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Thermoset Elastomers Derived from Carvomenthide

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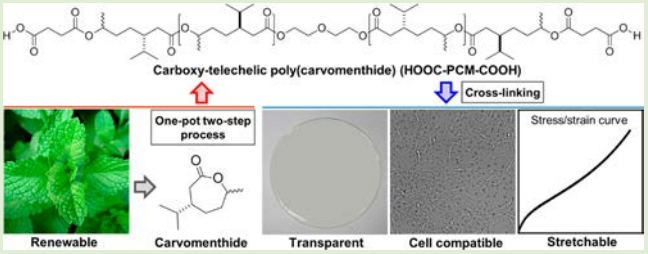
Supporting Information

ABSTRACT: Renewable thermoset elastomers were prepared using the plant-based monomer carvomenthide. Controlled ring-opening transesterification polymerization of carvomenthide using diethylene glycol as an initiator gave α,ω-dihydroxyl poly(carvomenthide) (HO-PCM-OH), which was subsequently converted to carboxy-telechelic poly(carvomenthide) (HOOC-PCM-COOH) by esterification with excess succinic anhydride through a one-pot, two-step process, leading to no crystallinity, high viscosity, strong thermal resistance, and low glass transition temperature of the resulting functionalized polyester. Thermal curing processes of the resulting 3, 6, and 12 kg mol^{-1} prepolymers were achieved with trifunctional aziridine to give cross-linked PCM elastomers. The thermal properties, mechanical behavior, and biocompatibility of the rubbery thermoset products were investigated by differential scanning calorimetry, thermal gravimetric analysis, dynamic mechanical analysis, tensile tests under static and cyclic loads, and cell adherence. These new materials are useful candidates to satisfy the design objective for the engineering of a variety of soft tissues.



INTRODUCTION

Current movement in the chemical industry toward replacing petroleum-based feedstock with renewable alternatives is being driven by (a) concerns about diminishing fossil resources or global warming, (b) present knowledge and technology allowing the processing of one type of biomass, such as lactic acid, furfural, or vegetable oil, with only small capital investment, (c) general demand for renewable or green products from consumers, and (d) concerns on the political side to reduce the dependence on fossil feedstock and to decrease the environment impact.[1] However, renewable feedstock can also provide an interesting sustainable platform through the intended design of biobased polymers having distinct or superior physichemical properties.[2−4]

One biorenewable resource is carvone, which is a component of the oils extracted from caraway seed *Carum carvi* and spearmint *Mentha spicata*.[5] Thousands of tons of carvone are harvested annually and used in the pharmaceutical, flavor, fragrance, insect control, and food industries.[6] Carvone is converted to carvomenthone via hydrogenation, which is subsequently followed by a Baeyer−Villiger oxidation to yield the seven-membered lactone carvomenthide, which is suitable for use as a polymerizable monomer.[7,8]

Telechelic polymer chains having reactive functional groups such as acrylate,[9] epoxide,[10] isocyanate,[11] hydroxyl,[12,13] and amine[14] are basic building blocks for various polymeric materials. In particular, carboxy-telechelic polymers with low molar mass have been highly favored owing to their ability to serve as starting materials for the preparation of polymers having ester and amide linkages.

Direct polymerization can enable a straightforward synthetic route to carboxy-ended polymers. Poly((*R*,*S*)-3-hydroxybutyrate) containing dicarboxylic acid as chain-end functionality was obtained by anionic polymerization of β-butyrolactone initiated by succinic acid disodium salt, which was followed by protonation.[15] Telechelic poly(butyl acrylate) and poly(styrene) with a carboxy group were produced in a single-step procedure with 4,4′-azobis(4-cyanovaleric acid) as an initiator via reversible addition−fragmentation chain transfer (RAFT) polymerization using dicarboxy trithiocarbonate as a chain transfer agent (CTA) and dead-end polymerization, respectively.[16,17] The use of unprotected maleic acid as a CTA led to efficient incorporation of carboxy end groups in

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poly(olefin) during ring-opening metathesis polymerization (ROMP) of the cyclic olefin, *cis*-cyclooctene (COE).[18]

Low T_g carboxy-telechelic poly(olefin)s were synthesized via ROMP of 3-hexyl-*cis*-cyclooctene (3-Hex-COE) and COE with maleic acid as a CTA, followed by subsequent hydrogenation. The prepolymers were chosen for the synthesis of cured elastomers in the presence of polyfunctional aziridines, showing T_g values similar to those of the starting polyolefins and elongations at break up to 230% with tensile strength in the range of 1.05 to 1.74 MPa.[19] Supramolecular polymer gels formed with carboxy-terminated telechelic poly(butadiene) ($PBD(COOH)_2$) and a linear poly(amidine) (PAmd) having an *N*,*N*′-disubstituted acetamidine group through use of a carboxylate salt bridge were studied. The gel exhibited a high G' value of about 1 MPa at ambient temperature and T_{gel} of 37 °C.[20] Viscoelastic properties for supramolecular soft materials formed by ionic hydrogen bonds between carboxy-terminated telechelic poly(ethyl acrylate) ($PEA(COOH)_2$) and poly(ethylenimine) were also investigated.[21]

On the other hand, the postpolymerization functionalization of an end group can lead to carboxy-telechelic macromolecules. End-carboxylated telechelic poly(ε-caprolactone) (PCL) (F = 1.4−2.0) was cross-linked thermally with poly(styrene)-epoxided poly(butadiene)-poly(styrene) triblock copolymer to investigate the curing behavior and the mechanical properties of the thermoset elastomers. The resulting cured polymers, having high temperature elasticity above the T_g of poly(styrene), showed stress−strain curves that depended on the blend ratio and molar mass of the carboxy prepolymer.[22] Mono-, bi-, and trifunctional carboxy-telechelic microspheres were prepared via suspension polymerization of carboxy-terminated oligocaprolactones and divinylbenzene. Their ion-exchange capacities corresponded to the total carboxy amount.[23] The direct polyesterification of hydroxyl-telechelic poly(ethylene terephthalate) (PET) with carboxy-terminated PCL (F = 1.98) or carboxy-ended poly(propylene oxide) (PPO), in which the number of functionality (F) was not determined, was used to synthesize a multiblock poly(ester-ether) exhibiting thermoplastic elastomer properties.[24,25] After the primary hydroxyl end group in poly(tetramethylene oxide) (PTMO) was converted to carboxylic acid with $F \sim 2.0$, as estimated by the chemical titration method, the carboxy-ended PTMO was cured with an epoxy resin and pyromellitic dianhydride (PMDA); the resulting material, however, showed no shape memory properties.[26]

Poly(glycerol sebacate) (PGS), commercially available as the brand Regenerez, is a tough polyester prepared via polycondensation of glycerol and sebacic acid for soft tissue engineering.[27] PGS exhibits biocompatibility, biodegradability, and bioresorbability as highly relevant properties in biomedical applications; in addition, it shows thermoset elastomeric properties.[28−30] The soft elastomeric nature of PGS, shown in its stress−strain curve, is similar to that of vulcanized rubber due to the three-dimensional network of random coils caused by both the covalent cross-linking and the hydrogen-bonding interactions among hydroxyl groups attached to the polymer backbone.[31] PGS materials have a tensile Young's modulus of 0.025 to 1.2 MPa, an ultimate tensile strength over 0.5 MPa, and strain to failure of greater than 330%.[27] The Young's modulus of PGS is between that of ligaments and human myocardium (0.02−0.5 MPa).[32] The maximum strain at break of PGS is similar to that of arteries and vein (<260%). The resulting superior mechanical properties make PGS capable of sustaining deformation, owing to its intrinsic elasticity, and of working in a mechanically dynamic environment such as that of cardiac tissue,[33] vascular tissue,[34] cartilage tissue,[35] retinal tissue,[36] nerve tissue,[37] and tympanic membrane.[38]

Herein, using the ring-opening transesterification polymerization (ROTEP) of carvomenthide (CM) followed by postpolymerization functionalization via a one-pot, two-step process, we report the preparation and characterization of a new thermoset elastomer system from renewable carboxy-telechelic poly(carvomenthide) (PCM). We demonstrated the tin-catalyzed polymerization of CM to give α,ω-dihydroxyl PCM (HO-PCM-OH) with various molar masses (M_n = 3, 5, and 12 kg mol^{-1}), precisely controlled low dispersities ($Đ$ = 1.05−1.09) that lead to a higher cross-linking state in the designed thermoset polymers, and low glass transition temperatures of about −36 °C without any crystallinity. We also prepared α,ω-dicarboxy-functionalized PCM (HOOC-PCM-COOH) prepolymer, through esterification of the polyol with succinic anhydride (SA), which was followed by curing with aziridine cross-linker to yield elastomeric materials. As a result, we postulated that thermoset elastomers, having potentially useful properties, could be generated with advantages such as no crystallinity and a flexible backbone of renewable polyester, whereas there was some crystallinity or rigid backbone in thermoset elastomers produced by petroleum-based monomers having no substitution such as cycloalkene and caprolactone.[19,22,39−41] We pursued a protocol for the synthesis of prepolymers that would make them greener and more amenable to large-scale preparations. Herein, we report (a) new methods for preparing HO-PCM-OH polyols and HOOC-PCM-COOH prepolymers with low dispersities, (b) the use of such prepolymers to prepare thermally cross-linked elastomers with triarmed aziridine, and (c) the characterization of these polyols, prepolymers, and elastomers using ^{1}H and ^{13}C NMR spectroscopy, size-exclusion chromatography (SEC), differential scanning calorimetry (DSC), thermal gravimetric analysis (TGA), dynamic mechanical analysis (DMA), tensile testing, and cytocompatibility. Depending on the application target of interest, these renewable elastomers hold promise for use as scaffolds for soft tissue engineering.

