Macromolecules

Catenated Poly(e-caprolactone) and Poly(L-lactide) via Ring-Expansion Strategy

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S Supporting Information

ABSTRACT: Catenated $poly(\varepsilon$ -caprolatone) (PCL) and $poly(\iota$ -lactide) (PLA) were synthesized by a ring-expansion strategy based on a catenated tin initiator. Catenated PCLs with different degrees of polymerization (DP_n) were obtained by modifying the feed ratios of monomer to initiator, and subsequent decomplexation rendered the copper-free catenated PCL. Both the Cu(I)-templated catenated PCL and Cu(I)-free catenated PCL were characterized by UV–vis, ¹H NMR, FT-IR, and GPC analyses. The comparative GPC analyses of catenated polymers and their linear analogues were also performed, which revealed a reduced hydrodynamic diameter for the catenated polymers. The crystallinity of the



catenated PCL compared to that of linear PCL was also studied by DSC and WAXS, and the Cu(I)-free catenated PCL exhibited a lower degree of crystallinity but larger crystallite size.

■ INTRODUCTION

Over the past few decades, there is a growing interest in the synthesis and study of topologically interesting molecules, such as catenanes, rotaxanes, and knots, due to their unique properties for a variety of applications.^{1,2} Thanks to the great progress in coordination chemistry and new methods of covalent bond formation, these molecules with unnatural configurations have reached an exciting stage and have been investigated for different applications, such as memory devices, drug delivery, catalysis, and molecular machines.³⁻¹⁰ With two or more mechanically interlocked macrocycles that cannot be separated without the cleavage of at least one covalent bond, catenanes exhibit higher degrees of freedom and mobilities compared to the covalently bonded molecules.¹¹ Successful synthesis of molecular catenanes with low molecular weights using metal templates (including active metal template), hydrogen bonding, donor-acceptor interactions, and hydrophobic effect have been reported.^{1,10-14} However, the preparation of catenanes with relatively high molecular weight, e.g., catenated polymers (or polymeric catenane), is still rarely investigated.

It is well accepted that a polymer's physical property is affected not only by its chemical components but also by its molecular architecture.^{11,15} For example, cyclic polymers exhibit higher glass transistion temperatures (T_g) , lower hydrodynamic diameters, lower intrinsic viscosities, higher thermal stabilities, and slower degradation rates as compared to their linear analogues.^{16–21} Aside from the "endless" structure, another interesting architectural property which can be introduced is mechanically interlocked bonding, i.e., catenation. Because of their unique topologically self-constrained structure.

tures, catenated polymers are expected to show unique dynamic, rheological, and mechanical properties.^{11,22} However, the investigation of the properties of these topologically interesting macromolecules is greatly limited by the difficulties in both synthesis and purification.¹¹

A catenated polymer was first synthesized by statistical methods, in which a linear polymer was statistically threaded through a cyclic polymer by entropic driving, which was followed by a ring-closure reaction of the linear precursor.^{23,24} Utilization of hydrogen-bonding and electrostatic interactions can help in the preorganization, although the interaction is still too weak for such a long polymer chain.²⁵ For all these reports, the yields of catenated polymers were lower than 7%. Using the metal-templated complex method, our group fabricated a supramolecularly templated atomic transfer radical polymerization (ATRP) initiator, and subsequent polymerization and ring-closing reaction afforded a catenated polymer.²⁶⁻²⁸ The catenated polystyrene and catenated poly(styrene-b-methyl methacrylate) were obtained in yields up to 60%. However, similar to the challenges involved in the synthesis of cyclic polymers by ring-closing reaction,^{17,18,21,29–31} highly dilute conditions are required for efficient intramolecular ring-closing reaction instead of intermolecular cross-linking. Therefore, the synthesis of catenated polymers in high quantity for further investigation is still difficult to achieve. Inspired by the success of cyclic polymers synthesized by a ring expansion strategy,^{17,21,32-34} we designed a novel scheme for catenated

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and trefoil knotted polymer synthesis that does not require dilute conditions.^{35,36} In this approach, a catenane initiator was first synthesized via the reaction of Cu(I)-templated phenon-throline complex and tin initiator, and subsequent addition of monomers grows the catenane initiator into a catenated polymer. The ring-expansion strategy allows us to obtain catenated polymers with higher yield and larger quantity, large enough to carry out experiments to investigate its properties for a plethora of applications.

Poly(ε -caprolatone) and poly(lactide) are two of the most important polyesters.^{16,37,38} Owing to their biodegradability and biocompatibility, and following the current trend of minimizing the impact of chemicals to the environment, they have attracted a lot of attention for daily commodities, such as thin film coating and packaging materials, and the biomedical field like dental implants, tissue engineering, and drug delivery.³⁹⁻⁴⁵ With unique biophysical properties, cyclic polyesters offer great potential for a wide range of biomedical applications.^{16,46,47} Compared to the cyclic polyesters, the catenated polyesters possess even lower hydrodynamic volumes, which may further affect their hydrolytic degradation behaviors, and the mechanically interlocking of the two cyclic polyesters would also provide some promise for a unique guest-host system.^{15,35} However, the synthesis and the study of the physical properties of catenated polyesters have rarely been reported.³⁵ Herein, (1) the synthesis of the catenated $poly(\varepsilon$ -caprolactone)s with different molecular weights was demonstrated, (2) the crystallization of this semicrystalline polyester was studied, and (3) the synthesis and characterization of catenated poly(L-lactide) were also reported. To the best of our knowledge, this is the first report on the study of the crystallization of a catenated polymer and the first attempt on the synthesis of catenated poly(L-lactide).

EXPERIMENTAL SECTION

Materials. Chemical reagents were purchased from Sigma-Aldrich and were used without further purification unless otherwise indicated. ε -Caprolactone (CL, 99%, Alfa) was distilled from CaH₂ under reduced pressure. L-Lactide was purchased from Alfa Aesar and was purified by recrystallization from toluene before use. Tri(ethylene glycol) was purchased from Alfa Aesar. Benzolylated cellulose tubing (MWCO 2000) was purchased from Sigma and was used directly.

