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UV Exposure Time Optimization for Enhanced Conversion, Hardness, and Flexural Strength in UDMA/TEG-DMA Composite Resins

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Abstract

This study examines the effects of varying ultraviolet (UV) exposure times on the properties of UDMA/TEG-DMA composite resins, focusing on degree of conversion, surface morphology, water absorption, shrinkage, hardness, and flexural strength. Composite resin samples were exposed to UV light for 30, 60, 90, and 120 min. The degree of conversion was assessed using Fourier Transform Infrared Spectroscopy (FTIR). Surface morphology was analyzed via Scanning Electron Microscopy (SEM). Water absorption and shrinkage were measured following standard procedures, while mechanical properties, including hardness and flexural strength, were evaluated using a Vickers hardness tester and a 3-point bending test, respectively. The results indicate that a UV exposure time of 90 min optimizes the composite resin properties, achieving the highest degree of conversion at 77 %, optimal surface morphology, minimal water absorption and shrinkage, and superior mechanical properties, including maximum flexural strength and hardness. In contrast, both shorter and longer UV exposure times detrimentally affected these properties, with prolonged exposure causing thermal degradation and reduced performance. This research underscores the importance of precise UV curing time control to enhance the performance and durability of UDMA/TEG-DMA composite resins, providing valuable insights and practical guidelines for their application in dental and industrial fields.

Keywords: UDMA/TEG-DMA composite resin, UV exposure, Degree of conversion, Surface morphology, Mechanical properties, Water absorption, Shrinkage

Introduction

Composite resins have revolutionized both dental and industrial fields due to their unique combination of properties. In dentistry, composite resins are predominantly used for restorative procedures, such as fillings, veneers, crowns, and inlays [1]. They offer a distinct advantage over traditional materials like amalgam due to their superior aesthetic properties, as they can be closely matched to the natural color of teeth. Additionally, composite resins exhibit excellent adhesion to dental structures Cadenaro *et al.* [2], reducing the need for extensive tooth preparation and preserving more of the natural tooth. Their biocompatibility ensures that they do not elicit adverse reactions in patients, making them a safe and reliable choice for dental restorations [3].

In industrial applications, composite resins are valued for their mechanical strength, chemical resistance, and versatility. They are extensively used in the manufacturing of high-performance components in the automotive and construction industries [4]. Composite resins can be tailored to enhance durability, flexibility, and resistance to environmental factors Hsissou *et al.* [5], making them ideal for use in coatings, adhesives, and structural materials in sensor applications [6]. The advancement of composite resin technology has also led to significant improvements in the efficiency and sustainability of manufacturing processes. For example, the use of photoinitiators and UV curing systems enables rapid and controlled polymerization, reducing production times and energy consumption [7]. This enhances productivity and minimizes the environmental impact of manufacturing operations. The significance of composite resins lies in their ability to combine functional performance with aesthetic and environmental benefits. Their continued development and optimization have the potential to further expand their application across various fields, driving innovation and improving outcomes in both dental and industrial contexts.

Urethane dimethacrylate (UDMA) and triethylene glycol dimethacrylate (TEG-DMA) are prominent monomers used in the formulation of composite resins due to their exceptional properties that enhance the performance of these materials [8,9]. UDMA is known for its high mechanical strength and excellent wear resistance, crucial for dental restorations that endure significant masticatory forces [10]. The molecular structure of UDMA, with its multiple functional groups, allows for extensive cross-linking during polymerization, resulting in a highly durable and stable polymer network. This characteristic makes UDMA-based resins particularly suitable for applications that require long-term reliability and resistance to mechanical degradation. Previous studies have demonstrated the significant role of UDMA in enhancing the mechanical performance and wear resistance of dental composites, making it a preferred choice for high-stress applications [8].

TEG-DMA complements UDMA by imparting flexibility and improved handling characteristics to the composite resins. TEG-DMA acts as a diluent monomer, reducing the viscosity of the resin mixture and facilitating easier manipulation and placement during dental procedures. This is especially beneficial in achieving precise and smooth finishes in dental restorations. Moreover, TEG-DMA enhances the overall degree of conversion during the curing process, leading to a more complete polymerization and improved mechanical properties of the final composite [11]. The presence of ethylene glycol units in TEG-DMA also contributes to the toughness and impact resistance of the resin, making it more resilient under dynamic loading conditions. Studies have shown that the inclusion of TEG-DMA improves the handling and performance characteristics of composite resins, making them easier to use and more effective in clinical settings.

