96.5	97.7		A2 × A3	0.007	B1 × C2	0.083
Total	96.0	1.7	92.3	99.6					
3 s									
A1	97.7	1.0	96.8	99.1		A1 × A2	0.003	A2 × B1	0.058
A2	94.7	1.6	92.8	96.2		A1 × A3	<0.001	A2 × C2	0.183
A3	90.3	2.0	87.2	92.8	F(4,20) = 21.037 <0.001	A1 × B1	0.171	A3 × B1	<0.001
B1	96.5	1.2	94.8	97.7		A1 × C2	0.053	A3 × C2	<0.001
C2	95.9	0.8	94.8	96.8		A2 × A3	<0.001	B1 × C2	0.532
Total	95.0	2.9	87.2	99.1					
5 s									
A1	96.8	2.3	93.3	99.0		A1 × A2	0.389	A2 × B1	0.078
A2	97.9	1.1	96.2	99.3		A1 × A3	0.001	A2 × C2	0.163
A3	91.7	2.1	89.2	94.6	F(4,20) = 6.575 0.002	A1 × B1	0.341	A3 × B1	0.008
B1	95.5	1.4	93.3	97.0		A1 × C2	0.576	A3 × C2	0.003
C2	96.0	3.0	91.4	99.0		A2 × A3	<0.001	B1 × C2	0.689
Total	95.6	2.9	89.2	99.3					
10 s									
A1	97.6	1.4	95.3	98.7		A1 × A2	0.659	A2 × B1	0.862
A2	97.0	1.6	95.0	98.9		A1 × A3	0.208	A2 × C2	0.378
A3	96.0	3.0	91.2	99.2	F(4,20) = 0.666 0.623	A1 × B1	0.540	A3 × B1	0.505
B1	96.8	1.6	94.4	98.3		A1 × C2	0.192	A3 × C2	0.963
C2	96.0	1.4	94.3	97.7		A2 × A3	0.403	B1 × C2	0.477
Total	96.7	1.8	91.2	99.2					
20 s									
A1	97.1	2.3	94.4	99.9		A1 × A2	0.857	A2 × B1	0.900
A2	96.9	1.0	95.3	97.9		A1 × A3	0.405	A2 × C2	0.204
A3	96.2	2.1	94.1	99.2	F(4,20) = 0.830 0.522	A1 × B1	0.957	A3 × B1	0.436
B1	97.0	1.0	95.6	98.1		A1 × C2	0.151	A3 × C2	0.527
C2	95.5	1.6	93.4	97.5		A2 × A3	0.512	B1 × C2	0.165
Total	96.6	1.7	93.4	99.9					

* By ANOVA test. ** By post-hoc test (LSD).

When the light-curing time was 3 s, there was also a significant association between the mean of the DC and the shades (p < 0.001), and nearly the same pattern was observed, where the lowest DC mean was for A3 (90.3%), which was significantly lower than the means of A1 (p < 0.001), A2 (p < 0.001), B1 (p < 0.001), and C2 (p < 0.001). The A2 mean was also significantly lower than the A1 mean (p = 0.003).

Still, the same pattern could be observed when the light-curing time was 5 s (p = 0.002), and the lowest mean of the DC was in A3 (91.7%), which was significantly lower than the means of A1 (p = 0.001), A2 (p < 0.001), B1 (p = 0.008), and C2 (p = 0.003).

No significant association was detected between the DC and shades when the curing time was 10 s (p = 0.623) or 20 s (p = 0.522), as presented in Table 8.

It is evident from Table 9 that there were no significant differences for the L1 shade in the means of the degree of conversion (DC) of different curing times (p = 0.844), but there were significant differences (p = 0.029) for the L2 shade, and the lowest DC mean was 94.7% when the curing time was 3 s. This mean was significantly lower than the other means for the monowave (p = 0.038) at 5 s (p = 0.002), 10 s (p = 0.018), and 20 s (p = 0.025). For the L3 shade, the differences between the DC means of different curing times were also significant (p = 0.001), but here the means of the 3 s (90.3%) and the 5 s (91.7%) curing times were significantly lower than the other means. In B1 and C2, the differences between the means of the DC of different curing times were not significant (p = 0.209, and p = 0.679, respectively), as presented in Table 9.

Table 9. Degree of conversion (%) by different light-curing intensity and time in each different shade category.