Characterization. ¹H nuclear magnetic resonance (NMR) spectra were recorded on a Varian Inova 600 MHz NMR spectrometer using chloroform-d. UV-vis spectra were recorded on a UV-vis-NIR spectrometer (StellarNet. Inc.), and the scanning range was 200-1000 nm. Infrared (IR) spectra were recorded on a Cary 600 Series FT-IR spectrometer (Agilent Technologies), and the scanning range was 4000-400 cm⁻¹. Dynamic light scattering (DLS) and static light scattering (SLS) measurements were performed using a DynaPro NanoStar (Wyatt). Gel permeation chromatography (GPC) measurements were carried out on a Viscotek 270 instrument with a triple detector array (RALS, IV, RI, or UV) equipped with two GMHHR-M and one GMHHR-L mixed bed ViscoGel columns (eluent: THF; flow rate: 1 mL min⁻¹). Thermal transitions of polymers were obtained using differential scanning calorimetry (DSC, TA Instruments Q100) at a heating rate of 10 °C/min over the appropriate temperature range of -80 to 120 °C. The sample was first heated to 120 °C and held at that temperature for 2 min to remove the thermal history. Wide-angle X-ray scattering (WAXS) patterns were obtained by aligning the incident X-ray beam parallel to the normal direction with a Bruker AXS (Madison, WI) HI-STAR area detector. The measurement was conducted using the same rotating anode X-ray generator, and the collimated beam size was 0.5 mm. The sample-to-dector distance was set to 74 mm, and the diffraction angle was calibrated using a CaF₂ standard. A Bruker AUTOFLEX III MALDI TOF/TOF mass

spectrometer was operated using HABA [2-(4-hydroxyphenylazo)benzoic acid] as matrix and sodium trifluoroacetate, Na(CF₃COO), as a doping salt. XPS data were recorded using a PHI 5700 X-ray photoelectron spectrometer. A monochromatic Al K α X-ray source was employed with 90° relative to the axis of hemispherical energy analyzer. High-resolution copper spectra were curve-fit using Gaussian–Lorentzian functions with a Shirley background correction.

Synthesis. Synthesis of 2-[2'-(2"-Hydroxyethoxy)ethoxy]ethanol 1-(4-Methylbenzenesulfonate) (2). The monotosylated tri(ethylene glycol) (TEG) was synthesized according to a previous reference with minor modification.⁴⁸ NaOH (2.74 g, 68 mmol) in water (15 mL) was added to a tetrahydrofuran (THF, 15 mL) solution of tri(ethylene glycol) (68 g, 452 mmol). Toluene *p*-sulfony chloride (8.4 g, 44 mmol) in 50 mL of THF was added slowly in an ice bath. After stirring for 5 h, the reaction mixture was poured into 250 mL of ice water. The organic layer was separated, and the aqueous layer was extracted with dichloromethane (DCM) (4 × 50 mL). The combined organic layer was washed with water (2 × 30 mL) and dried with Na₂SO₄, and the solid was filtered. The solvent was evaporated under reduced pressure to afford clear oil (10.05 g, 75%). ¹H NMR (δ ppm in CDCl₃): 7.80 (d, *J* = 12 Hz 2H), 7.35 (d, *J* = 6 Hz, 2H), 4.17 (t, *J* = 6 Hz, 4H), 3.72–3.57 (m, 8H), 2.45 (s, 3H).

Synthesis of 2,9-Bis(p-[2-[2'-hydroxyethoxy(ethoxy(ethoxv))]]phenyl)-1,10-phenanthroline (3). The synthesis of the 2,9-di(phydroxyphenyl)-1,10-phenanthroline (1) was reported by our group previously.^{26,35} A mixture of compound 1 (2.0 g, 5.5 mmol), compound 2 (3.65 g, 12 mmol), and K₂CO₃ (6.9 g, 50 mmol) in 50 mL of dimethylformamide (DMF) was placed in an oil bath at a temperature of 85 °C. After 24 h stirring, K₂CO₃ was filtered, and the solvent of the filtrate was removed under reduced pressure. The mixture was dissolved in 50 mL of dichloromethane (DCM), and the solution was washed with water (20 mL \times 3). Purification was achieved by column chromatography using 8% MeOH/DCM. Lastly, the pure product (2.7 g, 79%) as yellow solid (mp 60.9–62.0 °C) was obtained by recrystallization in methanol. ¹H NMR (CDCl₃), δ ppm: 8.42 (d, J = 9 Hz, 4H), 8.26 (d, J = 8 Hz, 2H), 8.08 (d, J = 8 Hz, 2H), 7.74 (s, 2H), 7.13 (d, J = 9 Hz, 4H), 4.27 (t, J = 5 Hz, 4H), 3.94 (t, J = 5 Hz, 4H), 3.79-3.69 (m, 12H), 3.63 (t, J = 5 Hz, 4H). ¹³C NMR (500 MHz, CDCl₃), δ ppm: 159.2, 156.4, 146.0, 136.9, 132.7, 129.0, 127.6, 125.6, 119.2, 114.8, 72.7, 69.7, 69.5, 67.6, 66.0, 61.6. m/z(+FAB) found 651.0 $[M + Na^+]$; calculated: 651.2 for $C_{36}H_{40}N_2O_8Na$.

