

Mechanically Enhanced Soft Contact Lenses from Photodimerization Cross-Linking

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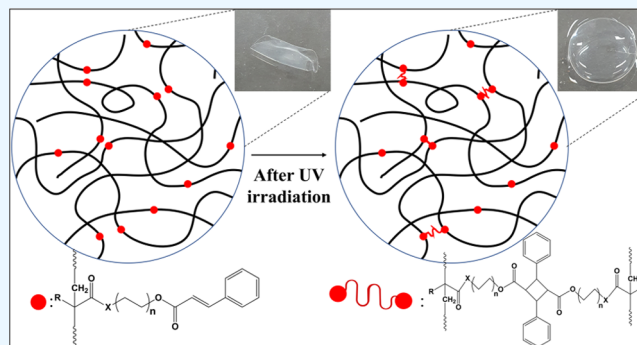


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ABSTRACT: In this study, we synthesized three novel acrylic monomers with a cinnamate group. We then mixed each monomer with 2-hydroxyethyl methacrylate (HEMA) to prepare soft contact lenses through bulk polymerization. Fourier transform infrared (FT-IR) and UV spectral analyses confirmed that the cinnamate group in the polymer undergoes a photodimerization reaction via UV irradiation. After UV curing, the present lenses stably maintained their shapes even in a water-swollen state and showed significantly improved mechanical properties compared to conventional lenses manufactured using a cross-linking agent. These lenses showed slightly lower water contact angles than the conventional lenses, although the water content was slightly reduced. The present photodimerization cross-linking method was found to be useful in reducing the tearability of soft lenses.



1. INTRODUCTION

A contact lens is worn directly on an eyeball for visual acuity correction and cosmetic effects. It is classified into hard and soft lenses, depending on its material. Hard lenses comprise poly(methyl methacrylate) and silicone-based rigid gas permeable lenses. These lenses exhibit optical excellence and mechanical durability because of their hydrophobic and amorphous structure but are relatively less comfortable to wear due to the hardness of the material.^{1,2} In comparison, soft lenses are made of a hydrophilic amorphous hydrogel material, which has a high water content and a low contact angle to water. Thus, they are much softer, more flexible, and more comfortable to wear than hard lenses,³ but they can easily tear compared to hard lenses, as they are always worn or stored in a water-swollen state. These lenses are manufactured using a cross-linking agent, which forms a network structure between polymer chains through chemical bonding, allowing shape stability of the lenses even in a water-swollen state.

In acrylic soft lenses that use ethylene glycol dimethacrylate (EGDMA), cross-linking cores and polymerization are generated at the same time. This forms a network structure with a significantly suppressed chain mobility (Figure 1a). Thus, hydrodynamic dimensional stability is secured, but elongation and flexibility are sacrificed, leading to a decrease in tensile strength in polymer gels.^{4,5} Lenses for astigmatism correction are very thin in some parts because a gradient in the thickness of the lens is necessary for optical purposes.⁶ Thus, this causes more frequent tearing of such lenses compared to that of lenses for other purposes. It is thus essential to develop a soft lens with a high tensile strength.

As mentioned above, the conventional cross-linking method sacrifices the elongation and flexibility of the soft lens, limiting the improvement of its tensile strength.^{7,8} On the other hand, photochemically induced polymer network structure has been examined in various research fields, such as biomedical, coating, and lithography.⁹ Thus, we thought of introducing a site-to-site linking network structure into the lens through a photodimerization reaction to manufacture soft contact lenses with improved mechanical properties. Accordingly, in this study, acrylic monomers having a photoreactive group were synthesized and then used in the manufacturing of the lens (Figure 2). These monomers contain a cinnamate group that readily undergoes a dimerization reaction between the C=C double bonds under UV light.¹⁰ This method formed a network structure by UV light irradiation while maintaining chain mobility after shaping lenses by bulk polymerization (Figure 1b). A low-density cross-linked structure is formed through the photodimerization reaction between the side cinnamate groups while sufficient degree of disorder of the chains in the lens is secured. The manufactured lenses showed high tensile strength and shape stability, even in a water-swollen state.