Curing Time	Mean	SD	Min.	Max.	p *	Groups	p **	Groups	p **
A1									
monowave	96.8	1.3	95.4	98.5		0 × 3	0.384	3 × 10	0.887
3 s	97.7	1.0	96.8	99.1		0 × 5	0.995	3 × 20	0.569
5 s	96.8	2.3	93.3	99.0	F(4,20) = 0.346 0.844	0 × 10	0.464	5 × 10	0.461
10 s	97.6	1.4	95.3	98.7		0 × 20	0.759	5 × 20	0.754
20 s	97.1	2.3	94.4	99.9		3 × 5	0.381	10 × 20	0.668
Total	97.2	1.6	93.3	99.9					
A2									
0 * **	96.7	1.7	95.6	99.6		0 × 3	0.038	3 × 10	0.018
3 s	94.7	1.6	92.8	96.2		0 × 5	0.206	3 × 20	0.025
5 s	97.9	1.1	96.2	99.3	F(4,20) = 3.383 0.029	0 × 10	0.730	5 × 10	0.350
10 s	97.0	1.6	95.0	98.9		0 × 20	0.840	5 × 20	0.284
20 s	96.9	1.0	95.3	97.9		3 × 5	0.002	10 × 20	0.886
Total	96.7	1.7	92.8	99.6					
A3									
0 * **	94.1	1.7	92.3	95.9		0 × 3	0.013	3 × 10	0.001
3 s	90.3	2.0	87.2	92.8		0 × 5	0.093	3 × 20	0.000
5 s	91.7	2.1	89.2	94.6	F(4,20) = 6.989 0.001	0 × 10	0.192	5 × 10	0.005
10 s	96.0	3.0	91.2	99.2		0 × 20	0.154	5 × 20	0.004
20 s	96.2	2.1	94.1	99.2		3 × 5	0.352	10 × 20	0.898
Total	93.7	3.1	87.2	99.2					
B1									
0 * **	95.5	1.2	93.8	97.0		0 × 3	0.240	3 × 10	0.678
3 s	96.5	1.2	94.8	97.7		0 × 5	0.999	3 × 20	0.503
5 s	95.5	1.4	93.3	97.0	F(4,20) = 1.617 0.209	0 × 10	0.118	5 × 10	0.118
10 s	96.8	1.6	94.4	98.3		0 × 20	0.073	5 × 20	0.073
20 s	97.0	1.0	95.6	98.1		3 × 5	0.239	10 × 20	0.797
Total	96.3	1.4	93.3	98.3					
C2									
0 * **	97.1	0.5	96.5	97.7		0 × 3	0.299	3 × 10	0.973
3 s	95.9	0.8	94.8	96.8		0 × 5	0.338	3 × 20	0.705
5 s	96.0	3.0	91.4	99.0	F(4,20) = 0.582 0.679	0 × 10	0.314	5 × 10	0.960
10 s	96.0	1.4	94.3	97.7		0 × 20	0.162	5 × 20	0.644
20 s	95.5	1.6	93.4	97.5		3 × 5	0.933	10 × 20	0.680
Total	96.1	1.6	91.4	99.0					

* By ANOVA test. ** By post-hoc test (LSD). Note: *** is monowave.

The degree of conversion of different shades of BCRs when cured with different light intensities and times is shown in Tables 8 and 9. The maximum degree of conversion (99.9%) was in the A1 shade when it was cured by polywave light-cure (Woodpecker O-Star Wide-Spectrum Curing Light) at normal intensity of 1200 mW/cm^2 for 20 s, while the minimum degree of conversion (87.2%) was seen in the A3 shade when it was cured by a polywave light-curing unit at the highest intensity of 3000 mW/cm^2 for 3 s.

4. Discussion

This research aimed to investigate the effect of light-curing intensity and wavelength spectrum on the heat generation and chemo-mechanical properties of five shades of BCRs. Our null hypotheses were not supported within the parameters of our investigation. The observed temperature increases and patterns of each composite were significantly impacted by the LCU type's light intensity and the shades ($p < 0.05$). There were significant differences ($p < 0.05$) in the temperature changes between the monowave and polywave LCUs with varying light intensity and matching curing times.

The current investigation found that when the curing period increased the temperature changed proportionately, which contradicts the conclusions drawn from earlier research [17,18]. Because of the exothermic polymerization reaction and the energy absorbed during polymerization, the rate of polymerization determines the temperature increase during resin curing. Light energy density increases with increasing light intensity. This may cause more energy to be absorbed during the polymerization process as heat, raising the temperature [19]. This study showed that the use of a monowave light-curing unit will produce the maximum peak heat generation, in contrast to another study that showed that a polywave light-curing unit produced the maximum heat generation [18].

The study's findings show that the temperature rises almost as soon as the light source is turned on, peaking in a matter of 3 to 20 s. There are two cooling phases: a slow, steady phase occurs between the temperature peak and the conclusion of curing, and a quick phase occurs between the end of the curing cycle and the temperature monitoring period.