EXPERIMENTAL SECTION

Materials. All air- or moisture-sensitive compounds were handled under an inert atmosphere in a glovebox. Diethylene glycol (Aldrich) used for polymerizations was distilled under reduced pressure over sodium and stored in a glovebox. Tin(II) 2-ethylhexanoate (Aldrich) used for polymerization was also distilled and stored in a glovebox. D-Hydrocarvone, palladium on carbon (10 wt %), succinic anhydride, Oxone, and *m*-chloroperoxybenzoic acid (*m*-CPBA, ≤77%) were used as received from Sigma-Aldrich without further purification. Trimethylolpropane tris(2-methyl-1-aziridinepropionate) (TAz) was obtained from Tokyo Chemical Industry. All other solvents and reagents were used as received from the commercial source without further purification.

Measurements. ^{1}H NMR spectra were collected from $CDCl_3$ solution on a Bruker DPX-500 spectrometer operating at 500 MHz. ^{13}C NMR spectra were also collected at 125 MHz. Proton and carbon chemical shifts were referenced to $CDCl_3$ (7.26 and 77.23 ppm, respectively). Polymer samples were prepared in $CDCl_3$ (Euriso-Top) at a concentration of approximately 10 mg mL^{-1} for ^{1}H NMR and 100 mg mL^{-1} for ^{13}C NMR. Molar masses (M_n and M_w) were determined by size-exclusion chromatography (SEC) in chloroform as the mobile phase at 40 °C versus poly(styrene) standards (Polymer Laboratories) under a constant volumetric flow rate (1 mL min^{-1}) using an Agilent

1260 LC system equipped with a Styragel guard column (30 × 4.6 mm) and three successive Styragel columns (300 × 7.8 mm) (HT4, HT3, and HT2) packed with rigid 10 μm styrene divinylbenzene particles. GC-MS experiments were conducted on an Agilent Technologies 6890 GC system equipped with a HP-1 capillary column (30 m × 0.25 mm × 0.1 μm) and 5973N MSD using electron ionization. Differential scanning calorimetry (DSC) measurements were performed using a TA Q-1000 DSC under a nitrogen flow of 50 mL min^{-1}. The polymer samples (7−10 mg) were heated at 150 °C, held for 5 min to erase the influence of thermal history, cooled to −80 °C, and then reheated at 200 °C. The rates of heating and cooling were 10 °C min^{-1}. The values reported were obtained from the second heating cycle. An indium standard was used for calibration. Total acid number (TAN) of the carboxy telechelic HOOC-PCM-COOH samples was determined using titration technique (ASTM D664) with a Metrohm 888 Titrando titrator. Thermal gravimetric analysis (TGA) was performed on a TA Q-500 TGA instrument under a nitrogen flow of 100 mL min^{-1} at a heating rate of 10 °C min^{-1} in a temperature range from 25 to 600 °C. Tensile testing for the cured elastomers was carried out at room temperature on a QRS-S11H universal testing machine (Quro) for normal strain−stress properties. Elastomeric recovery properties of the elastomers were also determined using an Instron 5567 universal testing machine at room temperature. Tensile properties of the ASTM D1708 microtensile bars, which had a uniform sheet thickness (~0.55 mm), were tested at strain rate of 130 mm min^{-1}; all values are reported as the average and standard deviation of at least four samples. Dynamic mechanical analysis (DMA) was carried out using an ARES-G2 rotational rheometer (Waters) under nitrogen. The shear modulus and tan δ with temperature from −50 to 170 °C was measured in a rectangular torsion fixture at ω = 1.0 rad s^{-1} and γ = 1.0%.

***In Vitro* Biocompatibility.** Glass Petri dishes (DURAN, 40 mm diameter) were coated with a chloroform solution (5%) of the aziridine and carboxy-telechelic prepolymers such as HOOC-PCM-COOH(3), HOOC-PCM-COOH(6), and HOOC-PCM-COOH(12). The coated dishes were transferred into a vacuum oven at 50 °C after evaporation of the solvent in air. The prepolymer was cross-linked into the elastomer after 24 h at 180 °C. A control dish was coated with $CHCl_3$ solution (5%) of PLGA (50:50, relative molar mass 30−60 kg mol^{-1}, Aldrich), and the solvent was evaporated for 24 h in air. An NIH 3T3 mouse embryonic fibroblast cell was grown in DMEM (Gibco) containing 10% FBS (Gibco) and antibiotics (penicillin 100 units/mL and streptomycin 100 μg/mL, Sigma-Aldrich) and kept in a 5% CO_2 incubator at 37 °C. The coated glass dishes were sterilized by UV radiation for 30 min and filled with growth medium for 4 h to eliminate impurities. Then, each dish was washed with sterilized water three times and seeded with 50 000 NIH 3T3 cells in 2 mL of cell culture media. At 72 h after plating, the morphology of the cells in each dish was observed under a bright-field light microscope (Eclipse Ti-U, Nikon). Cellar proliferation rate on PLGA and XL-PCM films was measured by MTT assay at days 1, 3, and 5 to probe mitochondrial activity. To obtain live/dead cell images, cells were observed with custom-built confocal microscope after staining with carboxyfluorescein succinimidyl ester (CFSE) and propidium iodide (PI).

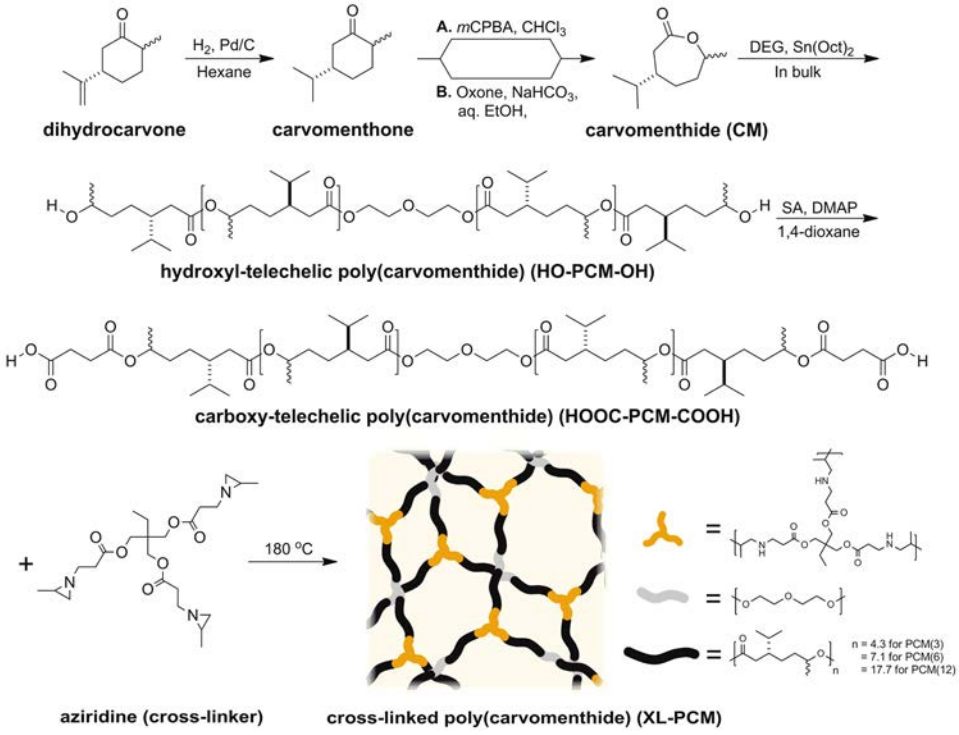
Synthesis of Carvomenthide (CM). CM was synthesized from D-dihydrocarvone using literature procedures with some modifications.[7,41] A high-pressure reactor (Parr Instrument Company) was charged with D-dihydrocarvone (100.0 g; 657 mmol), palladium on carbon (10 wt % and 1 g; 0.94 mmol), and *n*-hexane (300 mL). The reactor was sealed and charged three times with 15 bar of nitrogen to remove much of the air. The solution was then charged with 15 bar of H_2 and placed at room temperature while stirring rapidly. The reactor was recharged once when the pressure subsided to about 5 bar. The reaction was allowed to proceed like this for 12 h before disassembling the reactor. The reaction mixture was then vacuum filtered through Celite 545, washed with *n*-hexane, and dried under vacuum to give carvomenthone as colorless and transparent oil (100.3 g; 650 mmol and overall yield of 98.9%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 2.48−2.27 (m, 2H major, 3H minor), 2.12−2.02 (m, 2H major), 1.91−1.82 (m, 1H major, 1H minor), 1.75−1.38 (m, 3H major, 5H minor), 1.35−1.25 (m, 1H major), 1.09 (d, J = 7.0 Hz, 3H minor), 1.01 (d, J = 6.5 Hz, 3H major), 0.89 (m, 6H major, 6H minor). ^{13}C NMR (125 MHz, $CDCl_3$): δ 212.8, 46.2, 44.9, 44.4, 34.7, 32.3, 28.5, 19.2, 18.9, 13.9 (major isomer); 214.2, 44.3, 43.8, 42.6, 30.9, 30.1, 24.6, 19.6, 19.5, 15.4 (minor isomer). GC-MS data (m/z): 41, 55, 69, 83, 97, 110, 126.