A photoinitiator is a compound that, upon exposure to light, generates reactive species (free radicals or cations) capable of initiating polymerization [12]. In the context of dental and industrial composite resins, photoinitiators are crucial because they enable the controlled curing of the resin through light exposure, typically ultraviolet (UV) or visible light [13]. This process is essential for achieving the desired mechanical properties and durability of the composite material. Photoinitiators can be broadly classified into 2 types: Type I (cleavage-type) and Type II (hydrogen abstraction-type). Type I photoinitiators, such as TPO, generate free radicals through a unimolecular bond cleavage upon light exposure. Type II photoinitiators, such as CQ, require a co-initiator (typically an amine) to produce free radicals through a bimolecular reaction. The choice of photoinitiator and its concentration can significantly impact the polymerization kinetics, degree of conversion, and final properties of the composite resin [13,14].

Numerous studies have investigated the effects of different photoinitiators on the polymerization and performance of composite resins. For example, investigations into the use of CQ and TPO have shown that each photoinitiator offers distinct advantages and disadvantages. CQ is commonly used in dental applications due to its effective initiation of polymerization under visible light and its ability to produce composites with good mechanical properties. Studies have shown that CQ, when used in combination with co-initiators such as ethyl 4-dimethylaminobenzoate (EDMAB), can significantly enhance the degree of conversion and mechanical strength of the composite resin [15]. TPO, on the other hand, is known for its high reactivity under UV light, which helps achieve a higher degree of conversion and faster curing times. Research has demonstrated that TPO-based photoinitiating systems can produce composites with superior hardness and flexural strength compared to CQ-based systems [16]. However, TPO is less commonly used in dental applications due to its absorption spectrum being primarily in the UV range, which requires specialized light sources.

The previous research has shown that combining CQ and TPO can result in a synergistic effect, improving the overall properties of the composite resin [17]. This combination was selected over other potential initiators based on its proven effectiveness in previous studies and its ability to meet the specific needs of UDMA/TEG-DMA resin systems. Previous studies have extensively explored the effects of various photoinitiators on the properties of composite resins. For instance, Tichy and P Bradna [18] investigated the use of CQ and TPO in dental composites and found that TPO-based composites exhibited higher hardness and degree of conversion compared to CQ-based composites. Similarly, Kowalska *et al.* [19] demonstrated that the combination of CQ and TPO could enhance the curing efficiency and mechanical properties of dental composites, highlighting the potential of using multiple photoinitiators to achieve optimal performance. These findings underscore the importance of selecting appropriate photoinitiators and optimizing their concentrations to achieve the desired properties in composite resins.

Despite the valuable insights provided by existing studies, several gaps remain in the current understanding of UDMA and TEG-DMA-based composite resins. Notably, the optimal UV exposure times required to maximize the degree of conversion, hardness, and flexural strength of these resins are not well-defined, necessitating further investigation to establish effective curing guidelines. Additionally, while previous research has explored certain mechanical properties, a more comprehensive analysis that includes surface morphology, water absorption, and shrinkage in relation to UV exposure times is needed. This would provide a more holistic view of resin performance. Furthermore, the long-term stability and durability of UDMA/TEG-DMA composites under various UV curing conditions are not well-documented, highlighting the need for studies focusing on the aging and longevity of these materials.

The primary objectives of this research are to determine the optimal UV exposure time required to achieve the maximum degree of conversion in UDMA/TEG-DMA composite resins and to assess how this optimal exposure time impacts the hardness (HV) and flexural strength of the materials. Additionally, this research aims to analyze the effects of varying UV exposure times on surface morphology, water absorption, and shrinkage. This study introduces a novel approach by systematically exploring the effects of varying UV exposure times on a comprehensive set of properties of UDMA/TEG-DMA composite resins. By identifying the optimal UV exposure conditions, this research will contribute to the development of more reliable and efficient composite resins for both dental and industrial applications.