Synthesis of Cu(l)-Templated Complex (4).³⁵ Compound 3 (0.063 g, 0.10 mmol) in 25 mL of DCM and Cu(CH₃CN)₄PF₆ (0.023 g, 0.06 mmol) in 25 mL of acetonitrile (CH₃CN) were prepared separately, and both solutions were bubbled with N₂ for 20 min. The CH₃CN solution of Cu(CH₃CN)₄PF₆ was slowly transferred to the DCM solution of compound 3 with a cannula. After another 20 min stirring under N₂ atmosphere, the solvent was removed to obtain the complex as reddish solid (mp 111–113 °C). ¹H NMR (CDCl₃, 500 MHz), δ ppm: 8.49 (d, *J* = 9 Hz, 4H), 8.02 (s, 4H), 7.83 (s, 4H), 7.34 (d, *J* = 8 Hz, 8H), 6.06 (d, *J* = 9 Hz, 8H), 3.79–3.66 (m, 48H). ¹³C NMR (500 MHz, CDCl₃), δ ppm: 159.3, 153.3, 142.5, 137.4, 129.2, 128.0, 126.4, 119.6, 113.2, 111.7, 72.6, 70.8, 70.4, 69.5, 67.3, 61.8. *m/z* (+FAB) found 1319.8 [M⁺]; calculated: 1320.9 for C₇₂H₈₀N₄O₁₆Cu.

Synthesis of Catenane Initiator (5).³⁵ Complex 4 (0.043 g, 0.025 mmol) was dissolved in 200 mL of dried chloroform (CHCl₃). The solution in a round-bottom flask equipped with a condenser was bubbled with N₂ for 30 min, and dibutyldimethoxytin (0.016 g, 0.055 mmol) in 5 mL of CHCl₃ was added. The reaction mixture was heated to reflux overnight under N₂. The solvent was removed by vacuum to obtain the product as reddish solid (mp 108–111 °C) with 96% yield. ¹H NMR (CDCl₃, 500 MHz), δ ppm: 8.49 (d, *J* = 9 Hz, 4H), 8.02 (s, 4H), 7.83 (s, 4H), 7.34 (d, *J* = 8 Hz, 8H), 6.06 (d, *J* = 9 Hz, 8H), 3.79–3.66 (m, 48H), 1.85–1.33 (m, 24H), 0.96–0.87 (m, 12H). ¹³C NMR (CDCl₃), δ ppm: 159.3, 153.3, 137.5, 137.4, 129.2, 128.0, 126.4, 119.6, 113.2, 111.7, 72.6, 70.8, 70.4, 69.5, 67.3, 61.8, 29.8, 27.4, 26.7, 13.7. UV–vis spectrum: $\lambda_{max} = 281$, 330, 455, and 595 nm.

Synthesis of Caten-PCL₈ and Caten-PLA_n (6 and 8). A typical synthesis of Caten-PCL₈₈ was performed as follows. Catenane initiators (5, 0.055 g, 0.025 mmol) and caprolactone monomers



^aInsets are the optimized 3D structures of complex 4 and compound 5 using semiempirical MP3 (tm).

(571 mg, 5.0 mmol) were combined in a 50 mL round-bottom flask. The mixture was degassed by three freeze–pump–thaw cycles, backfilled with N₂, and then subjected to polymerization in an oil bath at 80 °C under a nitrogen atmosphere for 18 h. A typical synthesis of Caten-PLA₉₀ was performed similarly, and the polymerization was conducted at 120 °C.⁴⁹ UV–vis spectrum: $\lambda_{max} = 281, 330, 455$, and 595 nm (as shown in Figures S8 and S11). ¹H NMR spectra of Caten-PCL_n and Caten-PLA_n are shown in Figure S4 and Figure 3.

Decomplexation of Catenated Polymer ($\overline{7}$ and 9). A typical synthesis of De-Caten-PCL₈₈ follows. 100 mg of Caten-PCL₈₈ was dissolved in 10 mL of DMF with magnetic stirring, and 20 mg of KCN was added to the solution. The mixture was stirred overnight, and successful decomplexation was evidenced by the color change (from reddish to colorless). Solvent was removed by vacuum, and DCM was added to dissolve the resulting polymer. KCN was filtered, and the polymer was purified by dialysis against DCM. UV–vis spectrum: λ_{max} = 281 and 330 nm (as shown in Figures S8 and S11). ¹H NMR spectra of De-Caten-PCL_n and De-Caten-PLA_n are shown in Figures 2 and 3.

RESULTS AND DISCUSSION

Catenane Initiator. The design and synthesis of the catenane initiator were reported by our group in the past.³⁵ Herein, more detailed information, especially the ¹H NMR spectra analysis, is provided. The copper-templated phenan-throline complex popularized by Sauvage and co-workers was utilized due to its highly efficient formation.^{1,50} Compound 1 (2,9-di(*p*-hydroxyphenyl)-1,10-phenanthroline) in a yield of 63% was synthesized according to a previous publication (Scheme S1).⁵¹ Excess monotosylated tri(ethylene glycol) (2) was reacted with compound 1 to afford a phenanthroline moiety with both sides functionalized by tri(ethylene glycol).

The copper-templated complex was formed by slowly adding the $Cu(CH_3CN)_4PF_6$ in CH_3CN to 3 in DCM, which was

confirmed by a color change and UV–vis spectroscopy analysis.³⁵ Moreover, ¹H NMR spectroscopy was useful in quantifying the complex formation as shown in Figure S1. Upon formation of the complex, an upfield shift was observed for the protons in the TEG segment, e.g., protons g and f, due to the physical interactions between the oxygens in TEG segment and hydrogens in the phenanthroline group.⁵⁰ The significant chemical shift for the protons in the aromatic segment was mainly due to the π – π interactions between phenyl rings (π donors) and phenanthroline moieties (π acceptors). It is worth noticing that all of the signals derived from compound 3 completely disappeared, which suggested a nearly quantitative formation of the Cu(I)-templated complex.