A round-bottomed flask (1 L) was loaded with carvomethone (50.0 g; 324 mmol), chloroform (300 mL), and *m*-chloroperbenzoic acid (94.4 g; 421 mmol) at 0 °C with stirring. The reaction flask was capped, and the mixture was allowed to stir for approximately 48 h. The reaction mixture was filtered under reduced pressure to remove solids. The filtrate was washed with saturated sodium bisulfite solution (3 × 300 mL), saturated sodium bicarbonate solution (3 × 300 mL), deionized water (1 × 300 mL), and brine (2 × 300 mL), successively. The organic layer was dried over anhydrous magnesium sulfate and vacuum filtered through Celite 545. The filtrate was concentrated via rotary evaporation under reduced pressure to remove the solvent and to give a slightly yellow oil; there was a conversion of ~99%, as determined by ^{1}H NMR analysis. The product was purified by three times vacuum distillation (90−100 °C, 120 mTorr) to yield CM, which is a colorless and transparent oil (36.0 g; 212 mmol and overall yield of 65.4%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 4.42 (qdd, J = 9.6, 6.4, and 9.4 Hz, 1H major, 1H minor), 2.80 (dd, J = 5.7 and 14.1 Hz, 1H minor), 2.75 (dd, J = 3.7 and 14.1 Hz, 1H minor), 2.47 (m, 2H major), 1.91 (td, J = 3.8 and 15.2 Hz, 1H major, 1H minor), 1.81 (d, J = 13.3 Hz, 1H major, 1H minor), 1.73−1.40 (m, 4H major, 4H minor), 1.34 (dd, J = 6.4 and 1.6 Hz, 3H major, 3H minor), 1.03−0.88 (dd, J = 6.4 and 60.4 Hz, 6H minor), 0.91−0.85 (dd, J = 6.9 and 11.5 Hz, 6H major). ^{13}C NMR (125 MHz, $CDCl_3$): δ 174.7, 75.7, 39.7, 37.3, 35.2, 32.8, 30.5, 21.9, 18.1, 17.8 (major isomer); 173.3, 75.5, 38.1, 37.7, 31.5, 29.3, 28.3, 21.6, 20.0, 19.4 (minor isomer).

The following procedure was developed for the preparation of CM using Oxone in an aqueous ethanol solution. A round-bottomed flask (1 L) was charged with D-carvomenthone (6.850 g; 44.4 mmol), sodium bicarbonate (29.9 g; 355 mmol), and ethanol absolute (200 proof, 200 mL). The reaction was stirred at room temperature as a solution of Oxone (54.6 g; 177.6 mmol) in water (200 mL) was added via syringe pump over 48 h. After the addition was stopped, the reaction was allowed to stir for an additional 8 h. The reaction mixture was vacuum filtered through Celite 545 to remove the solids. The filtrate was concentrated to approximately 10 mL via rotary evaporation under reduced pressure, affording conversion of ~99%, as determined by ^{1}H NMR analysis. The product was purified by three time vacuum distillation (90−100 °C, 120 mTorr) to give CM, which is a colorless and transparent oil (4.19 g; 24.6 mmol and overall yield of 55.9%).

Synthesis of Hydroxyl-Telechelic Poly(carvomenthide) (HO-PCM-OH). The general procedure to prepare the hydroxyl-telechelic PCM using bulk ROTEP of CM was as follows:[41] In a nitrogen-filled glovebox, CM (19, 32, or 74 equiv) was transferred to a pressure vessel (350 mL) equipped with a stir bar. Diethylene glycol (1 equiv based on two end-hydroxyl groups) was injected into the reaction vessel followed by the addition of tin(II) 2-ethylhexanoate (0.2 or 0.5 equiv). The reaction vessel was sealed, taken out of the glovebox, and placed in a thermostatic oil bath at 100 °C for 22 h (94−97% conversion of monomer). The reaction was quenched by exposure to the air. The crude product was diluted with chloroform (ca. 30 mL). After pouring methanol (250 mL) into the crude product solution, the polymer solution was precipitated in order to recover the hydroxyl PCM and to remove the remaining monomer. The removal process was repeated twice. Sample was dried at 90 °C in a vacuum oven (60−70% isolated yield based on product weight calculated by conversion). ^{1}H NMR (500 MHz, $CDCl_3$): δ 4.85 (m, 1H, H_d from the repeating unit of hydroxyl PCM), 4.21 (m, 2H, H_b from incorporated initiator), 3.76 (m, 1H, H_a from the end unit of hydroxyl PCM), 3.67 (t, J = 4.9 Hz, 2H, H_c from incorporated initiator), 2.23 (dd, J = 5.4 and 15.1 Hz, 1H from the repeating unit of hydroxyl PCM), 2.08 (dd, J = 7.2 and 15.1 Hz, 1H from the repeating unit of hydroxyl PCM), 1.72 (m, 2H from the repeating unit of hydroxyl PCM), 1.56 (m, 1H from the repeating unit of hydroxyl PCM), 1.45 (m, 1H from the repeating unit of

Scheme 1



hydroxyl PCM), 1.31 (m, 1H from the repeating unit of hydroxyl PCM), 1.23 (m, 1H from the repeating unit of hydroxyl PCM), 1.18 (d, J = 6.1 Hz, 3H from the repeating unit of hydroxyl PCM), 0.83 (dd, J = 6.7 and 12.9 Hz, 6H from the repeating unit of hydroxyl PCM). ^{13}C NMR (125 MHz, $CDCl_3$) in Figure S2d: 173.7, 173.4 (C1), 173.3, 70.9 (C2), 69.0 (C3), 68.3 (C4), 67.8 (C4), 63.2 (C5), 40.5 (C6), 36.3 (C7), 33.4 (C8), 29.7 (C9), 26.6 (C10), 19.9, 19.1, 18.6.