Materials and methods

The materials used in this study include urethane dimethacrylate (UDMA), triethylene glycol dimethacrylate (TEG-DMA), camphorquinone (CQ), and diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide (TPO), all sourced from Sigma-Aldrich with a purity of 99 %. **Table 1** presents the composition design and variations in sample curing time. Initially, CQ and TPO were manually mixed using an agate mortar in a darkened room to prevent premature polymerization. This photoinitiator mixture was then combined with UDMA and TEG-DMA in a glass beaker and stirred on a magnetic stirrer at 100 rpm for 1 h, with intermittent manual stirring using a glass spatula. Once a paste-like consistency was achieved, the mixture was subjected to ultrasonication in a sonicator water bath for 15 min. The composite resin was then poured into coin-shaped fumed silica molds. These molds were exposed to UV light using the CURE lamp (Ivoclar Vivadent Pty Ltd) at an output power of 50 J/cm^2. In addition to the detailed investigation of UV exposure times, this study employs innovative aspects in its experimental setup that set it apart from previous research. Specifically, the use of a custom-designed UV curing chamber with precise control over exposure duration and intensity allows for a more accurate assessment of optimal curing conditions. The exposure times were varied to 60, 90, 120, 150, and 180 min according to the curing time variations specified in **Table 1**. The sample codes are designated as CRCT-x, where “x” represents the specific UV curing time. The UV exposure times were selected based on previous research that these durations could potentially reveal significant changes in the properties of UDMA/TEG-DMA composite resins (ref). The chosen time intervals allow for a detailed examination of the effects of varying UV exposure on degree of conversion, hardness, and flexural strength. Furthermore, this range was selected to align with conventional curing practices while also providing insight into the upper limits of UV exposure effects.

Table 1 Composition design and variations in sample curing time.

UDMA (wt. %)	TEG-DMA (wt. %)	CQ (wt. %)	TPO (wt. %)	UV Curing time (min)	Sample codes
50	50	0.2	0.4	60	CRCT-60
				90	CRCT-90
				120	CRCT-120
				150	CRCT-150
				180	CRCT-180

The surface morphology of the composite resins was analyzed using Scanning Electron Microscopy (SEM) models Zeiss and JEOL 6510LV. In addition to the qualitative analysis, surface roughness was quantified using Atomic Force Microscopy (AFM). Raman spectroscopy was performed using Fourier Transform Infrared (FTIR) Spectroscopy with an Agilent Cary 670 spectrometer, operating in the range of 9000 - 375 cm^{-1}. The excitation laser was directed at the most prominent area of the cylindrical specimen surface, positioned at the focus of the collecting lens with an excitation diameter of 0.3 mm. The degree of conversion (DC) or polymerization kinetics between 1500 - 1800 cm^{-1} was determined by measuring the relative change in the peak height of the spectral band at 1640 cm^{-1} (aliphatic C=C stretching). The bands at 1458 cm^{-1} (C-H stretching) were used as reference bands. The DC was calculated according to Eq. (1). The levels of water absorption and shrinkage were evaluated following ISO 4049 and ISO-17304 procedures, respectively, using Eq. (2) for water absorption and Eq. (3) for shrinkage.

$$\mathrm{DC}(\%) = \left(1 - \frac{\left(\frac{h_{1640}}{reference}\right)cured}{\left(\frac{h_{1640}}{reference}\right)uncured}\right) \times 100 \tag{1}$$

$$\mathrm{WS} = \frac{(m_2 - m_1)}{v} \tag{2}$$

$$\mathrm{S} = \frac{\rho_c - \rho_u}{\rho_c} x100 \tag{3}$$

Hardness (HV) was assessed using a ZWICK ZHV2 hardness tester (Zwick-Roell, Ulm, Germany), equipped with a Vickers indenter. A normal load of 10 N was applied for 10 s. Hardness values were calculated automatically, and 9 measurements per material were performed on randomly selected areas of the sample surface. Flexural strength was tested using a Universal Testing Machine (3-point test) (Jinan Hensgrand Instrument Co., Ltd) after storing the samples in distilled water at 37 °C for 24 h. The evaluation followed the International Standard ISO-4049 guidelines, with the exception of sample dimensions. The unpolymerized composite resin was placed into a silicone mold (10×2×2 mm^3) and cured on both sides for 20 s using a UV lamp. Post-polymerization, the specimen dimensions (n = 10) were measured with a digital caliper accurate to 0.01 mm. Flexural strength and elasticity modulus (E) for each specimen were obtained from the automatic computerized chart recorder and analyzed with using TestXpert® III.