Received: June 23, 2023

Accepted: August 24, 2023

Published: September 8, 2023



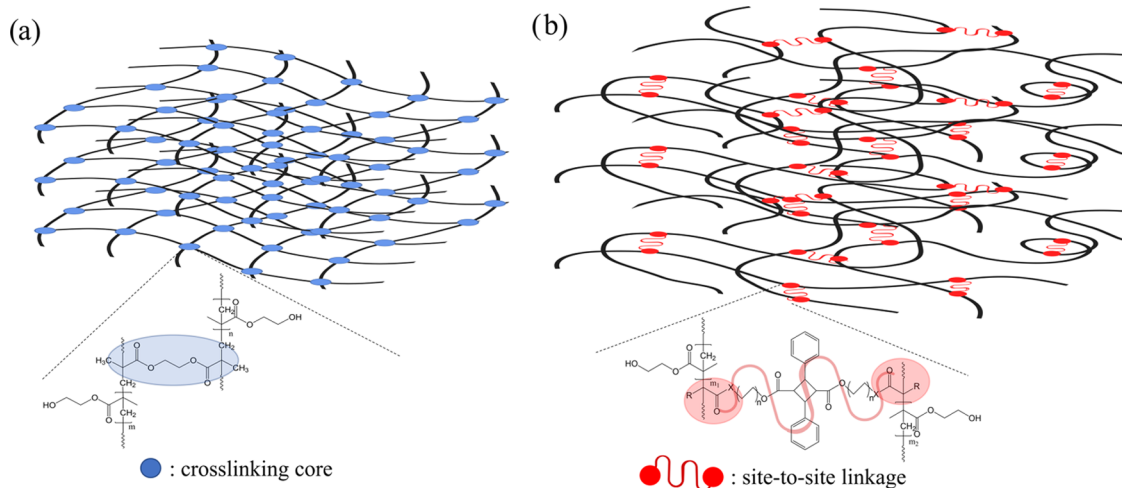


Figure 1. Schematic diagrams of (a) the common network structure and (b) the present one.

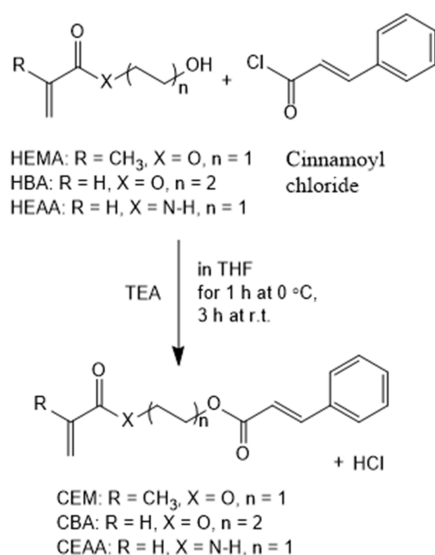


Figure 2. Synthesis of new acrylic monomers containing a cinnamate group.

2. EXPERIMENTAL SECTION

2.1. Materials. Cinnamoyl chloride and EGDMA were purchased from Sigma-Aldrich. 2-Hydroxyethyl methacrylate (HEMA), tetrahydrofuran (THF), and dichloromethane were purchased from Daejung Chemicals & Metals Co. 4-Hydroxybutyl acrylate (HBA) and 2-hydroxyethyl acrylamide (HEAA) were purchased from Tokyo Chemical Industry. Triethylamine (TEA) was purchased from Samchun Chemical Co., Ltd.; 2,2'-azobisisobutyronitrile (AIBN) from Junsei Chemical Co., Ltd.; HCl aqueous solution from DC Chemicals; and MgSO₄ from Duksan Pure Chemicals Co., Ltd. All of these reagents and solvents were used as purchased without purification.

2.2. Synthesis of Monomers. **2.2.1. Synthesis of 2-(Cinnamoyloxy)ethyl Methacrylate (CEM).** For this, 3.254 g (25 mmol) of HEMA was added to a 250 mL three-necked flask in a glovebox and then diluted with 50 mL of THF. In a separate vial, 4.165 g (25 mmol) of cinnamoyl chloride was added and then diluted with 10 mL of THF. After 2.78 g (27.5 mmol) of TEA was added to the flask, it was allowed to react for 1 h by slowly dropping the cinnamoyl chloride solution