Dibutyldimethoxytin was reacted with the hydroxyl-terminated Cu(I)-templated complex to close the rings and enable the polymerization by monomer insertion. In reaction, the preorganized complex structure in which the two terminal hydroxyl groups are positioned together in space greatly favors the formation of the desired product other than noninterlocked molecules, such as macrocyles and threads.¹ The optimized 3D conformation of the Cu(I)-templated complex (4) with the lowest energy modeled by the Spartan 08 program, as shown in Scheme 1, confirmed the assumption. The conformational restriction was provided by the rigid ligand (the aromatic part of the complex 1), and the secondary interaction was provided by hydrogen bonding. The heat of reaction from complex 4 to initiator 5 was calculated to be -0.87 hartree or -2276 kJ/mol, which demonstrated the favorable nature of the reaction (see Table S1). Unfortunately, the sensitivity of the Sn-O bonds during ionization process prevents reliable matrix-assisted laser desorption/ionization time-of-flight mass measurement.⁵² The

Scheme 2. Synthesis of Catenated Poly(ε -caprolactone) and Catenated Poly(L-lactide)



Table 1. Combined ¹H NMR and GPC Analyses of Catenated Poly(*e*-caprolactone), Catenated Poly(*L*-lactide), and Corresponding Linear Analogues

samples	feed ratio	calcd DP_n^a	monomer $\operatorname{conv}^a(\%)$	$M_{\rm n}^{\ a}~({\rm kDa})$	retention vol (mL)	$M_{\rm n}^{\ b}~({\rm kDa})$	$M_{\rm w}^{\ b}$ (kDa)	PDI			
Caten-PCL ₄₃	50:1	43.2	87.5	12.0	27.7	7.1	10.3	1.45			
Caten-PCL ₈₈	100:1	87.9	87.9	22.2	27.0	12.6	16.9	1.34			
Caten-PCL ₁₈₀	200:1	179.8	89.4	43.2	26.3	20.8	23.7	1.31			
De-Caten-PCL ₄₃	50:1	42.5		11.5	28.5	7.7	9.7	1.27			
De-Caten-PCL ₈₈	100:1	82.0		20.5	27.3	11.1	13.7	1.23			
De-Caten-PCL ₁₈₀	200:1	167.5		40.1	25.7	19.2	24.6	1.28			
Lin-PCL99	100:1	98.6	98.6	11.5	27.0	10.8	15.0	1.55			
Lin-PCL ₁₈₁	200:1	181.2	90.6	21.0	25.0	21.3	29.2	1.32			
Caten-PLA ₉₀	100:1	90.8	90.8	26.6	27.8	11.3	32.1	2.84			
De-Caten-PLA ₉₀	100:1	87.6		26.5	27.8	11.8	17.9	1.52			
Lin-PLA ₈₇	100:1	86.5	86.5	12.8	26.85	13.9	25.1	1.81			
^a Data calculated from the ¹ H NMR spectrum. ^b Data obtained from the GPC analysis.											

¹H NMR spectrum of the catenane initiator, as shown in Figure S2, confirmed the successful insertion of the tin initiator and a relatively stable Cu(I)-templated complex (only the signals from the complex were observed). To test the efficiency of the ring-closing reaction, GPC analysis of the catenane initiator and its decomplexed product was performed as shown in Figure S3.³⁵ Catenane initiator **5** exhibited lower retention volume compared to the catenane ligand **3** due to the increased hydrodynamic diameter. After decomplexation, the catenane initiator with one or two unclosed cycles become single cycles or linear polymers/ligands and hence have lower hydrodynamic diameter. By integrating the GPC curve, 78% of the trace remained in the same hydrodynamic volume, suggesting a 78% yield of the desired product.

Cu(I)-Templated Catenated Poly(ε -caprolactone) via Living Polymerization. Based on the cyclic tin initiator, a cyclic polyester was prepared by Kricheldorf et al. under kinetic control with no side reactions observed.⁵³ Herein, a catenated poly(ε -caprolatone) was synthesized by inserting monomers into the Sn–O bond of the catenane initiator as demonstrated in Scheme 2. Since DP_n was defined as the sum of monomers in the two polymer chains derived from one tin atom,³⁵ the feed ratio is also defined as the ratio of monomers to tin atoms. Therefore, the monomer number in one catenated polymer is twice the DP_n due to the presence of the two tin initiating sites per catenane initiator.

With different feed ratios, catenated $poly(\varepsilon$ -caprolatone)s with different molecular weights were obtained by bulk polymerization. To prevent the possible hydrolysis and alcoholysis of the Sn-O bond during purification process, the unreacted monomer was removed by dialysis against DCM instead of the usual precipitation in methanol or water. The purified product was analyzed by ¹H NMR as shown in Figure S4. After 18 h of polymerization and 40 h of dialysis, the Cu(I)templated complex was still very stable as evidenced by the signals derived from the complex. Calculated from the comparative integrations of the peak derived from the CH₂ (proton p in Figure S4) next to ester bond in the PCL segment to the peak corresponding to one of the phenonthroline protons (proton b in Figure S4), the DP_n of catenated poly(ε caprolactone) increased proportionally with the feed ratios, and the monomer conversion was calculated to range from 87% to 90% (see Table 1). Moreover, the absolute molecular weight of catenated PCL was also calculated based on the chemical structure and DP_n (Table 1; see Figure S4 for calculation details). The purified Caten-PCL_n was also characterized by FT-IR spectroscopy (Figure S5). Caten-PCL, exhibited peaks at 1720 and 1182 cm⁻¹ that corresponded to the stretching vibrations of C=O and C-O bonds in the $poly(\varepsilon$ caprolactone), respectively, while the peaks at 732 and 841 cm⁻¹ originated from the out-of-plane bending of C-H in the phenanthroline groups. Moreover, the increased area ratio of

the peak at 1720 cm^{-1} to the peak at 841 cm^{-1} also demonstrated the increased monomer number per Cu(I)-templated phenanthroline complex.