Results and discussion

Surface morphology

Figure 1 presents SEM images at a magnification of 10,000x for the entire set of samples. Sample CRCT-60 reveals a rough morphology with an uneven surface, characterized by visible bumps and cracks. This suggests an incomplete polymerization process, where insufficient UV exposure time has not allowed for a full cross-linking of the resin components [20,21]. Sample CRCT-90 shows a smoother and flatter surface with only a single small mound. The surface becomes noticeably more homogeneous, with only minor imperfections. This improvement suggests that additional UV energy facilitates a higher degree of monomer conversion, resulting in better cross-linking. The presence of only a small mound indicates that while the polymerization is more complete, there may still be areas of inconsistency due to variations in UV light penetration or resin composition.

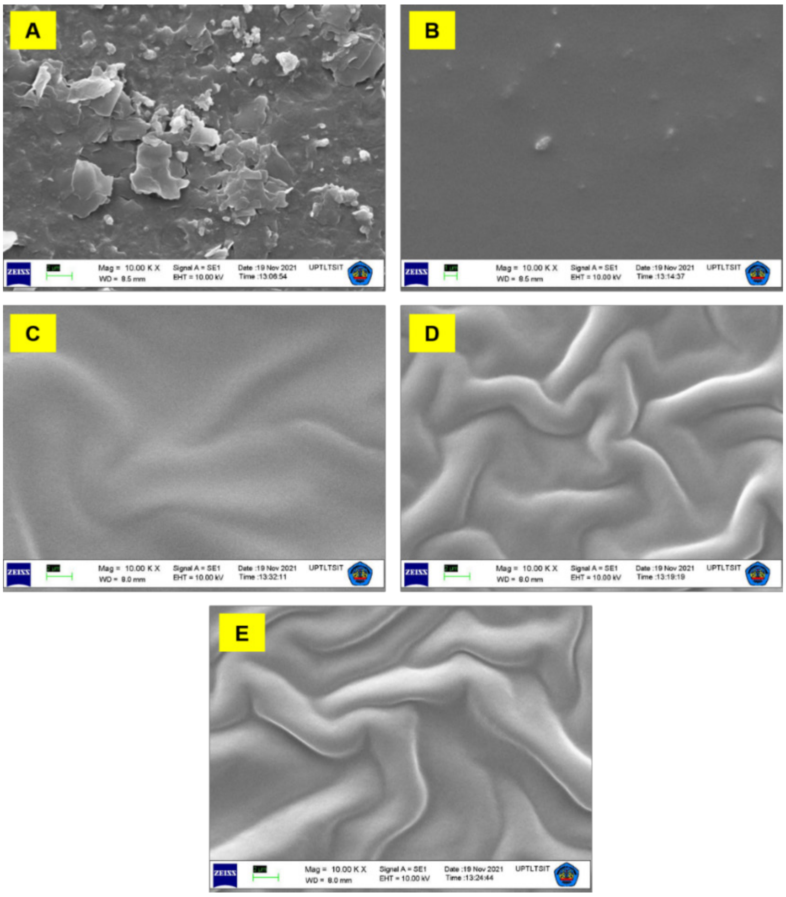

Figure 1 SEM image of UDMA/TEG-DMA composite resins at 10000 times of magnification with various UV curing time of (A) 60, (B) 90, (C) 120, (D) 150, and (E) 180.

Sample CRCT-120 exhibits the formation of hill waves on its surface, indicating an intermediate stage where increased UV exposure has started more significant polymerization, though uniformity has not yet been achieved. Sample CRCT-150 shows more pronounced hill waves, suggesting that polymerization is becoming more extensive and structured with longer exposure times. Finally, sample CRCT-180 reveals that the hill waves have evolved into overlapping folds, signifying a highly developed polymer network. At 120 min of exposure (CRCT-120), the surface begins to exhibit wave-like structures, referred to as hill waves. This phenomenon suggests that the polymer network is forming more extensively, and the resin is undergoing significant structural changes [22].