The following shades were evaluated, with varying overall temperature changes during curing, and were tested in ascending order: B1, A1, A2, C2, and A3. There are several methods for classifying composite shades. The commonly used resin composite hues are arranged in the following sequence if grouping is conducted based on brightness degree: B1, A1, B2, D2, A2, C1, C2, D4, A3, D3, B3, A3.5, B4, C3, A4, and C4.

From the first temperature peak to the completion of the photocure, the composite's temperature steadily dropped. Our study found that the peak temperatures were recorded for the darker shades in comparison to the lighter shades, and the temperatures of the darker shades remained higher than those of the lighter ones, a result that is supported by a previous study [20]. This could suggest that the darker shades were exposed to a continuous pace of polymerization and heat response over this period. The longer time taken for light to reach the darker hues and start polymerization could be because there were more free radicals and leftover monomers present after the initial polymerization peak. It has been demonstrated that to reach the same depth of cure, darker composite shades require longer exposure than lighter shades [21]. Conversely, darker shades might hold onto the heat because of the kind and quantity of the pigments in the resin matrix.

According to earlier research, a temperature increase of 5.5–5.6 °C might have some negative effects on the pulp [22]. Pulp temperature rise should be kept as low as feasible during the polymerization of resin ingredients to avoid any possibility of hurting the pulp. The critical temperature rise that causes pulp necrosis and the period required are still debatable [22], highlighting how crucial it is to choose the right LCU and cure intensity.

Regarding the degree of conversion, again our null hypothesis was rejected because using different shades and light cures significantly affected the results of the degree of conversion ($p < 0.05$). Whereas our study showed that a high degree of conversion of up to 90% could be recorded for the different shades, generally, these numbers were not recorded in the previous studies. Just one study showed that in one composite type the

degree of conversion was 94% [23], which was recorded after 24 h of sample preparation and agrees with our test results for the same time interval used. The recording of these high numbers might be due to the presence of two novel methacrylate monomers in this composite brand (3M™ Filtek™ One Bulk Fill Restorative, St.Paul, Minnesota, USA). The manufacturer claims that the first monomer is a high-molecular-weight aromatic urethane dimethacrylate (AUDMA), which decreases the number of reactive groups in the resin. This helps to moderate the volumetric shrinkage as well as the stiffness of the developing and final polymer matrix—both of which contribute to the development of polymerization stress. The second unique methacrylate represents a class of compounds called addition fragmentation monomers (AFM), and, like any other methacrylate, AFM reacts with the growing polymer during polymerization, forming cross-links between neighboring polymer chains. During polymerization, a third reactive site in AFM cleaves by a fragmentation mechanism. This procedure offers a way for the growing network to unwind and therefore relieve tension. Nonetheless, the fragments can still react with other reactive sites in the growing polymer or with one another. In this way, stress reduction is achievable without compromising the polymer's physical characteristics.

A previous study found that one bulk-fill restorative, Filtek, showed the lowest degree of conversion (30.62%) in comparison to the other bulk-fill composites used [18], which is not in agreement with our research, since our degree of conversion along all the five shades was beyond (90%). This may be due to use of a different methodology or insufficient light intensity.

Different shades play an important role in the degree of conversion, and our study showed that brighter colors (e.g., B1) have a higher degree of conversion compared to dark shades, with A3 showing the lowest degree of conversion in comparison to all intensities of light cures for the other colors. In this regard, our findings agree with [24] which found that darker shades showed lower degrees of conversion in comparison to lighter colors. The type and quantity of dark pigments, which absorb more light, may be the cause of the discrepancy, since they reduce the amount of free radicals available for polymerization, which lowers their DC [20]. Furthermore, it has been demonstrated that to achieve the same cure depth, darker shades require more irradiation than lighter shades [25].

Another investigation revealed that the effectiveness of polymerization can be affected by shade [26]. The lighter shades in this investigation had the greater DC.

It is harder to transmit light through dark shades, because of their opacity. Since the photopolymerization initiation rate is dependent on the incident light intensity, the DC decreases when the light intensity is lower.

5. Conclusions

Within the limitations of the current study, the conclusions are as follows: the maximum heat generations recorded are more related to the extent of curing time than the increases in the intensity of light curing; darker shades of composite lead to more heat generation in comparison to lighter shades and also retain more heat than lighter ones; lighter shades of bulk-fill composite lead to a higher percentage of conversion in comparison to darker shades when the time of the curing is increased.

Author Contributions: H.A.H. made substantial contributions to conception and design, acquisition of data, analysis, and interpretation of data. H.M.M.S. was involved in drafting the manuscript and revising it critically for important intellectual content. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data will be available upon request.

Acknowledgments: Zamand Saeed, Lazyan Lateef, Hana Abdulsalam, Aras jalal, the authors are sincerely grateful to all the above individuals for helping throughout the study.

Conflicts of Interest: The authors do not have any personal financial interests related to the subject matters discussed in this manuscript.

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