Synthesis of Carboxy-Telechelic Poly(carvomenthide) (HOOC-PCM-COOH). The general procedure to prepare the carboxy-telechelic PCM via postpolymerization functionalization was as follows:[25] The hydroxyl-telechelic PCM (1 equiv based on two end-hydroxyl groups) was introduced into a pressure vessel (350 mL) with a magnetic stir bar. 1,4-Dioxane was added to the vessel, and the mixture was stirred to completely dissolve the polymer at room temperature for 30 min. An excess of succinic anhydride (SA) (8 or 12 equiv for one hydroxyl group (1 equiv) in HO-PCM-OH) and dimethylaminopyridine (DMAP) (0.01 equiv) as a catalyst were added to the vessel. The reaction vessel was sealed and placed in a thermostatic oil bath at 90 °C for 50 h. After cooling the vessel, the reaction was quenched by cooling and then adding chloroform (300 mL) to precipitate most of the unreacted SA. The solution was vacuum filtered through Celite 545 to remove the solids. The filtrate was centrifuged at 3000 rpm for 10 min to remove small amounts of reprecipitated SA, and then the supernatant was completely concentrated via rotary evaporation under reduced pressure. The concentrated polymer solution was suspended with n-hexane (800 mL). Small quantities of chloroform (10–20 mL) were added to dissolve the polymer in the suspension and to keep the tiny amounts of SA undissolved. The polymer solution was vacuum filtered through Celite 545 to remove the solids. The filtrate was completely concentrated via rotary evaporation under reduced pressure. It was dried at 90 °C in a vacuum oven (60–70% isolated yield based on product weight calculated by conversion). ^{1}H NMR (500 MHz, $CDCl_3$): δ 4.83 (m, 1H, H_d from the repeating unit of carboxy PCM), 4.19 (m, 2H, H_b from incorporated initiator), 3.65 (t, J = 4.8 Hz, 2H, H_c from incorporated initiator), 2.59 (dd, J = 6.0 and 24.2 Hz, 4H, H_e from the end unit of carboxy PCM), 2.21 (dd, J = 6.3 and 15.1 Hz, 1H from the repeating unit of carboxy PCM), 2.08 (dd, J = 7.3 and 15.1 Hz, 1H from the repeating unit of carboxy PCM), 1.69 (m, 2H from the repeating unit of carboxy PCM), 1.54 (m, 1H from the repeating unit of carboxy PCM), 1.43 (m, 1H from the repeating unit of carboxy PCM), 1.27 (m, 1H from the repeating unit of carboxy PCM), 1.20 (m, 1H from the repeating unit of carboxy PCM), 1.16 (d, J = 6.2 Hz, 3H from the repeating unit of carboxy PCM), 0.81 (dd, J = 6.8 and 15.3 Hz, 6H from the repeating unit of carboxy PCM). ^{13}C NMR (125 MHz, $CDCl_3$): 176.3 (C1), 173.5, 173.3 (C2), 173.2, 171.6 (C3), 71.4 (C4), 70.7 (C5), 68.9 (C6), 63.1 (C7), 40.4, 36.2, 33.3, 29.6, 29.1, 28.8 (C8), 26.4, 19.8, 19.0, 18.5.

One-Pot, Two-Step Process for Synthesis of Carboxy-Telechelic Poly(carvomenthide) (HOOC-PCM-COOH). In a nitrogen-filled glovebox, CM (19, 32, or 64 equiv) was transferred to a pressure vessel (350 mL) equipped with a stir bar. Diethylene glycol (1 equiv based on two end-hydroxyl groups) and tin(II) 2-ethylhexanoate (0.2 or 0.5 equiv) were injected into the reaction vessel.. The reaction vessel was sealed, taken out of the glovebox, and placed in a thermostatic oil bath at 100 °C for 22 h (94–97% conversion of monomer). After cooling the vessel to room temperature, the vessel was charged with 1,4-dioxane, and the mixture was stirred to completely dissolve the polymer. An excess of SA (8 or 12 equiv for one hydroxyl group (1 equiv) in HO-PCM-OH) and DMAP (0.01 equiv) as a catalyst were added to the vessel. The vessel was sealed and returned to 90 °C for 50 h (>99% conversion from hydroxyl group to carboxy group). The reaction was quenched by cooling and then adding chloroform, suspended to remove the remaining SA, and precipitated into methanol to remove unreacted CM. The recovered carboxy PCM was dried at 90 °C in a vacuum oven (61–95% isolated yield based on product weight calculated by conversion).

Thermal Cross-linking of Carboxy-Telechelic Poly(carvomenthide). The general procedure to prepare the cross-linked poly(carvomenthide) elastomers via thermal curing was as follows with some modifications:[19] Carboxy-telechelic PCM and trimethylolpropane tri(2-methyl-1-aziridine propionate) (TAz) in 3:2.1 molar ratio (acid/aziridine = 1:1.06) were charged into a round-bottomed flask with a magnetic stir bar. Chloroform was added to the flask, and the mixture was stirred to completely dissolve the prepolymer and TAz at room temperature for 10 min. The mixture was then slowly cast into a

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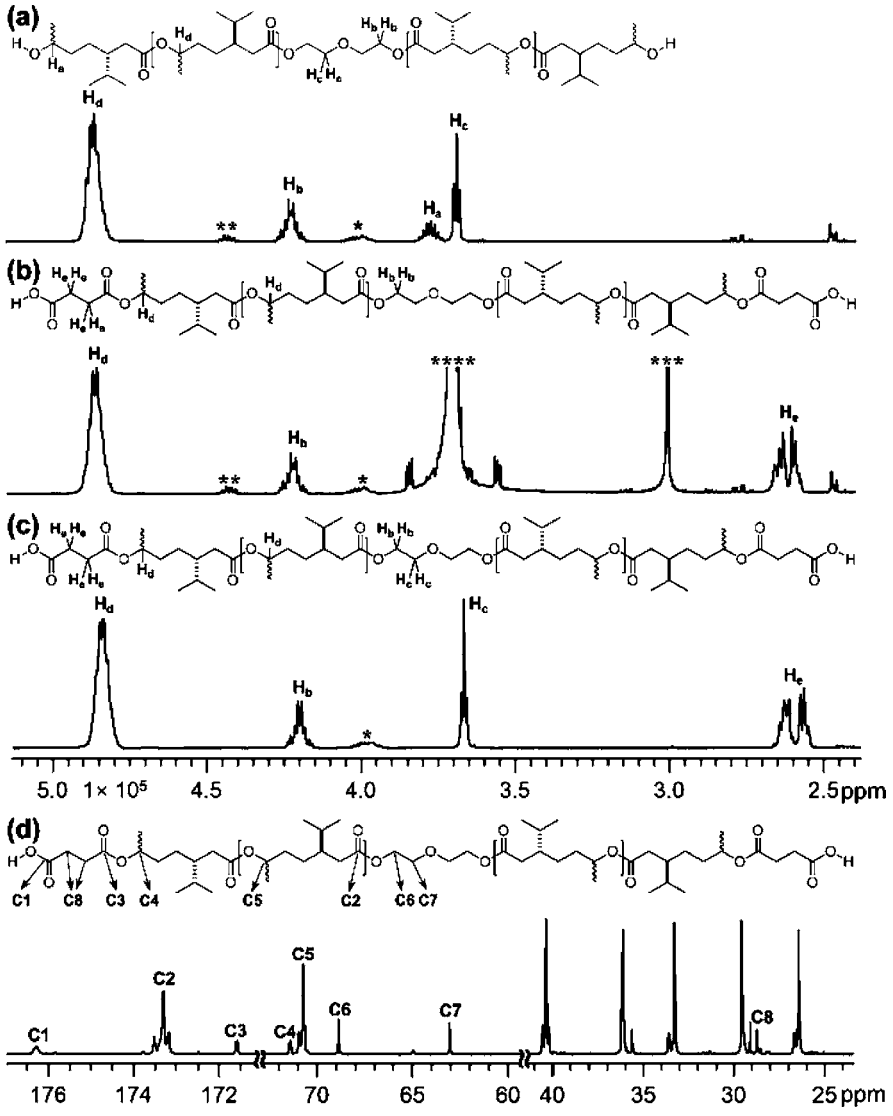

Figure 1. Expanded region of the ^{1}H NMR spectra (500 MHz, $CDCl_3$) of (a) HO-PCM-OH(3) before purification, (b) after performing one-pot, two-step process and before purification of HOOC-PCM-COOH(3), (c) purified HOOC-PCM-COOH(3) after precipitation, and (d) three enlarged regions of $^{13}C\{^{1}H\}$ NMR spectrum (125 MHz, $CDCl_3$) of HOOC-PCM-COOH(3) after precipitation (* = PCM homopolymer,[42] ** = unreacted CM, *** = remained SA, and **** = 1,4-dioxane).

PFA Petri dish to make a film. The cast solution was placed under a flow of air at room temperature for 24 h to evaporate the solvent, which was subsequently dried at 50 °C in a vacuum oven for 12 h to completely remove chloroform. The dish was placed in a preheated oven at 180 °C, and the material was cured for 10 min. A slightly yellow transparent thermoset elastomer was obtained. Densities of 1.0357 ± 0.002, 1.0205 ± 0.001, and 1.0067 ± 0.006 g/cm^3 were obtained for XL-PCM(3), XL-PCM(6), and XL-PCM(12), measured with density determination kit in MeOH at 25 °C, respectively.