The appearance of hill waves can be indicative of increased internal stresses and reorganization within the polymer matrix as the cross-linking process becomes more advanced [23]. By 150 min of UV exposure (CRCT-150), the hill waves become more pronounced, indicating that the polymer network is continuing to develop and solidify. The increased prominence of these waves suggests a higher degree of internal stress release and stabilization within the polymer structure [24]. The surface morphology at this stage is more defined, reflecting a mature stage of polymerization.

At the longest exposure time of 180 min (CRCT-180), the surface morphology is characterized by overlapping folds. This complex structure indicates a highly developed polymer network with extensive cross-linking. The folding suggests that the material has undergone significant reorganization, potentially due to the relaxation of internal stresses and the final stages of polymerization. This highly cross-linked structure results in a more rigid and stable composite resin [22]. The roughness average (Ra) values were determined for each sample, providing a detailed measure of surface texture. The results showed a clear trend of decreasing Ra values with increasing UV exposure time. Specifically, the Ra values were 0.98 μm for CRCT-60, 0.73 μm for CRCT-90, 0.61 μm for CRCT-120, 0.47 μm for CRCT-150, and 0.32 μm for CRCT-180. This progressive decrease in surface roughness indicates a smoother and more uniform surface morphology as UV exposure time increases. These quantitative measurements corroborate the SEM observations, demonstrating that extended UV exposure leads to a more complete polymerization process and a higher degree of cross-linking within the composite resin matrix. This results in reduced surface irregularities and a more refined surface texture, highlighting the importance of optimizing UV curing times to enhance the performance and reliability of UDMA/TEG-DMA composite resins [25].

The observed trends in surface morphology with increasing UV exposure time can be explained by the principles of photopolymerization. Longer UV exposure times provide more energy to activate the photoinitiators (CQ and TPO) in the resin mixture, leading to a higher degree of monomer-to-polymer conversion [26]. This increased conversion results in more extensive cross-linking within the polymer matrix, producing a smoother and more homogeneous surface. Additionally, the increased UV exposure allows for the completion of polymerization reactions, reducing the presence of unreacted monomers and improving the overall integrity of the composite resin [27]. This finding has significant implications for practical applications, particularly in dental restorations. A smoother and more homogeneous surface enhances the bonding strength between the composite resin and dental tissues, leading to more durable and reliable restorations. In industrial applications, the enhanced surface characteristics and mechanical properties resulting from optimal UV curing conditions can improve the performance of composite resins in high-stress environments.

Degree of conversion (DC)

Table 2 presents the degree of conversion (DC) data for UDMA/TEG-DMA composite resins subjected to varying UV curing times. The degree of conversion represents the percentage of monomers that have polymerized into a cross-linked network. The degree of conversion (DC) is a critical parameter that determines the mechanical and physical properties of polymer composite resins. In this study, the DC values were found to vary significantly with different UV curing times. The highest DC value (77 %) was observed for the sample cured for 90 min (CRCT-90), while the lowest DC value (54 %) was recorded for the sample cured for 180 min (CRCT-180).

Table 2 Degree of conversion of UDMA/TEG-DMA composite resins with various UV curing time.

No	Sample codes	DC (%)
1	CRCT-60	61
2	CRCT-90	77
3	CRCT-120	65
4	CRCT-150	59
5	CRCT-180	54

The DC value increased from 61 % (CRCT-60) to 77 % (CRCT-90) as shown in **Figure 2**, indicating that extending the UV curing time from 60 to 90 min allowed for a more complete polymerization process. With longer UV exposure, more photoinitiators (CQ and TPO) are activated, generating more free radicals that initiate the polymerization of the monomers [7,28]. This leads to a higher degree of monomer conversion. Longer exposure times provide more energy, facilitating the cross-linking reactions necessary for forming a stable polymer network [29]. In addition, UV exposure helps to mitigate the effects of oxygen inhibition, a common issue in free-radical polymerization where oxygen interferes with the polymerization process [21]. Prolonged UV curing can reduce the concentration of oxygen at the surface, enhancing polymerization. Interestingly, the DC values decreased after 90 min of curing highlights the adverse effects of overexposure to UV light. Prolonged UV exposure can lead to thermal degradation of the polymer network [5].