Compared to the catenane initiator, catenated $poly(\varepsilon$ caprolactone) exhibited larger hydrodynamic diameter evidenced by the reduced retention volume in the GPC curve (Figure 1). The hydrodynamic diameter increased with



Figure 1. Comparative GPC curves of catenane initiator, Caten-PCL₄₃, Caten-PCL₈₈, and Caten-PCL₁₈₀.

increased DP_n of catenated poly(ε -caprolactone), which was also confirmed by DLS analysis. The average hydrodynamic radii of Caten-PCL43, Caten-PCL88, and Caten-PCL178 were measured to be 5.49 \pm 0.28, 12.2 \pm 0.59, and 21.4 \pm 1.0 nm, respectively (Figure S6), and the broad distributions were probably due to the relatively high polydispersity of the poly(ε caprolactone). Based on commercially available poly(styrene) standards for calibration, the number-average molecular weight (M_n) and polydispersity (PDI) obtained by GPC analysis are summarized in Table 1. To compare the properties against their linear analogues, linear poly(ε -caprolactone)s with feed ratios of 100 and 200 were also synthesized under the same conditions as shown in Figure S7. Because of the presence of two Sn atoms in one catenated PCL, the absolute molecular weight $(M_{n,NMR})$ of Caten-PCL₄₃ is comparable to that of Lin-PCL₉₉, and the $M_{n,NMR}$ of Caten-PCL₈₈ is comparable to that of Lin-PCL₁₈₁. It was seen that with similar $M_{n,NMR}$ the catenated polymer exhibited reduced hydrodynamic diameter compared to their linear analogues due to their compact structure.

Copper-Free Catenated Polymer by Decomplexation. To obtain a genuine catenated $poly(\varepsilon$ -caprolatone) without the restriction of a copper template, a decomplexation procedure was performed with excess KCN in DMF. The disappearance of the reddish color of the polymer solution was observed after overnight stirring. Further evidence was provided by the disappearance of the absorption peaks in the visible region, i.e., peaks at 437 and 585 nm that are attributed to the metal-toligand transition (MLCT) and ligand-to-metal transitions (LMCT) (Figure S8). The ¹H NMR spectrum of decomplexed catenated PCL (Figure 2) exhibited significant chemical shift compared to that of Cu(I)-templated catenated PCL (Figure S4), and complete disappearance of the peaks attributed to the complex confirmed the successful decomplexation. To monitor the removal process of copper, XPS was also utilized to analyze the catenated PCLs before and after decomplexation. However, due to the relatively low content of copper element (<0.1%) in



Figure 2. ¹H NMR spectra (CDCl₃, 600 MHz) of (A) De-Caten-PCL₄₃, (B) De-Caten-PCL₈₈, and (C) De-Caten-PCL₁₈₀.

the catenated PCL, it is difficult to confirm the presence of copper even before decomplexation. Hence, the catenane initiator was decomplexed under the same conditions, and the samples were analyzed instead. It can be seen from the XPS spectra that the copper was completely removed under this condition (Figure S9).

The ¹H NMR spectra of the copper-free catenated PCLs with different DP_ns are shown in Figure 2. A similar trend was observed in which the comparative integrations of peaks in the PCL segment (e.g., p and l in Figure 2) to the peaks in the phenanthroline moieties (e.g., d and e in Figure 2) increased proportionally with the feed ratio. It is worth noticing that the calculated DP_n of De-Caten-PCL from the integration of the ¹H NMR spectrum is slightly different from that of the Caten-PCL. One possibility is that after decomplexation the unclosed Caten-PCL became two polymers with lower molecular weight and hence was removed by dialysis. The well-known integration errors of ¹H NMR spectroscopy may also contribute to this difference. However, to avoid confusion, the same DP_n number was utilized to label the catenated PCL after decomplexation as shown in Figure 2 and Table 1.

The dramatic decrease in elution volume was also observed for the De-Caten-PCL with increased DP_n (Figure S10). The broader GPC curve of De-Caten-PCL compared to that of Caten-PCL is perhaps due to the relatively high conformational freedom after removing the restriction of the copper-template (see comparative GPC curves of Caten-PCL₈₈ and De-Caten-PCL₈₈). Based on the linear PS standards, M_{p_1} , M_{w_2} and PDI with similar values compared to Cu(I)-templated catenated polymer were obtained (Table 1).



Figure 3. Comparative ¹H NMR spectra (CDCl₃, 600 MHz) of Caten-PLA₉₀ and De-Caten-PLA₉₀.

Catenated Poly(L-lactide) via Ring-Expansion Strategy. The synthesis of catenated poly(L-lactide) was performed in bulk under a nitrogen atmosphere because our initial trial in an organic solvent failed. After 18 h of polymerization, Caten-PLA was purified by dialysis to remove the unreacted monomer. Instead of precipitation in methanol, purification was done by dialysis to prevent possible side reactions.⁴⁹ The strong signals at 5.2 and 1.6 ppm, which are typical peaks from the PLA, suggested successful polymerization of L-lactide.^{54,55} The monomer conversion was calculated to be 90.8% according to the relative peak integration in the ¹H NMR spectrum Article

(Figure 3A). Moreover, the signals corresponding to the Cu(I)-phenanthroline complex confirmed the robustness of the complex after polymerization and purification. It was also validated by the presence of absorption peaks corresponded to the MLCT and LMCT in the UV-vis spectrum (Figure S11).

The strong absorption peak centered at 1745 cm⁻¹ in the IR spectrum of Caten-PLA₉₀ is attributed to the stretching vibration of the C=O bond, with a frequency that is a little higher than that of the C=O bond of Caten-PCL₈₈, which is probably due to the inductive effect. The broad absorption band at 2800-2950 cm⁻¹ is from the stretching vibration of saturated C-H bonds, and the intensity is lower than that of Caten-PCL₈₈ when the C=O bond intensity is fixed. This is due to the presence of a larger amount of ester bonds in PLA compared to PCL, which is probably the main reason for different hydrolysis behavior of these two well-known polyesters. GPC analysis of the obtained Caten-PLA₉₀ revealed a relatively high polydispersity (PDI), and it was explained that the propagation rate was higher than initiation rate under this polymerization condition.⁴⁹ More studies on reducing the PDI of Caten-PLA, such as in-solution polymerization, are under way.³⁸ Linear PLA was also synthesized for the purpose of comparison as shown in Figure S13. Similarly, the obtained catenated PLA exhibited reduced hydrodynamic diameter than that of linear analogue due to its compact polymer structure (Table 1).