RESULTS AND DISCUSSION

Synthesis of Prepolymers. *Synthesis of Carvomenthide.* Dihydrocarvone was hydrogenated using palladium on carbon (Pd/C) to prepare carvomenthone, which was subsequently oxidized into carvomenthide (CM) using *m*-chloroperbenzoic acid (*m*-CPBA) in a chlorinated solvent with a modified literature procedure (Scheme 1A).[7,41] In addition, we now report the Baeyer–Villiger oxidation of carvomenthone using Oxone ($KHSO_5{\cdot}KHSO_4{\cdot}K_2SO_4$), which is a green inorganic oxidant and an ethanol/water/$NaHCO_3$ system as a potentially eco-friendly alternative (>99% conversion) to the above-mentioned method of using petroleum-based chemicals (Scheme 1B), which is followed by several distillations for purification (Figure S1).[41] Isolated yield of obtained CM was over 56%. Detailed characterization data for carvomenthone and CM are provided (see Experimental Section).

Preparation of Hydroxyl-Telechelic Poly(carvomenthide). As can be seen in Scheme 1, α,ω-hydroxyl-functionalized poly(carvomenthide) (HO-PCM-OH) was prepared by ring-opening polymerization transesterification polymerization (ROTEP) of CM. The polymerization was carried out in bulk using tin(II) ethylhexanoate ($Sn(Oct)_2$) as a catalyst and diethylene glycol (DEG) as a bifunctional initiator at 100 °C under an inert atmosphere for 22 h on a 30 g scale (see Experimental Section for more details). Initial carvomenthide/DEG ratios of 19:1, 32:1, and 74:1 were selected to target molar masses of 3.0, 6.0, and 12.0 kg mol^{-1}, designated as HO-PCM-OH(3), HO-PCM-OH(6), and HO-PCM-OH(12), respectively. ^{1}H NMR spectroscopy analysis (Figures 1a and S2a) was used to determine DEG chain connectivity, monomer

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Table 1. Characterization Data for HO-PCM-OH and HOOC-PCM-COOH[a]

polymer	$[M]_0/[I]_0$	M_n (theo.) (kg mol^{-1})[d]	M_n (NMR) (kg mol^{-1})[e]	M_n (SEC) (kg mol^{-1}) ($Đ$)[f]	M_n (titr.) (kg mol^{-1}) (TAN)[g]	F[h]	T_g (°C)[j]	T_d (°C)[k]
HO-PCM-OH(3)	19[b]	3.2	3.0	5.0 (1.09)		2.01[h]	−35	255
HO-PCM-OH(6)	32[b]	5.3	5.0	7.8 (1.06)		2.02[h]	−38	301
HO-PCM-OH(12)	74[b]	11.9	11.5	17.4 (1.05)		1.99[h]	−34	299
HOOC-PCM-COOH(3)[l]	8[c]	3.4	3.4	4.4 (1.10)	2.9 (38.5)	2.05[i]	−27	293
HOOC-PCM-COOH(6)[l]	8[c]	5.5	5.6	7.4 (1.06)	5.6 (20.2)	1.97[i]	−28	310
HOOC-PCM-COOH(12)[l]	12[c]	12.0	12.4	16.5 (1.06)	13.6 (8.2)	1.98[i]	−27	317

[a]See Experimental Section for synthetic details. [b]M is carvomenthide (CM), and I is diethylene glycol (DEG). [c]M is succinic anhydride (SA), and I is dihydroxyl-terminated poly(carvomenthide) (HO-PCM-OH) macroinitiator. [d]Calculated based on monomer conversion, as determined by ^{1}H NMR spectroscopy. [e]Calculated from relative integrations of PCM repeating units and DEG for PCM by ^{1}H NMR spectroscopy. [f]Determined by size-exclusion chromatography (SEC) in $CHCl_3$ at 40 °C relative to poly(styrene) standards. [g]Calculated based on total acid number (TAN), which was a quantity of KOH in milligrams needed to react with the acid in an amount of the carboxy-telechelic PCM in grams. [h]Functionalities for hydroxyl group calculated from relative integration of methylene protons of DEG and a methine proton of terminal chain for dihydroxyl-terminated PCM by ^{1}H NMR spectroscopy. [i]Functionalities for carboxylic acid group determined from relative integration of methylene protons of DEG and methylene protons of terminal chain for dicarboxy-terminated PCM by ^{1}H NMR spectroscopy. [j]Determined by DSC (2nd heating cycle) at 10 °C min^{-1}. [k]5% weight loss determined by TGA at 20 °C min^{-1} in N_2. [l]Performed by one-pot, two-process reaction (sequential addition).

conversion, and M_n for PCM. Changing DEG into the corresponding ester in the PCM induced a quantitative downfield shift of the two methylene proton peaks (H_b and H_c; Figures 1 and S2). The methine proton resonance adjacent to the end hydroxyl group of a PCM chain was observed (H_a) at δ 3.76 ppm. Comparison of the integration values between the methine proton (H_a) at the PCM end chain and the methylene protons (H_b and H_c) from the DEG initiator showed a ratio of exactly 2:8, proving the presence of two terminated hydroxyl groups per chain with minimized adventitious initiation. On the basis of the conversion (97, 96, and 93%) and the initial monomer-to-initiator contents, the theoretical M_n values for HO-PCM-OH(3), HO-PCM-OH(6), and HO-PCM-OH(12) were found to be 3.2, 5.3, and 11.9 kg mol^{-1}, respectively (Table 1). M_n values of 3.0, 5.0, and 11.5 kg mol^{-1} were also obtained by calculations of the relative integration between the methylene protons of the incorporated DEG at δ 4.21 and 3.67 ppm (4 protons) and the methine protons (H_d) from PCM repeating units at δ 4.85 ppm in the ^{1}H NMR spectra of telechelic hydroxyl PCM samples; these results are in good agreement with the theoretical values, indicating well-controlled molar mass. By size-exclusion chromatography (SEC) using poly(styrene) standards, the M_n values for the hydroxyl-terminated PCM polymers were 5.0, 7.8, and 17.4 kg mol^{-1}, respectively; the polydispersity ($Đ$) values were 1.09, 1.06, and 1.05, individually (Table 1 and Figure S3). Finally, three PCM polyols having different molar masses were prepared to investigate the effect of the PCM chain length on the properties of the resulting cross-linked elastomers. Hydroxymethylene protons at the initiating portion of the PCM homopolymer, which resulted from small quantities of water in CM, were observed at δ 3.98 ppm (* in Figure 1) even if CM monomer was distilled three times with CaH_2 to completely remove the aqueous impurity.[42] However, no evidence of PCM homopolymer in SEC analysis was apparent, and the SEC traces of the hydroxyl-telechelic PCM samples were symmetrically unimodal with low $Đ$ values, demonstrating that the PCM homopolymer had a very low molar mass, like that of an oligomer, with negligible quantities. In short, this simple way of preparing α,ω-hydroxyl-terminated poly(lactone) shows significant advances over previously reported synthetic methods.[43,44]

Synthesis of Carboxy-Telechelic Poly(carvomenthide). The secondary hydroxyl terminal groups of the PCM samples were converted to carboxy end groups using succinic anhydride (SA) as a reagent and dimethylaminopyridine (DMAP) as a catalyst via a postpolymerization functionalization, designated as HOOC-PCM-COOH(3), HOOC-PCM-COOH(6), and HOOC-PCM-COOH(12).[24,25] Upon completion of the reaction, the resonance of the terminal methine proton (H_a) of the hydroxyl-terminated PCM at δ 3.76 ppm disappeared, and a new signal for the two terminal methylene protons of the carboxy-terminated PCM was observed at δ 2.59 ppm in the ^{1}H NMR spectrum (H_e; Figures 1b,c and S2b,c) with high levels of coupling (>99% conversion). HOOC-PCM-COOH(3), when compared to that of HO-PCM-OH(3) (Figure S2d), also exhibited new resonances in the ^{13}C NMR spectrum at δ 176.3 (C1), 171.6 (C3), 71.4 (C4), and 28.8 (C8) ppm, corresponding to the carbonyl groups, methine carbon, and methylene carbons of the terminal carboxy group (Figure 1d).