while cooling it using an ice bath. Thereafter, the ice bath was removed, and the mixture underwent further reaction at room temperature for 3 h. The solvent was then removed from the reaction vessel by using a rotary evaporator. The remaining solid components were dissolved in dichloromethane and then washed sequentially with a 1 M HCl aqueous solution and distilled water. The organic layer was separated, dried over MgSO₄, and filtered, and the solvent was removed using a rotary evaporator. Finally, it was purified through column chromatography (eluent; dichloromethane). Yield: 68.0%. ¹H NMR (500 MHz, CDCl₃): δ = 7.73, 7.70 (d, 1H, C=CH-C), δ = 7.52–7.54 (d, 2H, aromatic), δ = 7.39, 7.40 (t, 3H, aromatic), δ = 6.45–6.48 (d, 1H, OC-CH=C), δ = 6.15, 6.16 (d, 1H, CH-C=C), δ = 5.60 (t, 1H, CH-C=C), δ = 4.43–4.46 (t, 4H, O-CH₂-CH₂-O), and δ = 1.96 (t, 3H, C=CH-C). FT-IR (ATR): 3100–3000 cm⁻¹ (aromatic C-H stretching), 3000–2840 cm⁻¹ (aliphatic C-H stretching), 1711 cm⁻¹ (conjugated carbonyl C=O stretching), and 1635 cm⁻¹ (alkene C=C stretching).

2.2.2. Synthesis of 4-(Cinnamoyloxy)butyl Acrylate (CBA). To synthesize (CBA), HBA was used instead of HEMA under the same procedures and conditions as in the case of CEM. Yield: 62.0%. ¹H NMR (500 MHz, CDCl₃): δ = 7.67, 7.71 (d, 2H, aromatic), δ = 7.52–7.55 (d, 1H, C=CH-C), δ = 7.38–7.40 (t, 3H, aromatic), δ = 6.39–6.46 (d, 2H, OC-CH=C), δ = 6.10–6.16 (d, 1H, C=CH-C), δ = 5.82–5.84 (d, 1H, CH-C=C), δ = 4.42–4.47 (m, 4H, O-CH₂-C), and δ = 1.79–1.86 (m, 4H, C-CH₂). FT-IR (ATR): 3100–3000 cm⁻¹ (aromatic C-H stretching), 3000–2840 cm⁻¹ (aliphatic C-H stretching), 1710 cm⁻¹ (conjugated carbonyl C=O stretching), and 1636 cm⁻¹ (alkene C=C stretching).

2.2.3. Synthesis of 2-(Cinnamoyloxy)ethyl Acrylamide (CEAA). To synthesize CEAA, HEAA was used instead of HEMA under the same procedures and conditions as those in the case of CEM. Yield: 78.0%. ¹H NMR (500 MHz, CDCl₃): δ = 7.70–7.88 (d, 1H, C=CH-C), δ = 7.51–7.59 (d, 2H, aromatic), δ = 7.38–7.45 (t, 3H, aromatic), δ = 6.43–6.55 (d, 1H, C=CH-C), δ = 6.29–6.33 (d, 1H, OC-CH=C), δ = 6.10–6.15 (d, 1H, OC-CH=C), δ = 6.04 (s, 1H, C-NH-C), δ = 5.66, 5.68 (t, 1H, CH-C=C), δ = 4.35–4.37 (t, 2H, C-CH₂-O), and δ = 3.68–3.71 (q, 2H, N-CH₂-C). FT-IR (ATR): 3292 cm⁻¹ (amide N-H stretching), 3100–3000 cm⁻¹ (aromatic C-H stretching), 3000–2840 cm⁻¹ (aliphatic

Table 1. Properties of Lenses Manufactured in This Study

run	lens components (unit: wt %) ^a					UV curing time (min)	lens properties				
	HEMA	CEM	CBA	CEAA	EGDMA		tensile strength (MPa)	modulus (MPa)	elongation at break (%)	contact angle (deg)	EWC (%)
1	99				1	0	0.41	1.24	124.3	61.4	49.6
2	99	1				0	0.95	4.40	285.4	52.5	37.6
3	99	1				30	0.70	2.76	259.1	56.3	38.0
4	95	5				0	0.83	4.28	196.1	60.4	27.8
5	95	5				30	0.66	3.11	183.9	69.5	40.0
6	90	10				0	0.73	4.50	160.1	65.2	48.5
7	90	10				30	0.57	2.75	148.2	64.2	44.5
8	99		1			0	0.63	3.40	205.7	41.1	39.3
9	99		1			30	0.50	2.65	142.2	42.9	42.2
10	95		5			0	1.04	2.85	342.5	43.6	36.1
11	95		5			30	0.70	2.45	234.8	44.8	42.0
12	90		10			0	1.18	2.93	324.9	51.4	42.4
13	90		10			30	0.85	2.71	276.2	52.0	40.5
14	99			1		0	0.67	3.00	182.1	49.5	38.1
15	99			1		30	0.57	2.37	214.5	43.6	40.6
16	95			5		0	0.76	3.35	189.2	53.7	37.2
17	95			5		30	0.70	4.69	122.6	50.4	37.4
18	90			10		0	0.68	2.64	234.4	62.0	37.0
19	90			10		30	0.64	3.11	183.8	59.9	35.4

^aPolymerized as described in the Experimental Section 2.3

C–H stretching), 1702 cm⁻¹ (conjugated carbonyl C=O stretching), 1662 cm⁻¹ (amide N–H bending), and 1627 cm⁻¹ (alkene C=C stretching).