Decomplexation of Caten-PLA₉₀ rendered a copper-free catenated polymer featured by the absence of MLCT and LMCT bands in the UV–vis spectrum (Figure S11). As shown in Figure 3, the dramatic chemical shifts of the signals in both the phenanthroline segment (peak a to e) and the tri(ethylene glycol) moieties (peak e to k) demonstrated the complete decomplexation process. The presence of peaks for both phenanthroline and PLA after dialysis confirmed the successful coordination polymerization.³⁸ GPC analysis of the De-Caten-PLA₉₀ suggested a comparable hydrodynamic diameter with the Caten-PLA₉₀, and the calculated M_n based on linear PS was also similar.

Crystallinity of Catenated Poly(*e***-caprolatone).** Thanks to the great success of cyclic polyester synthesis, the effect of

Table 2. Crystallinity Analysis of Catenated PCL, Linear PCL, and Decomplexed Catenated PCL

samples	$T_{\rm m}$ (°C)	$(^{\circ}C)$	$\frac{\Delta H_{\rm m}}{({\rm J/g})}$	deg of crystallinity ^a (%)	Miller index (<i>hkl</i>)	2θ Cu Kα	d spacing (Å)	crystallite size (nm)	deg of crystallinity ^b (%)
Caten-PCL ₄₃	46	20	61	45	(110)	21.7	4.09	27.9	41.5
					(200)	24.0	3.69	29.7	
Caten-PCL ₈₈	51	28	69	50	(110)	21.6	4.11	21.0	49.3
					(200)	23.9	3.72	16.6	
Caten-PCL ₁₈₀	54	33	71	51	(110)	21.6	4.11	13.4	55.4
					(200)	24.0	3.70	11.0	
Lin-PCL99	53	29	77	55	(110)	21.8	4.08	23.5	52.1
					(200)	24.1	3.69	20.0	
Lin-PCL ₁₈₁	54	30	80	57	(110)	21.6	4.12	22.9	56.7
					(200)	23.9	3.72	17.4	
De-Caten-PCL ₄₃	44	17	69	46	(110)	21.9	4.06	33.8	39.7
					(200)	24.3	3.67	27.9	
De-Caten-PCL ₈₈	49	24	68	48	(110)	21.7	4.09	24.0	46.9
					(200)	24.1	3.70	23.4	
De-Caten-PCL ₁₈₀	52	27	79	55	(110)	21.7	4.10	23.5	52.4
					(200)	24.1	3.70	18.6	

 a Values were obtained based the 100% PCL heating enthalpy (139.3 J/g). b Values were calculated from the comparative integrations of crystalline peak to that of amorphous area.

topology on the crystallinity of PCL has been investigated.^{56–58} Previous studies showed that cyclic polymers possess unique thermal properties in terms of melting point, crystallization temperature, and crystallization rate due to their special architecture.^{56,59} The thermal characterization of catenated poly(ε -caprolactone)s and their linear analogues was performed by DSC analysis, and the results are summarized in Table 1. All of the DSC analysis was performed with a heating and cooling rate of 10 °C/min under a nitrogen atmosphere, and melting point ($T_{\rm m}$) was recorded from the second heating scan.

DSC curves of Caten-PCL and De-Caten-PCL exhibited melting and crystallization behavior similar to Lin-PCL as shown in Figures S15 and S16. The melting endotherms in the second heating runs revealed a bimodal distribution of melting points. The first melting peak comes from the fusion of the crystals formed during the previous cooling scan, and the second peak is attributed to a partial melting and reorganization process.^{56,60} The copper-free catenated PCLs exhibited slightly lower $T_{\rm m}$ and $T_{\rm c}$ values than those of the Cu(I)-templated catenated PCLs, which is perhaps due to the relatively higher conformational freedom.

The degree of crystallinity based on the second heating scan was also calculated and listed in Table 2. It is worth noticing that the Caten-PCL43 possessed an absolute molecular weight similar to Lin-PCL₉₉, while in terms of DP_n, Caten-PCL₈₈ is more comparable with Lin-PCL₉₉ (Table 1). This renders a problem regarding the linear analogue options for catenated polymers. However, it can be seen that the catenated PCLs always exhibited a lower degree of crystallinity compared to the linear PCL analogues in either molecular weight or DP_n aspect. In terms of comparable molecular weight, the shorter $poly(\varepsilon$ caprolactone) chain has the lower degree of crystallinity as compared to its linear analogue. With the comparable DP_n and hence similar polymer chain length with the linear analogues, the catenated polymers possess larger polymer sizes, selfconstrained architectures, and hence lower mobilities, which also renders a lower degree of crystallinity.^{56,58} Moreover, it was demonstrated that the De-Caten-PCL also exhibited lower T_m and $T_{\rm c}$ values compared to their linear analogues perhaps due to similar reasons.

The catenated polymers and their linear analogues were also analyzed by WAXS, and the results are summarized in Table 2. Similar to the linear PCL (Figure S17A), the WAXS patterns of Caten-PCL (Figure S18A) and De-Caten-PCL (Figure 4A) exhibited two main diffraction rings from the orthorhombic crystal structure of PCL. The inner diffraction ring ($2\theta =$



Figure 4. (A) Representative 2D WAXS pattern of De-Caten-PCL $_{88}$ crystal. (B) 1D profile of copper-free catenated PCL.