To simplify the carboxy-terminated PCM synthesis further, we developed a one-pot, two-step method. As shown in Scheme 1, CM was first polymerized using a bulk system with DEG and $Sn(Oct)_2$ to obtain the corresponding polyols, which were not isolated or purified. Instead, SA, DMAP, and 1,4-dioxane were added to the reaction mixture, and heating was continued at 90 °C for 50 h. The conversion of CM from secondary hydroxyl group to carboxy group at the termini of the PCM chains reached over 99%. The residual CM was a constant 3−7% before and after the postpolymerization functionalization of SA, suggesting that the CM was not involved in the carboxy-telechelic PCM (Figures 1a,b and S2a,b). As illustrated in Figure 1c, the relative integration between the carboxy terminal PCM methylene protons (4 protons in the half chain) and the initiated DEG methylene protons (4 protons in the half chain) led to a ratio of exactly 1 to 1 and suggested that the conversion was almost completed with the range of functionalities (F = 1.97−2.05) (Table 1).[19,45,46] Using another relative integration between the methylene protons of the incorporated DEG portion and the methine protons from the PCM repeating units in the ^{1}H NMR spectrum (Figures 1c and S2c), M_n values of 3.4, 5.6, and 12.4 kg mol^{-1} were determined for HOOC-PCM-COOH(3), HOOC-PCM-COOH(6), and HOOC-PCM-COOH(12), respectively, nearly identical to those calculated for the hydroxyl-terminated PCM samples (Table 1). The M_n values for the carboxy-terminated PCM samples using SEC with chloroform as an eluent and calculated with poly(styrene) standards were

4.4, 7.4, and 16.5 kg mol^{-1}, individually; the respective $Đ$ values were 1.10, 1.06, and 1.06 (Table 1 and Figure 2). These values

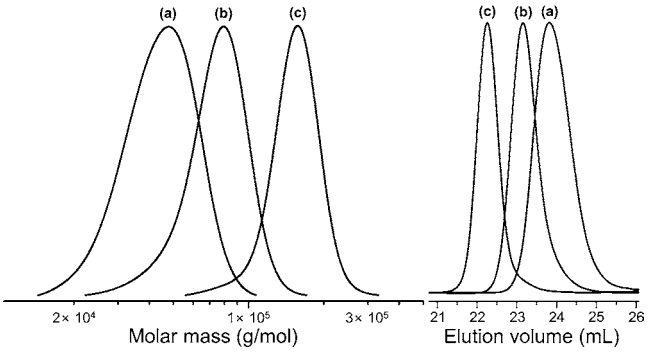

Figure 2. Size-exclusion chromatography data (1 mg/mL chloroform) for (a) HOOC-PCM-COOH(3), (b)HOOC-PCM-COOH(6), and (c) HOOC-PCM-COOH(12).

were comparable to those of the starting hydroxyl-terminated PCM samples. In addition, after measuring total acid number (TAN) of the carboxy-telechelic PCM samples using chemical titration (ASTM D664), the TAN values of 38.5, 20.2, and 8.2 mg KOH g^{-1} were altered to molar masses of 2.9, 5.6, and 13.6 kg mol^{-1}, respectively (Table 1).

Taken together, all data related to the molar mass obtained by the one-pot, two-step method indicated that the postpolymerization functionalization did not induce adverse side reactions leading to cleavage or cross-linking of polymer chains. In sum, this simple method for the preparation of α,ω-carboxy-terminated poly(lactone) using succinic anhydride was a new attempt to make a renewable secondary hydroxyl-terminated poly(lactone), going beyond previously reported synthetic protocols regarding petroleum-based primary hydroxyl group-containing polyols.[23−25,47]

Preparation of Thermoset Elastomers. The carboxy groups at the termini of the PCM chains can be used as a reactive moiety for the prepolymer for the synthesis of higher molar mass, optically clear, flexible, and stretchable elastomers via thermal cross-linking (Scheme 1 and Figure S4). Using HOOC-PCM-COOH(3), HOOC-PCM-COOH(6), and HOOC-PCM-COOH(12), we carried out successful cross-linking reactions with trifunctional amine to form a secondary amine and an ester in the three-dimensional-network polymers; however, there was slight polymer yellowing due to partial amine oxidation caused by high-temperature curing (∼180 °C). During the thermal cross-linking reaction between carboxy and aziridine functionalities, the acid played the role of a proton donor for N-protonation of the aziridine; the acid followed this by attacking the nitrogen atom to open the aziridine ring and then to generate a carbocation as an intermediate, the counterion COO^-.[48,49] The cured elastomers, which had high degrees of cross-link density, were prepared using commercially available trimethylolpropane tri(2-methyl-1-aziridine propionate) (TAz) as a trifunctional cross-linking agent. Aziridine and the carboxy-telechelic PCM were formulated using chloroform as a solvent. The mixture was transferred to a perfluoroalkoxy (PFA) Petri dish. The solvent in the cast solution was evaporated at ambient temperature in an air flow hood; then, the cast film was dried at 50 °C under reduced pressure to completely remove remaining chloroform. The dish with the mixture was placed in an oven preheated at 180 °C; the dish with mixture was subsequently cured for 15 min, leading to slightly yellow and transparent thermoset elastomers (Figure S4). Three sets of elastomers were prepared using a method in which α,ω-dicarboxy-functionalized PCM samples having different molar masses (3.4, 5.6, and 12.4 kg mol^{-1}) were mixed with TAz at a 3:2.1 mole ratio. It was significant that the mole ratio of the aziridine to the acid of the sets of elastomers must be kept constant at about 1:1. The gel fraction test was used to demonstrate that 0−3 wt % of soluble materials in the cross-linked elastomer remained after the cross-linking reaction owing to the presence of a small portion of unreacted bifunctional chains and the resulting aziridine decomposition during the curing (Table 2).

Thermal Properties. The thermal properties of the hydroxyl-terminated PCM (HO-PCM-OH), carboxy-functionalized PCM (HOOC-PCM-COOH), and cross-linked PCM (XL-PCM) samples were studied by differential scanning calorimetry (DSC, Figure 3). We observed a slightly higher glass transition temperature (ca. −27 °C) for the HOOC-PCM-COOH samples compared to those of the corresponding polyols (ca. −36 °C) (Table 1). This small increment can be expected given that hydrogen bonding between the terminated carboxy group and repeating ester group in HOOC-PCM-COOH polymers is stronger than that between the end hydroxyl group and repeating ester group in HO-PCM-OH polymers.[50] However, the effect of having the carboxyl groups on dimer formation ought to be more important for leading to a higher cross-linking state. A slightly higher glass transition

Table 2. Characterization Data for Cross-Linked Carboxy-Telechelic Poly(carvomenthide)[a]

polymer	gel fraction[b]	T_g (°C)[c]	T_g (°C)[d]	T_d (°C)[e]	storage modulus G' (10^5 Pa)[f]	Young's modulus E (MPa)[g]	tensile strength σ_b (MPa)[g]	strain at break ε_b (%)[g]	degree of cross-linking (n)[h]	residual strain ε_R (%)[g]	
										cycle 1[i]	cycles 2 to 20[i]
XL-PCM(3)[j]	0.983	−15	−10	298	2.2−3.4	1.13 ± 0.13	1.14 ± 0.09	181 ± 8	152 ± 18	2−3	0−1
XL-PCM(6)[j]	0.999	−17	−14	313	1.4−2.5	1.04 ± 0.09	1.16 ± 0.13	224 ± 18	121 ± 12	2−3	0−1
XL-PCM(12)[j]	0.968	−19	−15	321	0.8−2.0	0.52 ± 0.04	1.24 ± 0.19	625 ± 61	70 ± 5	7−8	2−4

[a]See Experimental Section for details. [b]Determined by shaking the samples in a large excess of methylene chloride for 96 h, changing the solvent every 24 h. The samples were dried at 50 °C until constant weight was obtained. [c]Determined by DSC (2nd heating cycle) at 10 °C min^{-1}. [d]Determined by DMA with rectangular torsion fixture. Oscillation test from −50 to 170 °C at 3 °C min^{-1}, ω = 1.00 rad s^{-1} and γ = 1.0%. [e]5% weight loss determined by TGA at 20 °C min^{-1} in N_2. [f]Determined by DMA with an 8 mm parallel plate geometry. Oscillatory frequency sweep test at 25 °C min^{-1}; γ = 1.0% and ω = 0.1−100 rad s^{-1}. [g]Mechanical properties determined on an ASTM D1708 microtensile bars. [h]Degree of cross-linking (n) was calculated with E values obtained from the tensile tests. [i]Percent of plastic deformation measured after 1 cycle or 20 cycles from 0 to 50% strain at 130 mm min^{-1}. [j]8.8, 5.5, and 2.8 wt % TAz were mixed with the carboxy-telechelic PCM samples before curing for XL-PCM(3), XL-PCM(6), and XL-PCM(12), respectively.