2.3. Preparation of Lens. The obtained monomer was added in required amounts to a vial containing HEMA and 0.03 wt % AIBN. The mixture was then stirred at room temperature for 30 min. Thereafter, 120 μL of this mixture was put into the lens mold using a micropipette and reacted in a convection oven at 90 °C for 2 h.

2.4. Photodimerization. Only the female mold was removed immediately after polymerization. UV irradiation was performed on the lens attached to the male mold for 30 min using a UV lamp (light intensity: 2.5 mJ/cm²). The lens was then immersed in hot methanol for 30 min to remove the unreacted monomers and initiators. Then, methanol was wiped off the surface of the lens and dried at room temperature; it was stored in a phosphate-buffered saline (PBS) solution.

2.5. Measurements. Tensile strength and elastic modulus: tensile strength and elastic modulus of the lens were measured by using a universal test machine (UTM; SHIMADZU, AGS-X 20N). The specimen was adjusted to have a thickness of 0.145 mm, a width of 10 mm, and a gauge length of 10 mm in the hydrated state and was measured at a speed of 10 mm/min (Figure S1). The experiment was repeated 5 times for each sample, and then the average value was obtained.

2.5.1. Equilibrium Water Content (EWC). The prepared contact lens was immersed in a PBS solution for 48 h, and then water was removed from the surface. The weight of the hydrated lens was measured, and water content was calculated using eq 1. The experiment was repeated three times for each sample to obtain the average value.

$$\text{EWC (\%)} = 100 \times \frac{(\text{hydrated lens weight} - \text{dried lens weight})}{\text{hydrated lens weight}} \quad (1)$$

2.5.2. Contact Angle. The contact angle of the lens was measured using a Phoenix 150 Manual Contact angle analyzer (Surface Electro Optics). A water droplet of 10 μL was dropped on the surface of the hydrated lens, and the angle was measured by reading the photograph.

Fourier transform infrared (FT-IR) spectra were recorded using a JASCO FT/IR-4100 spectrometer (JASCO, Japan) equipped with a JASCO ATR model PR0450-S. ¹H NMR spectroscopy was performed using an AVANCE III 500 MHz spectrometer (Bruker). UV spectra were recorded by using a JASCO V-650 spectrophotometer (JASCO, Japan).

2.5.3. Refractive Index. The measurement was based on an ISO 18369-4. After hydrating the lens in a PBS solution for 24 h, the moisture on the lens surface was removed, and the refractive index was measured using an Abbe refractometer (1T (1212), ATAGO, Japan). Five samples were measured per composition and expressed as the average value.

2.5.4. Oxygen Permeability (Dk). Oxygen permeability analysis was conducted by the polarographic method,¹¹ based on ISO 18369-4, and a lens hydrated in a PBS solution for 24 h was used. The thickness of the lens center was measured using a low pressure dial-gauge (VL-50-B, Mitutoyo, Japan). The current value was measured using an Oxygen Permeation Analyzer (201T, Rehder) while maintaining a temperature of 35 °C and a humidity of 98% in a constant temperature & humidity chamber (WL1000S, Withlab, Korea). Oxygen permeability was calculated using eq 2. The unit of Dk uses 10⁻¹¹ (cm²/s)·(mL·O₂)/(mL·mmHg).

$$Dk = Dk/t \times t \quad (2)$$

where *t* is the thickness of the lens.

2.5.5. Optical Transmittance. Optical transmittance was evaluated according to the Soft (Hydrophilic) Daily Wear Contact Lenses, Performance Criteria for Safety and Performance Based Pathway (FDA-2019-D-4843). Visible light transmittance was also recorded using a JASCO V-650 spectrophotometer (JASCO, Japan). The contact lenses used

to measure light transmittance were used after 24 h of hydration in a PBS solution. The measurement was carried out by inserting a hydrated lens between the slide glasses. The measured results were expressed as an average value of light transmittance from 380 to 780 nm in the visible light region.