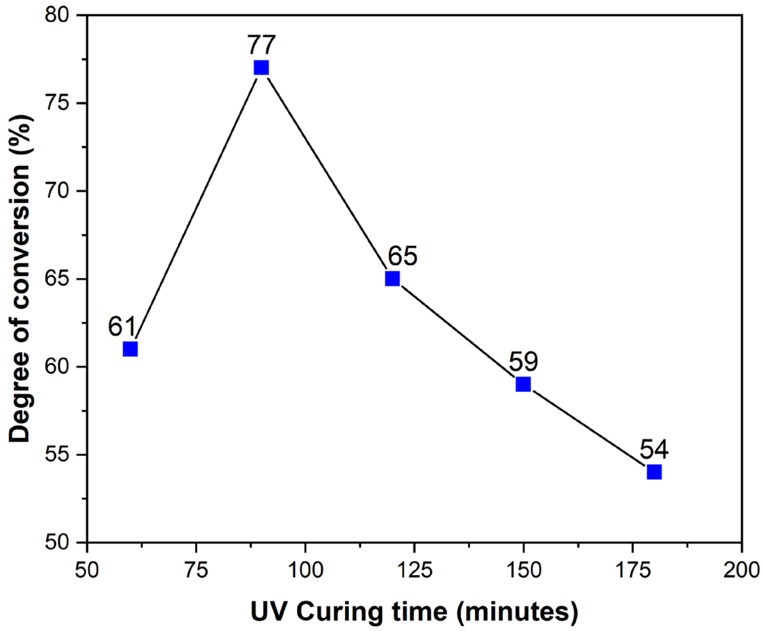

Figure 2 Values of the degree of conversion (%) as a function of UV curing time of UDMA/TEG-DMA composite resins.

Excessive heat generated during long UV curing times can break down polymer chains, reducing the overall degree of conversion. Extended exposure can lead to the depletion of photoinitiators [30]. Once the photoinitiators are exhausted, no new free radicals are generated to continue the polymerization process, resulting in a plateau or decrease in the degree of conversion [31]. As polymerization progresses, the system becomes more viscous, leading to vitrification - a state where the mobility of the reactive species is severely restricted. This can trap unreacted monomers and hinder further polymerization, resulting in a lower degree of conversion [32].

The surface morphology observed in the SEM images correlates with the degree of conversion data. The smoother surface of CRCT-90 aligns with its highest DC value, indicating a more complete and uniform polymerization process [25]. Conversely, the irregular and uneven textures of CRCT-60 and CRCT-180 are associated with lower DC values, which suggest incomplete polymerization and possible degradation. Previous research backs this observation, showing that ideal UV exposure times are essential for attaining the highest degree of conversion and optimal mechanical properties. For instance, Par *et al.* [33]. found that optimal light transmittance and degree of conversion were achieved with specific exposure times, beyond which the performance deteriorated due to similar factors of overexposure and thermal effects. Szczesio-Wlodarczyk *et al.* [9] also highlighted the importance of balancing curing time to maximize polymerization without inducing thermal degradation or vitrification.

Water absorption and shrinkage

Figure 3 graphically represents the water absorption and shrinkage characteristics of UDMA/TEG-DMA composite resins as a function of UV curing time. The optimal UV exposure time of 90 min (CRCT-

90) results in the lowest water absorption (0.50 %) and shrinkage (0.26 %). This can be attributed to the optimal degree of conversion and cross-linking density achieved at this curing time.