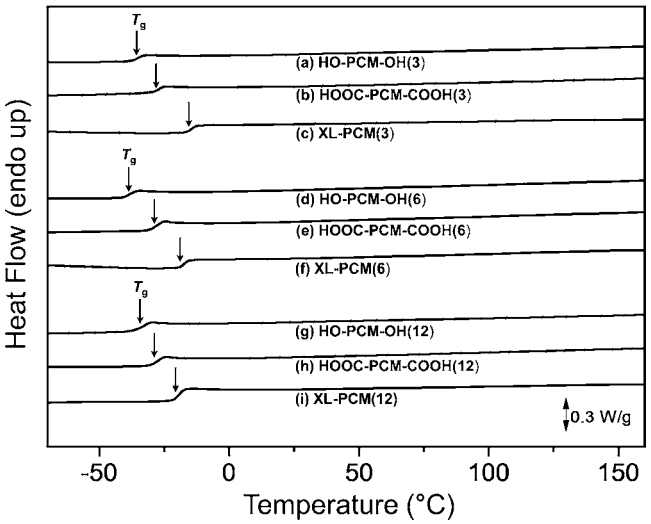

Figure 3. DSC analysis for HO-PCM-OH polyols, HOOC-PCM-COOH prepolymers, and XL-PCM cross-linked polymers.

temperature (−19 to −15 °C) for the XL-PCM samples (Table 2) was also found in comparison with those of the corresponding carboxy prepolymers. It is assumed that the thermal cross-linking limited the motion of the polymer chain ends.

The thermal stability of HO-PCM-OH, COOH-PCM-COOH, and XL-PCM polymers was assessed using thermal gravimetric analysis (TGA; Figure S5). Taking into consideration the fact that the 5% mass loss (excluding small amounts of solvent) temperatures of the polyols were in the range of 255−299 °C under a nitrogen atmosphere, the carboxy-telechelic polymers and the PCM samples led to improved thermal stabilities (293−317 and 298−321 °C, respectively) (Tables 1 and 2). The TGA of the cured polymers in particular showed a slightly higher decomposition temperature (5% weight loss) than that of the carboxy prepolymers.

Dynamic Mechanical Properties. Dynamic mechanical analysis (DMA) experiments of XL-PCM samples demonstrated the effect of temperature and frequency on dynamic elastic properties. The storage moduli (G') of the cured elastomers as a function of temperature and frequency are shown in Figure S6 and 4.

The low-temperature (<−25 °C) shear modulus was constant at about 1×10^9 Pa. Pronounced drops in G' (Figure S6a) and sharp tan δ peaks (Figure S6b) occurred around the T_g values (−15 to −10 °C) of the XL-PCM samples; these peaks and drops were observed by DSC (−19 to −15 °C) (Figure 3). Therefore, the T_g values obtained from DSC and DMA were in good agreement (Table 2). In addition, the T_g values of the XL-PCM materials obtained by DSC and DMA increased with decreasing PCM chain length, indicating a higher density of cross-linking (Figure S6a).[51] In particular, the tan δ (= G''/G') values decreased as the molar mass of the prepolymer dropped, suggesting a higher cross-linking density and greater hardness in the XL-PCM elastomers (Figure S6b).[52] The stable plateau in the storage modulus for the XL-PCM(3, 6, and 12) samples started at ca. −5 to −10 °C and extended to 170 °C. The G' values of the XL-PCM(3, 6, and 12) samples decreased as the chain length between coupling junctions of the XL-PCM materials increased and the corresponding cross-linking decreased (Figure 6a).

When DMA experiments with temperature were performed with a rectangular torsion fixture, tension force was applied to prevent curvature development in the samples caused by thermal expansion. However, since XL-PCM polymers had a rubbery property and could be elongated by tension force above the glass transition temperature (T_g −20 to −10 °C), the dimensions of the samples could be changed over a range of temperatures, whereas the dimensions of samples in the oscillatory frequency sweep test under isothermal conditions were constant. The G' values at 25 °C obtained by oscillatory frequency sweep tests were used to calculate the entanglement molar mass, M_e.[19] The G' values of the XL-PCM(3, 6, and 12) samples over a frequency range from 0.1 to 100 rad s^{-1} were 0.22−0.34, 0.14−0.25, and 0.08−0.20 MPa, respectively (Table 2 and Figure 4). The entanglement molar masses $M_e \approx$ 7.6−

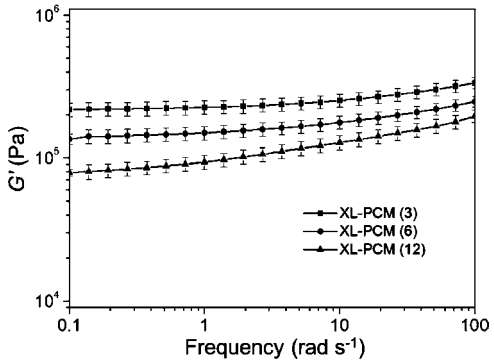

Figure 4. Viscoelastic properties (storage modulus, G') versus frequency at 25 °C for the cured XL-PCM polymers.

11.7, 10.1−18.1, and 12.5−31.1 kg mol^{-1} for the XL-PCM(3, 6, and 12), respectively, were approximated by the following equation

$$M_e = \rho RT/G$$

where ρ is the density, R is the universal gas constant, T is the temperature, and G is the storage shear modulus. The M_e values between coupling junctions in the cross-linked polymer is inversely proportional to the density of the coupling junctions.[53] Although the calculated M_e values are higher than those of the carboxy-telechelic PCM samples, the M_e values increased as the chain length of the carboxy-telechelic PCM samples increased (3.4, 5.6, and 12.4 kg mol^{-1}, respectively). However, further studies are needed to explain the cause of difference between calculated M_e values and the molar masses of the PCM samples.

Tensile Properties. The mechanical properties of three cross-linked elastomers (ASTM D1708 microtensile bars) having different molar masses of HOOC-PCM-COOH (3.4, 5.6, and 12.4 kg mol^{-1}) were investigated (Table 2 and Figure 5). All values in the analysis were obtained from at least four XL-PCM samples. Linear responses at low strains (<20%) were observed in the stress−strain (S−S) curves for all of the thermally cured polymers. Young's moduli (E) (0.52−1.13 MPa) for the XL-PCM samples increased significantly with an increase of the trifunctional cross-linker (TAz) content (2.8, 5.5, and 8.8 wt %, respectively), indicating higher cross-linking density. The cross-linking densities of the XL-PCM(3, 6, and 12) elastomers were expressed by n (moles of active network chains per unit volume); these n values were 152 ± 18, 121 ±

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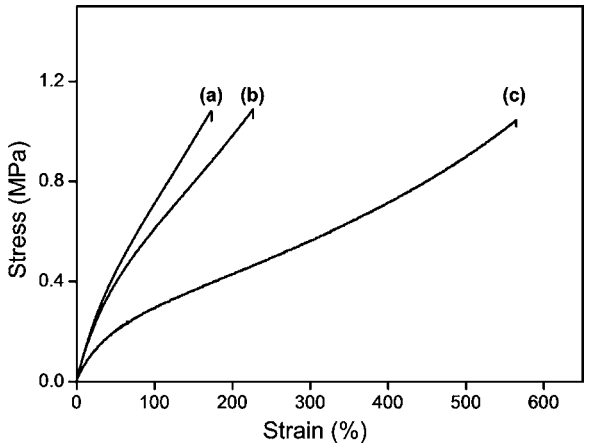

Figure 5. Representative stress–strain curves for (a) XL-PCM(3), (b) XL-PCM(6), and (c) XL-PCM(12) of cross-linked polymers.

12, and 70 ± 5 mol m^{-3}, respectively, calculated using the following equation[54]

$$n = E/3RT$$

where E is Young's modulus, R is the universal gas constant, and T is the temperature. The n values also can be calculated using the relation in which the Young's modulus E is three times the shear modulus G when Poisson's ratio is 0.5 for rubber-like materials.[55] The n values from the G' values for the XL-PCM(3, 6, and 12) were 89–137, 57–101, and 32–81 mol m^{-3}, respectively. Therefore, the n values obtained from oscillatory frequency sweep tests were comparable to those obtained from tensile tests. We also observed that, when compared to ultimate elongation of the XL-PCM(3 and 6) (ca. 181 and 224%), the elongation (ε_b) of XL-PCM(12) (ca. 625%) significantly improved with the increased length of the carboxy-terminated prepolymer to 12.4 kg mol^{-1} and the decreased cross-linking density. In contrast, the tensile strengths (σ_b) of all XL-PCM samples were similar (1.14–1.24 MPa) regardless of the increased chain extender content or the PCM chain length.[19] The mechanical strengths are comparable or superior to those of previous reported elastomers.[56,57]

To further understand the elastic recovery and level of plastic deformation of the cured elastomers, a cyclic tensile test to determine the true elasticity of the XL-PCM(3, 6, and 12) samples was carried out, subjecting the tensile bars prepared by ASTM D1708 to 20 loading/unloading cycles at a strain of 50% with a constant speed of displacement (130 mm min^{-1}). The hysteresis loops of the cross-linked polymers for cycles 1, 2, 3, 10, and 20 were compared (Figure 6). The reciprocating tensile test showed small unrecoverable plastic deformation (ca. ε_R = 2–8%) in the first cycle, which might be caused by the initial alignment of the microstructure (Table 2);[58−60] however, the XL-PCM(3 and 6) samples having a higher cross-link density exhibited negligible values of residual strain (ε_R = 0–1%) (Table 2 and Figure 6a,b) from cycles 2 to 20 when compared to those of XL-PCM(12) with reduced connection points (Table 2 and Figure 6c); the XL-PCM(3 and 6) samples also maintained mechanical integrity, which is highly desirable for elastomeric material. The results confirm that these thermoset elastomers showed excellent levels of recovery with a maximum strain of 50%.