3. RESULTS AND DISCUSSION

Polymers having a cinnamate group in the side chain easily undergo photodimerization reaction by UV irradiation, resulting in cross-linking.^{12,13} Thus, in this study, we introduced a cross-linked structure through UV light irradiation to manufacture acrylic-based soft lenses. Novel acrylic monomers having a cinnamate group were obtained in a relatively high yield of more than 60% (CEM, CBA, CEAA in Figure 2) since the electrophile cinnamoyl chloride readily undergoes alcoholysis by the nucleophilic attack of hydroxyl-containing acryl compounds (HEMA, HBA, HEAA). ¹H NMR analysis showed peaks due to the protons of the acryl and cinnamoyl groups. FT-IR analysis confirmed the characteristic vibrational absorption peaks due to these functional groups (¹H NMR, FT-IR spectra, Figure S2 in the Supporting Information).

The new monomers were partially mixed with HEMA to prepare contact lenses through conventional bulk polymerization in a mold, using AIBN as an initiator. HEMA-based lenses containing 1, 5, and 10 wt % of each of the new monomers were obtained (run 2–19 in Table 1). A conventional soft lens (run 1 in Table 1), made from HEMA containing 1 wt % EGDMA, was also fabricated for comparison with the above lenses.

The photodimerization reaction of the cinnamate group in the lens was monitored through FT-IR and UV spectroscopic analysis. However, distinguishable spectral changes were difficult to observe because the lens samples contained only a small amount of cinnamate groups. Therefore, CEM was polymerized alone under the same conditions (90 °C, 2 h) as in the manufacture of HEMA-based lenses and then produced in the form of a film in order to obtain samples suitable for spectroscopic analysis. First, the change in the FT-IR spectra over time was observed while irradiating the film with UV light (Figure 3a). The carbonyl group has a large oscillating electric field due to a large dipole moment and, thus, exhibits a strong vibrational absorption signal in the IR region. The carbonyl group of an unsaturated conjugated ester, such as a cinnamate group, due to a resonance effect, exhibits an absorption signal at a slightly lower wavenumber than the usual carbonyl group of an acrylic group.¹⁴ Typically, the carbonyl group shows a signal at around 1710 cm⁻¹ for the conjugated signal and at 1740 cm⁻¹ for the usual one. The lenses prepared in this study have both types of carbonyl groups. Nevertheless, they could not be distinguished since the two absorption signals overlapped with each other.¹⁵ However, it was observed that the carbonyl peak gradually decreased with the increase in UV irradiation time (inset 1 of Figure 3a). The carbonyl peak was arbitrarily deconvoluted to further investigate the signal change (inset 2 of Figure 3a). The absorption signal at around 1710 cm⁻¹ after UV irradiation decreased, while the one around 1740 cm⁻¹ increased. This observation indicates that the cinnamate group reduces gradually by undergoing the photoisomerization reaction, resulting in the formation of the cyclic cross-linked structure. The absorption signal at 1635 cm⁻¹ due to C=C stretching also showed a decrease with UV irradiation time, reconfirming that the cinnamate group

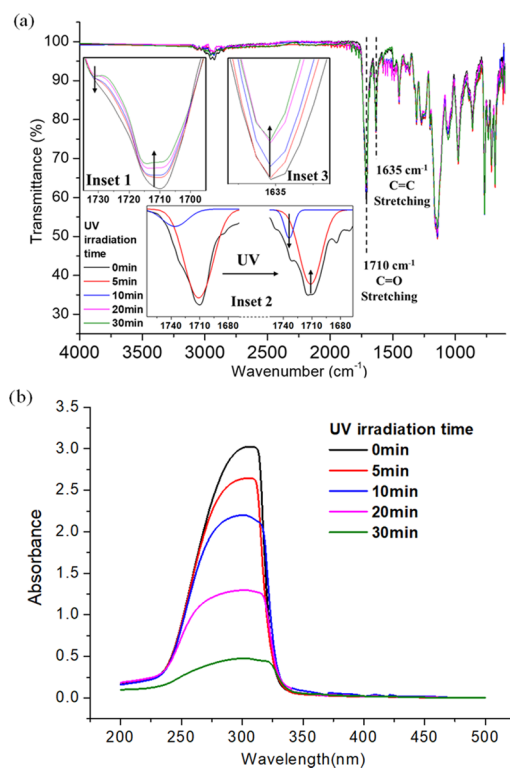


Figure 3. (a) FT-IR and (b) UV spectra of CEM polymer irradiated with UV light. Inset: enlarged peaks.

undergoes photodimerization (inset 3 of Figure 3a). As shown in Figure 3b, the broad absorption band at around 300 nm due to the cinnamate group gradually reduced as the UV irradiation time increased, confirming the photodimerization reaction.