21.57°-21.89°) contained the PCL (110) reflections, and the outer diffraction ring $(2\theta = 23.90^{\circ} - 24.26^{\circ})$ was the PCL (200) plane.⁶¹ The equatorial (110) and (200) intensities demonstrated the isotropic crystallinity of the polymers in the plane. Utilizing the Debye-Scherrer method, the XRD was also proven useful in determining the mean size of crystallites in nanocrystalline bulk materials.⁶² The equation is $D_{hkl} = K\lambda/(B_{hkl} \cos \theta)$, in which the D_{hkl} is the crystallite size in the direction to the lattice planes, *K* is a numerical factor frequently referred as the crystallite-shape factor, B_{hkl} is the full width at half-maximum of the X-ray diffraction peak, θ is the Bragg angle, and λ is the wavelength of the X-ray. The crystallite sizes of different PCL polymers were calculated with K = 0.9, and the results are summarized in Table 2. The longer polymer chains tend to form compact crystalline structures which was confirmed by the decreased crystallite size with increased DP_n . Compared to the linear analogue and Cu(I)-templated catenated polymer, the copper-free catenated polymer tends to form larger crystallites. Moreover, the degree of crystallinity was calculated based the comparative area of crystalline peak and amorphous area. Compared with Lin-PCL, a lower degree of crystallinity was also observed for the De-Caten-PCL, which is consistent with the DSC analysis.

CONCLUSION

Catenated poly(ε -caprolatone)s with different DP_ns were synthesized by changing the feed ratio of monomer to catenane initiator, which was confirmed by the ¹H NMR spectrum, GPC, and IR spectrum. The UV-vis and ¹H NMR spectra of Cu(I)templated catenated PCL confirmed the stability of the complex. Copper-free catenated PCL with different polymer chain lengths was obtained by the decomplexation, and the De-Caten-PCL exhibited a broader GPC curve compared to Caten-PCL due to the higher conformational freedom. Caten-PLA was also synthesized by bulk polymerization using the same catenane initiator, and subsequent decomplexation rendered a copper-free catenated PLA. Compared to their linear analogues with the same absolute molecular weight, the catenated PCL and PLA exhibited higher retention volume due to their lower hydrodynamic diameter. The presence of the tin initiator in the catenated polyester is problematic in both characterization and application aspects; further research on tin-free catenated polyester is underway.

The crystallinity analysis of De-Caten-PCL revealed a relatively lower $T_{\rm m}$ value and degree of crystallinity than their linear analogues. The crystallite sizes of De-Caten-PCL calculated by the Debye–Scherrer equation are larger than those of the linear analogue. The different crystallinity behavior of the De-Caten-PCL is perhaps due to the unique polymer topology and architecture. Deeper understanding of the crystallinity behavior of this semicrystalline catenated polymer is being studied.

ASSOCIATED CONTENT

Supporting Information

Synthesis of catenated ligand, ¹H NMR spectra, GPC, UV-vis spectra, IR spectra, and DSC curves of catenated polymers and their linear analouges. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.macromol.5b00470.

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Notes

The authors declare no competing financial interest.

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■ NOMENCLATURE

Caten-PCL_n, Cu(I)-templated catenated poly(ε -caprolactone) with degree of polymerization (DP_n) to be *n*; Caten-PLA_n, Cu(I)-templated catenated poly(L-lactide) with degree of polymerization (DP_n) to be *n*; Lin-PCL_n, Linear poly(ε -caprolactone) with degree of polymerization (DP_n) to be *n*; De-Caten-PLA_n, catenated poly(L-lactide) after the removal of the Cu template; De-Caten-PLA_n, catenated poly(L-lactide) after the removal of the Cu template; DP_n, sum of the two polymer chains derived from one tin atom, which is consistent with our previous report.^{35,36}

REFERENCES

- (1) Beves, J. E.; Blight, B. A.; Campbell, C. J.; Leigh, D. A.; McBurney, R. T. Angew. Chem., Int. Ed. 2011, 50, 9260-9327.
- (2) Arunachalam, M.; Gibson, H. W. Prog. Polym. Sci. 2014, 39, 1043-1073.
- (3) Hanni, K. D.; Leigh, D. A. Chem. Soc. Rev. 2010, 39, 1240-1251.
- (4) Lindoy, L. F.; Park, K.-M.; Lee, S. S. Chem. Soc. Rev. 2013, 42, 1713-1727.
- (5) Stoddart, J. F. Chem. Soc. Rev. 2009, 38, 1802-1820.
- (6) Coti, K. K.; Belowich, M. E.; Liong, M.; Ambrogio, M. W.; Lau,

Y. A.; Khatib, H. A.; Zink, J. I.; Khashab, N. M.; Stoddart, J. F. Nanoscale 2009, 1, 16–39.

- (7) Grunder, S.; McGrier, P. L.; Whalley, A. C.; Boyle, M. M.; Stern, C.; Stoddart, J. F. J. Am. Chem. Soc. **2013**, 135, 17691–17694.
- (8) Shinkai, S.; Ikeda, M.; Sugasaki, A.; Takeuchi, M. Acc. Chem. Res. 2001, 34, 494–503.
- (9) Neal, E. A.; Goldup, S. M. Chem. Commun. 2014, 50, 5128-5142.
- (10) Olson, M. A.; Coskun, A.; Fang, L.; Basuray, A. N.; Stoddart, J. F. Angew. Chem., Int. Ed. **2010**, 49, 3151–3156.
- (11) Niu, Z.; Gibson, H. W. Chem. Rev. 2009, 109, 6024-6046.
- (12) Crowley, J. D.; Goldup, S. M.; Lee, A.-L.; Leigh, D. A.; McBurney, R. T. Chem. Soc. Rev. 2009, 38, 1530-1541.
- (13) Fang, L.; Basu, S.; Sue, C.-H.; Fahrenbach, A. C.; Stoddart, J. F. J. Am. Chem. Soc. **2010**, *133*, 396–399.
- (14) Cougnon, F. B. L.; Ponnuswamy, N.; Jenkins, N. A.; Pantoş, G. D.; Sanders, J. K. M. J. Am. Chem. Soc. **2012**, 134, 19129–19135.
- (15) Yamamoto, T.; Tezuka, Y. Polym. Chem. 2011, 2, 1930-1941.
- (16) Hoskins, J. N.; Grayson, S. M. Polym. Chem. 2011, 2, 289–299.
- (17) Laurent, B. A.; Grayson, S. M. Chem. Soc. Rev. 2009, 38, 2202–2213.
- (18) Tang, Q.; Wu, Y.; Sun, P.; Chen, Y.; Zhang, K. Macromolecules **2014**, *47*, 3775–3781.
- (19) Bunha, A.; Cao, P.-F.; Mangadlao, J. D.; Advincula, R. C. React. Funct. Polym. 2014, 80, 33-39.
- (20) Hoskins, J. N.; Grayson, S. M. Macromolecules 2009, 42, 6406–6413.
- (21) Jia, Z.; Monteiro, M. J. J. Polym. Sci., Part A: Polym. Chem. 2012, 50, 2085–2097.
- (22) Pakula, T.; Jeszka, K. Macromolecules 1999, 32, 6821-6830.