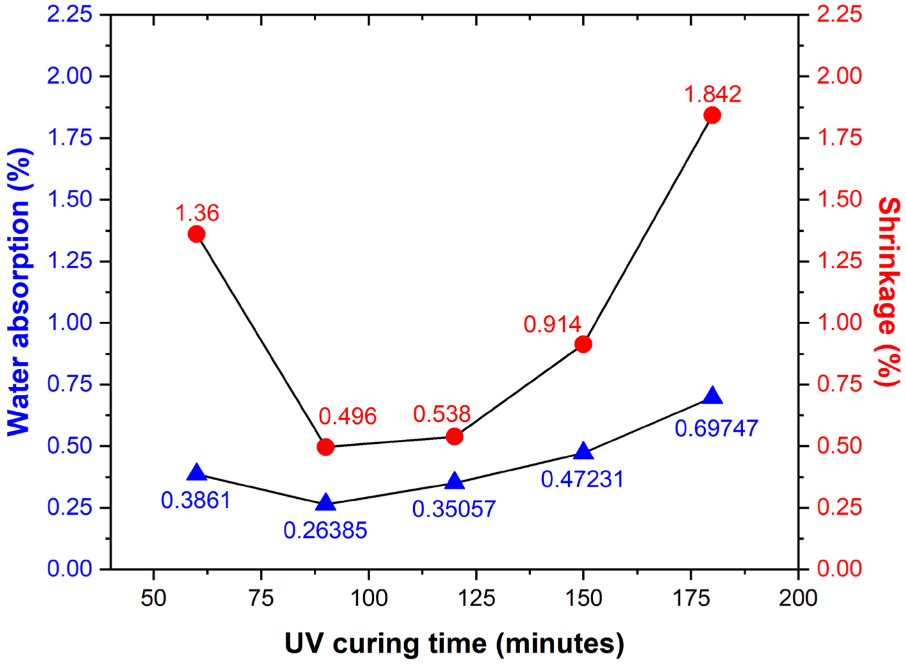

Figure 3 Water absorption and shrinkage characteristics of UDMA/TEG-DMA composite resins as a function of UV curing time.

Higher degrees of conversion and cross-linking create a more tightly packed polymer network, which reduces the composite's affinity for water [26,34]. This is supported by studies like Par *et al.* [33], which found that increased polymerization leads to less water absorption due to a denser polymer matrix. Increased polymerization generally leads to greater shrinkage due to the reduction in volume as monomers convert to a polymer network. However, the data indicate that an optimal curing time minimizes this shrinkage. The shrinkage values are lowest at 90 min of curing (0.26 %), indicating that optimal polymerization has been achieved without significant over-curing. This balance reduces internal stresses and deformation, supporting better dimensional stability.

Extended UV exposure times (CRCT-150 and CRCT-180) result in increased water absorption and shrinkage. This can be attributed to thermal degradation and increased porosity, as indicated by Lempel *et al.* [27], who reported that rapid high-intensity curing can lead to greater porosity and unreacted monomer elution. These porosities increase the material's water absorption capacity, facilitating hydrolysis and degradation of the composite resin [35]. Increased water absorption allows water molecules to penetrate the resin matrix, leading to the hydrolysis of ester bonds within the polymer network. This hydrolytic degradation weakens the composite's structural integrity by breaking down the polymer chains, which results in diminished mechanical properties and increased brittleness [7]. Additionally, the presence of water accelerates the leaching of unreacted monomers and other residual compounds, further reducing the resin's durability. These factors highlight the need to optimize UV curing conditions to achieve a balance between adequate polymerization and minimal thermal and structural damage, thereby improving the long-term performance of UDMA/TEG-DMA composite resins.

Mechanical properties

Figure 4 illustrates the strain-stress relationship for the 5 samples, with a separate graph embedded for the CRCT-60 sample due to its significantly lower stress values. The CRCT-90 sample exhibited the highest stress at 0.185 MPa, while the CRCT-60 sample showed the lowest stress at 0.018 MPa. This disparity indicates a significant difference in mechanical performance among the samples based on their curing times. **Table 3** presents the data for flexural strength (FM), elastic modulus (EM), and Vickers hardness (HV) test results for each sample. These results show that the mechanical properties of the composite resins vary significantly with different UV curing times.