Figure 4 shows the tensile strength and elongation of the lenses hydrated with a PBS solution (*S*–*S* curves in Figure S3). The tensile strength (0.60–1.20 MPa) of the lenses before UV irradiation (run No. 2, 4, 6, 8, 10, 12, 14, 16, 18 in Table 1 and Figure 4a) improved by approximately 1.5–3 times compared to that (0.41 MPa) of the lens cross-linked with EGDMA (run No. 1 in Figure 4a). This could be explained by the increased elongation due to the absence of a cross-linked structure (Figure 4b). However, all of these non-cross-linked lenses were severely distorted when immersed in PBS solution, and the original shape of the lens could not be maintained (photographs, Figure S4). This is because the shape stability deteriorates due to the remarkable hydrodynamic mobility of polymer chains in a water-swollen state, although the elongation and tensile strength are improved. Even though these lenses showed a slight decrease in tensile strength and elongation after UV irradiation (run nos. 3, 5, 7, 9, 11, 13, 15, 17, and 19 in Figure 4a,4b), those values were still higher than that of the EGDMA-cross-linked lens. Eventually, the lenses showed a tensile strength of approximately 0.5 to 0.85 MPa after UV irradiation. Notably, these cured lenses could maintain their shapes even in a water-swollen state (photographs, Figure S4), probably because the formation of a cross-linked structure through the photodimerization reaction induced shape stability. In the case of the CEM-containing lens, the tensile strength of the lens decreased as the amount of added photodimerizable monomer increased. In the CBA-containing lens, on the contrary, the tensile strength of the lens

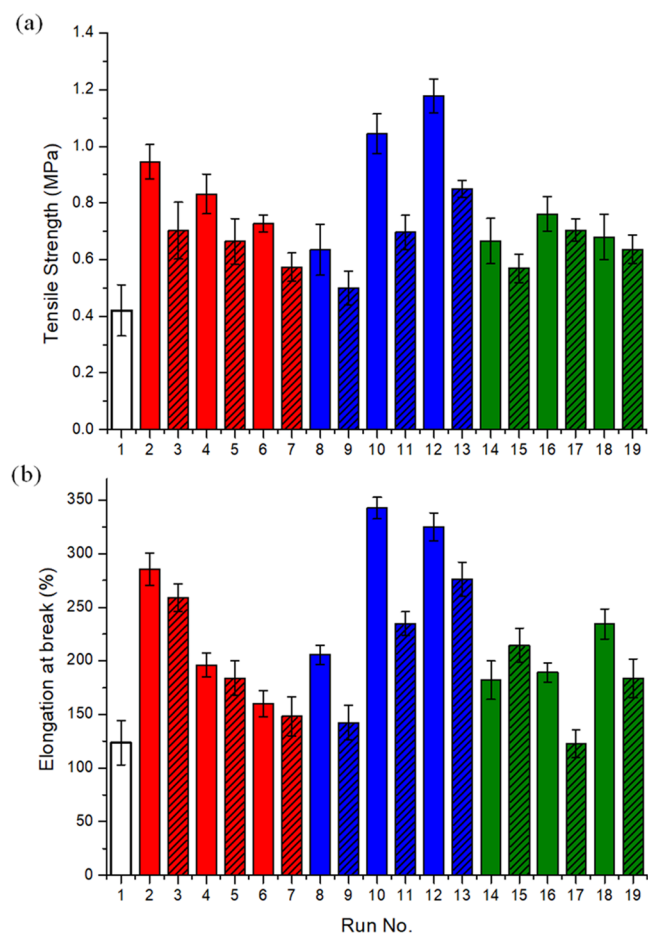


Figure 4. (a) Tensile strength and (b) elongation at break of manufactured lenses in Table 1. Red: CEM-containing lenses, Blue: CBA-containing lenses, Green: CEAA-containing lenses. The shaded peaks indicate that UV irradiation has been performed.