***In Vitro* Cytocompatibility.** The cured PCM elastomers appeared to be biocompatible *in vitro*. In order to investigate cell adherence and proliferation on the elastomer surface, NIH 3T3 mouse fibroblast cells were seeded homogeneously on glass Petri dishes coated with three kinds of XL-PCM films as well as with the control PLGA films. At day 1 after seeding, no significant difference was found between XL-PCM samples and PLGA ($P < 0.05$). At day 5, each XL-PCM material showed a significantly higher growth rate than that on the control PLGA ($P < 0.05$), showing no tendency toward molar mass among the three XL-PCM groups, which was related to the elastic property of the rubbers (Figure 7). The cellular morphology on the control PLGA surface and on the XL-PCM surfaces at days 1 and/or 3 after seeding was visualized with a fluorescence microscope for live/dead staining (Figure 8) as well as with a bright-field light microscope (Figure S7). The cells on the cured PCM coatings showed cellular morphologies and growth

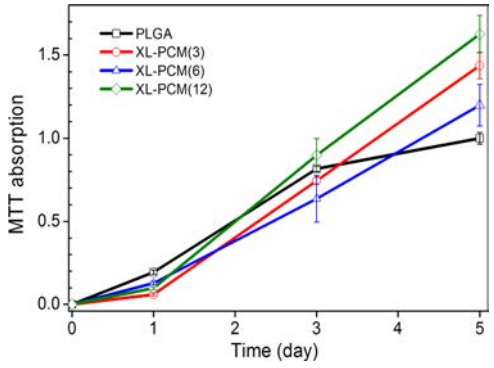

Figure 7. Comparison of growth rate of NIH 3T3 mouse fibroblast cells cultured on glass dishes coated with XL-PCM(3, 6, and 12) or PLGA (control). MTT absorption measured at 570 nm.

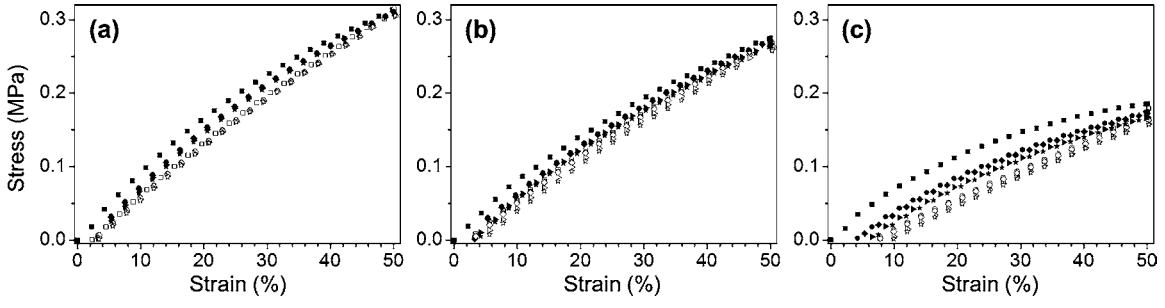

Figure 6. Tensile recovery properties of (a) XL-PCM(3), (b) XL-PCM(6), and (c) XL-PCM(12) from 0 to 50% strain at 130 mm min^{-1} for 20 cycles: five loadings (filled symbols) and unloadings (open symbols) were performed for cycles 1 (■), 2 (●), 3 (◆), 10 (▶), and 20 (★).

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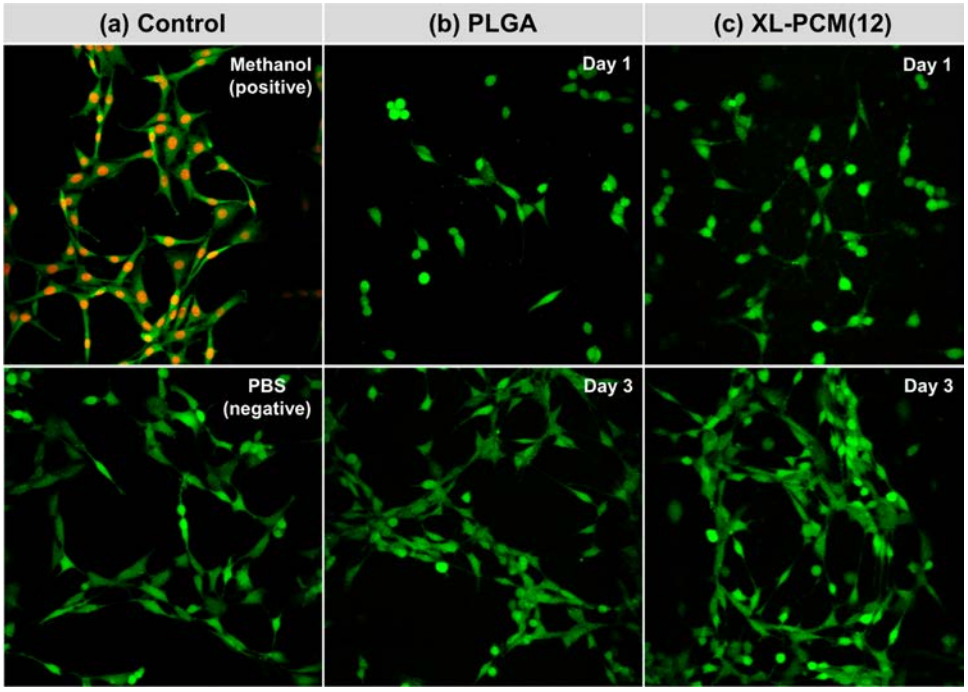

Figure 8. Live/dead cell staining images of NIH 3T3 mouse fibroblast cells. Carboxyfluorescein succinimidyl ester (CFSE, green) stains all cells, and propidium iodide (PI, red) stains only dead cells. (a) All dead cells damaged by a 30 min incubation with 70% methanol were stained by PI (positive control), whereas no cells were stained by PI after a 30 min incubation with a phosphate buffer solution (PBS, negative control). (b, c) No dead cell staining was observed for NIH 3T3 mouse fibroblast cells cultured on glass dishes coated with PLGA and XL-PCM(12) at days 1 and 3.

rates superior to those on the control PLGA, suggesting that PCM is at least as biocompatible as that of PLGA *in vitro*.[61]

CONCLUSIONS

A thermoset elastomer system using renewable PCM derived from plant-based materials and having superb mechanical properties was designed. The hydroxyl terminated PCM polyols having controlled molar masses were synthesized through ROTEP of CM with $Sn(Oct)_2$. Subsequently, dicarboxy end-functionalized PCM prepolymers to produce cured elastomers with no crystallinity, high viscosity, strong thermal resistance, and low glass transition temperature were prepared through esterification using SA. NMR spectroscopy confirmed well-defined polymer structures, and SEC showed narrow molar mass distributions. We also reported a one-pot, two-step method for the synthesis of carboxy-telechelic polyester. Using trifunctional aziridine, three carboxy-telechelic PCM prepolymers having varied molar masses were thermally cross-linked to give three-dimensional network polyester elastomers. All polymers including polyols, prepolymers, and elastomers exhibited high thermal resistance. Dynamic mechanical analysis (DMA) of XL-PCM samples demonstrated the viscoelastic properties of the XL-PCM biomaterials. Tensile experiments demonstrated rubbery behaviors with exceptional elongation at break, tensile strength, and recovery under static or cyclic load. These results offer useful approaches for the molecular design and synthesis of engineering thermoset elastomers and related materials including tissue engineering scaffolds.

ASSOCIATED CONTENT

Supporting Information

^{1}H and ^{13}C NMR spectra of carvomenthone, carvomenthide synthesized using Oxone, HO-PCM-OH, HOOC-PCM-COOH, and XL-PCM samples for sequential additions, SEC traces for HO-PCM-OH polyols, optical images for the thermoset PCM elastomer films, and TGA for all polymers. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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