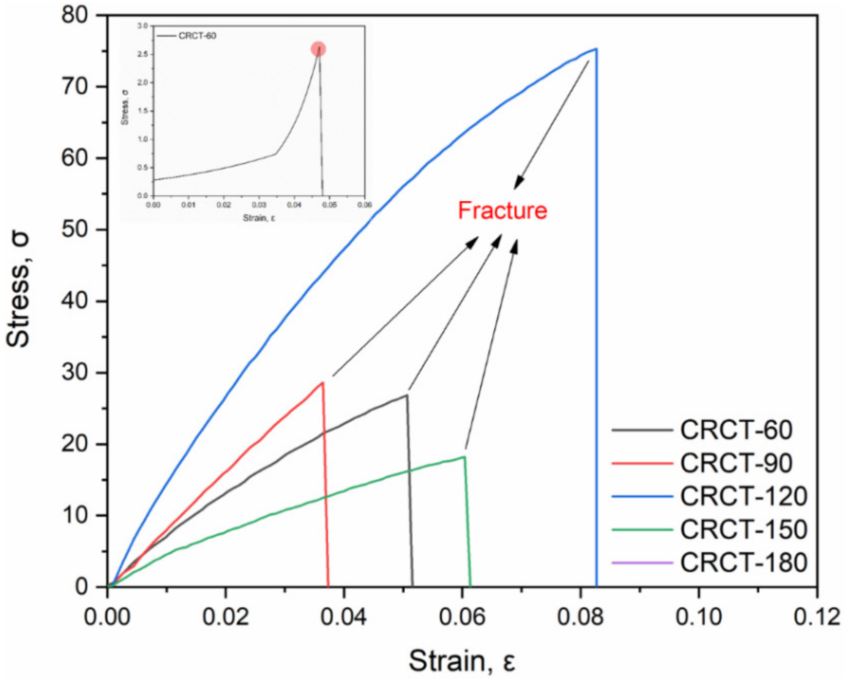

Figure 4 Strain-stress curve of UDMA/TEG-DMA with different UV curing time.

The CRCT-90 sample demonstrated the highest flexural strength, elastic modulus, and hardness, indicating an optimal balance of curing conditions that maximized these properties [26]. This aligns with Wlodarczyk's [9] findings, where a composite resin of UDMA/bis-GMA/TEG-DMA/HEMA exhibited a flexural strength of 92.9 MPa, an elastic modulus of 128 MPa, and a hardness value of 16. Similarly, Krasowski *et al*. [8] reported a flexural strength of 84.38 MPa, an elastic modulus of 1.85 GPa, and a hardness value of 27 for UDMA/bis-EMA/TEGMA/bis-GMA resin composites. The enhanced degree of conversion (DC) correlates with increased hardness and flexural strength. A higher degree of conversion results in the CRCT-90 sample having a more rigid and cohesive polymer network, thus improving the mechanical properties of the composite resin [23].

Table 3 Mechanical Properties of UDMA/TEG-DMA Composite Resins at Various UV Curing Times.

No	Sample codes	Flexural Strngth (MPa)	Elasticity Modulus (GPa)	Hardness Vickers
1	CRCT-60	89.7	1.23	16
2	CRCT-90	225.4	5.12	29
3	CRCT-120	210	4.63	25
4	CRCT-150	190.95	2.47	17
5	CRCT-180	180.58	1.89	19

The CRCT-90 sample had the best overall mechanical properties, suggesting that this curing time allowed sufficient polymerization without inducing excessive internal stresses or porosity. On the other hand, extended UV exposure times (CRCT-150 and CRCT-180) resulted in decreased mechanical properties, likely due to over-curing, leading to increased porosity and potential thermal degradation, as discussed [27]. The increase in porosity and unreacted monomer elution at higher UV exposure times can facilitate water absorption and hydrolytic degradation, as previously discussed. Therefore, while a higher degree of conversion generally enhances mechanical strength, excessive UV exposure can have the opposite effect, emphasizing the need for careful optimization of curing protocols to achieve the best mechanical performance of UDMA/TEG-DMA composite resins.

Conclusions

This study systematically investigates the impact of varying UV exposure times on the properties of UDMA/TEG-DMA composite resins. An optimal UV exposure time of 90 min was identified, resulting in the highest degree of conversion (77 %), superior surface morphology with minimal imperfections, and the most favorable mechanical properties, including maximum flexural strength and hardness. Additionally, this optimal curing time resulted in the lowest water absorption and shrinkage, indicating improved structural integrity and dimensional stability. Both shorter and longer exposure times negatively impacted these properties. The optimal UV exposure time of 90 min has significant practical benefits for dental restorations and industrial applications, enhancing bonding strength, longevity, and overall performance. These findings fill a critical gap in current knowledge and suggest future research directions, including the long-term durability and clinical performance of optimized composite resins under realistic conditions and exploring alternative photoinitiators and resin formulations. Future research should focus on investigating the long-term durability and clinical performance of these optimized composite resins under realistic conditions, such as extended exposure to oral environments in dental applications or various stress conditions in industrial settings. Additionally, exploring the effects of alternative photoinitiators and resin formulations could further enhance the understanding and application of these materials.

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