gradually increased as the amount of addition increased. This should be because the alkylene length of the side group is different between the two monomers. Before photodimerization, it is thought that a longer alkylene group plasticizes the lens more, resulting in an increase in the mobility of the main chain. Accordingly, the spacer length of the cross-linked structure formed by photodimerization should also be different between the two monomers (Figure S5). In the case of CBA-containing lens with a longer spacer length, the hydrodynamic mobility of polymer chains is assumed to be effectively maintained in the swollen state even after cross-linking, resulting in increased elongation and tensile strength despite the increase in cross-linking points. In the CEM-containing lens, the increase in cross-linking points resulted in a decrease in elongation and tensile strength since the cross-linking spacer formed by photodimerization is not very long. Meanwhile, the lenses containing CEAA with an amide group in the side chain showed the least significant increase in tensile strength before and after UV irradiation compared to EGDMA-cross-linked lens. This is probably because the sp^2 -hybridized resonance structure of the side amide groups and the strong hydrogen bonding between them restrict the chain mobility even in a swollen state, regardless of the formation of the cross-linking structure. The present lenses showed much higher values (2.37–4.69 MPa in Table 1) even in tensile modulus compared to the EGDMA-cross-linked lens (1.24 MPa). All of the present soft contact lenses cross-linked by photodimerization showed a slightly lower water content (35–45% in Table 1) compared to the EGDMA-cross-linked lens (run No. 1, 49.6%) because they contained the present novel monomers with high hydrophobicity. However, no clear tendency was observed in the variation of water content according to the type and content of the monomer. The contact angles were similar to or slightly lower than that of the EGDMA-cross-linked lens (run No. 1, 61.4°). The CBA-containing lenses showed relatively lower contact angles (41 – 52° in Table 1) because they have the loosest cross-linked

Table 2. Other Properties of Lenses Manufactured in This Study

run	lens components (unit: wt %) ^a					UV curing time (min)	Lens Properties		
	HEMA	CEM	CBA	CEAA	EGDMA		refractive index	oxygen permeability (Dk)	optical transmittance (%)
1	99				1	0	1.438	11.35	95.2
2	99	1				0	1.438	12.01	95.0
3	99	1				30	1.439	11.27	94.9
4	95	5				0	1.448	9.40	93.8
5	95	5				30	1.449	9.05	93.8
6	90	10				0	1.456	7.40	92.1
7	90	10				30	1.458	7.18	92.2
8	99		1			0	1.437	11.70	94.9
9	99		1			30	1.438	10.01	94.9
10	95		5			0	1.442	9.18	92.1
11	95		5			30	1.443	8.79	92.0
12	90		10			0	1.448	7.61	90.3
13	90		10			30	1.449	7.13	90.1
14	99			1		0	1.436	11.70	95.6
15	99			1		30	1.436	11.22	95.3
16	95			5		0	1.443	11.18	93.1
17	95			5		30	1.444	9.70	93.3
18	90			10		0	1.448	8.70	92.0
19	90			10		30	1.450	7.74	91.8

^aPolymerized as described in the Experimental Section 2.3

structure, which causes the water molecules to protrude the most out of the surface of the hydrated lens.

In addition to the above-described characteristics, other physical properties required for soft contacts were evaluated (Table 2). Refractive index indicates how much light is refracted at the interface of two different media. This may be a measure of EWC in soft contact lenses, and the higher the hydrophobicity of the lens, the higher the refractive index.¹⁶ As expected, the higher the content of CEM, CBA, and CEAA, the higher the refractive index. This should be due to the hydrophobicity of these monomers. In hydrogels, since oxygen molecules exist in the aqueous phase, the less hydrophilic the matrix is, the lower the oxygen permeability.¹⁷ In fact, the higher the content of CEM, CBA, and CEAA, the lower the oxygen permeability. Moreover, the oxygen permeability decreased slightly after photodimerization in all lenses. This should be because the free volume in the lens decreases due to the increase in cross-linking density, which slows down the diffusion of oxygen.¹⁸ As the content of the photodimerizable monomers increased, the light transmittance decreased, but all still maintained 90% or more, so they meet the FDA's standards for use (88% or more).

4. CONCLUSIONS

We synthesized three novel acrylic monomers having a cinnamate group. Our findings showed that the fabricated lenses showed improved tensile strength, elongation, and shape stability even in a water-swollen state compared to the conventional EGDMA-cross-linked lens. This study provides a technology that can easily manufacture mechanically enhanced lenses by introducing a simple UV curing process to conventional soft lens manufacturing. Thus, the present photodimerizable monomers, in combination with various hydrophilic acrylic monomers other than HEMA, are expected to be applied in the manufacturing of new, mechanically robust soft lenses.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsomega.3c04489>.

Additional data, including a schematic drawing of UTM loading, FT-IR/¹H NMR spectra of monomers, S–S curves, and photographs of lenses (PDF)

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Author Contributions

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work is the result of the project for fostering the vision aids industry based on advanced functional materials, supported by the ministry of Trade, Industry and Energy.

■ REFERENCES

- (1) Moreddu, R.; Vigolo, D.; Yetisen, A. K. Contact Lens Technology: From Fundamentals to Applications. *Adv. Healthcare Mater.* **2019**, *8*, No. 1900368.
- (2) Musgrave, C. S. A.; Fang, F. Contact Lens Materials: A Materials Science Perspective. *Materials* **2019**, *12*, 261.
- (3) Nicolson, P. C.; Vogt, J. Soft contact lens polymers: an evolution. *Biomaterials* **2001**, *22*, 3273–3283.
- (4) Fernandes, P. A. L.; Schmidt, S.; Zeiser, M.; Fery, A.; Hellweg, T. Swelling and mechanical properties of polymer gels with cross-linking gradient. *Soft Matter* **2010**, *6*, 3455–3458.
- (5) Nam, S. Y.; Nho, Y. C.; Hong, S. H.; Chae, G. T.; Jang, H. S.; Suh, T. S.; Ahn, W. S.; Ryu, K. E.; Chun, H. J. Evaluation of Poly(vinyl alcohol)/Alginate Hydrogels Cross-linked by γ -ray Irradiation Technique. *Macromol. Res.* **2004**, *12*, 219–224.
- (6) Edrington, T. B. A Literature Review: The Impact of Rotational Stabilization Methods on Toric Soft Contact Lens Performance. In *Contact Lens and Anterior Eye*; Elsevier, 2011; Vol. 34, pp 104–110.
- (7) Tranoudis, I.; Efron, N. Tensile Properties of Soft Contact Lens Materials. In *Contact Lens and Anterior Eye*; Elsevier, 2004; Vol. 27, pp 177–191.
- (8) Bhamra, T. S.; Tighe, B. J. Mechanical properties of contact lenses: The contribution of measurement techniques and clinical feedback to 50 years of materials development. In *Contact Lens and Anterior Eye*; Elsevier, 2017; Vol. 40, pp 70–81.
- (9) Blasco, E.; Wegener, M.; Barner-Kowollik, C. Photochemically driven polymeric network formation: synthesis and applications. *Adv. Mater.* **2017**, *29*, No. 1604005.
- (10) Hyer Ali, A.; Srinivasan, K. S. V. Photoresponsive Functionalized Vinyl Cinnamate Polymers: Synthesis and Characterization. *Polym. Int.* **1997**, *310*–316.
- (11) Ye, K. H.; Sung, A. Synthesis and Application for Ophthalmic Material of Polydimethylsiloxane with Methacrylate End group. *J. Korean Chem. Soc.* **2009**, *53*, 335–339.
- (12) Sugiyama, H.; Sato, S.; Nagai, K. Photo-isomerization, photodimerization, and photodegradation polyimides for a liquid crystal alignment layer. *Polym. Adv. Technol.* **2022**, *33*, 2113–2122.
- (13) Bisoyi, H. K.; Li, Q. Light-driven liquid crystalline materials: from photo-induced phase transitions and property modulations to applications. *Chem. Rev.* **2016**, *116*, 15089–15166.
- (14) Infrared Spectroscopy and Mass Spectrometry. In *Organic Chemistry*, 2nd ed.; Klein, D. R., Ed.; Wiley: New York, 2013; Chapter 15.

(15) Jiao, Y.; Guo, J.; Dong, X.; Li, R.; Wei, J. Kinetic Analysis of Solid-State Photodimerization Reaction of Photosensitive Monomers and a Polymer with Cinnamoyl Moieties. *J. Appl. Polym. Sci.* **2010**, *116*, 3569–3580.

(16) Varikooty, J.; Keir, N.; Woods, C. A.; Fonn, D. Measurement of the refractive index of soft contact lenses during wear. *Eye Contact Lens* **2010**, *36*, 2–5.

(17) Tran, N. P. D.; Yang, M. C. Synthesis and characterization of soft contact lens based on the combination of silicone nanoparticles with hydrophobic and hydrophilic monomers. *J. Polym. Res.* **2019**, *26*, No. 143.

(18) Mohammed, A. H.; Ahmad, M. B.; Ibrahim, N. A.; Zainuddin, N. Effect of crosslinking concentration on properties of 3-(trimethoxysilyl) propyl methacrylate/N-vinyl pyrrolidone gels. *Chem. Cent. J.* **2018**, *12*, 15.