- (23) Gan, Y.; Dong, D.; Hogen-Esch, T. E. Macromolecules 2002, 35, 6799-6803.
- (24) Ohta, Y.; Kushida, Y.; Kawaguchi, D.; Matsushita, Y.; Takano, A. *Macromolecules* **2008**, *41*, 3957–3961.
- (25) Ishikawa, K.; Yamamoto, T.; Asakawa, M.; Tezuka, Y. *Macromolecules* **2009**, *43*, 168–176.
- (26) Bunha, A.; Tria, M. C.; Advincula, R. Chem. Commun. 2011, 47, 9173–9175.
- (27) Bunha, A. K.; Mangadlao, J.; Felipe, M. J.; Pangilinan, K.; Advincula, R. *Macromol. Rapid Commun.* **2012**, *33*, 1214–1219.
- (28) Pangilinan, K.; Advincula, R. Polym. Int. 2014, 63, 803-813.
- (29) Quirk, R. P.; Wang, S.-F.; Foster, M. D.; Wesdemiotis, C.; Yol, A. M. *Macromolecules* **2011**, *44*, 7538–7545.
- (30) Stanford, M. J.; Pflughaupt, R. L.; Dove, A. P. *Macromolecules* **2010**, *43*, 6538–6541.
- (31) Voter, A. F.; Tillman, E. S.; Findeis, P. M.; Radzinski, S. C. ACS Macro Lett. 2012, 1, 1066–1070.
- (32) Kudo, H.; Sato, M.; Wakai, R.; Iwamoto, T.; Nishikubo, T. *Macromolecules* **2008**, *41*, 521–523.
- (33) Jeong, W.; Hedrick, J. L.; Waymouth, R. M. J. Am. Chem. Soc. 2007, 129, 8414-8415.
- (34) Zhang, K.; Zha, Y.; Peng, B.; Chen, Y.; Tew, G. N. J. Am. Chem. Soc. 2013, 135, 15994–15997.
- (35) Cao, P.-F.; Bunha, A.; Mangadlao, J.; Felipe, M. J.; Mongcopa, K. I.; Advincula, R. *Chem. Commun.* **2012**, *48*, 12094–12096.
- (36) Cao, P.-F.; Mangadlao, J.; Advincula, R. Angew. Chem., Int. Ed. 2015, 54, 5127–5131.
- (37) Raquez, J.-M.; Habibi, Y.; Murariu, M.; Dubois, P. Prog. Polym. Sci. 2013, 38, 1504–1542.
- (38) Dechy-Cabaret, O.; Martin-Vaca, B.; Bourissou, D. Chem. Rev. 2004, 104, 6147-6176.
- (39) Ha, C.-S.; Gardella, J. A. Chem. Rev. 2005, 105, 4205-4232.
- (40) Cao, P.-F.; Felipe, M. J.; Advincula, R. C. Macromol. Chem. Phys. 2013, 214, 386–395.
- (41) Cao, P.-F.; Zhao, R.-X.; Li, L.; Yang, W.-W.; Cheng, F.; Chen, Y.; Lu, C.-H.; Jiang, S.-C. J. Polym. Sci., Part A: Polym. Chem. 2012, 50, 227–236.
- (42) Cao, P.-F.; Xiang, R.; Liu, X.-Y.; Zhang, C.-X.; Cheng, F.; Chen, Y. J. Polym. Sci., Part A: Polym. Chem. 2009, 47, 5184–5193.
- (43) Faÿ, F.; Linossier, I.; Langlois, V.; Renard, E.; Vallée-Réhel, K. *Biomacromolecules* **2006**, *7*, 851–857.
- (44) Becker, J. M.; Pounder, R. J.; Dove, A. P. Macromol. Rapid Commun. 2010, 31, 1923–1937.
- (45) Surnar, B.; Jayakannan, M. Biomacromolecules 2013, 14, 4377–4387.
- (46) Li, H.; Jérôme, R.; Lecomte, P. Macromolecules 2008, 41, 650-654.
- (47) Li, H.; Debuigne, A.; Jérome, R.; Lecomte, P. Angew. Chem., Int. Ed. 2006, 45, 2264–2267.
- (48) Ashton, P. R.; Huff, J.; Menzer, S.; Parsons, I. W.; Preece, J. A.; Stoddart, J. F.; Tolley, M. S.; White, A. J. P.; Williams, D. J. *Chem.*— *Eur. J.* **1996**, *2*, 31–44.
- (49) Kricheldorf, H. R.; Lee, S.-R.; Bush, S. Macromolecules **1996**, 29, 1375–1381.
- (50) Weck, M.; Mohr, B.; Sauvage, J.-P.; Grubbs, R. H. J. Org. Chem. 1999, 64, 5463–5471.
- (51) Dietrich-Buchecker, C.; Sauvage, J.-P. Tetrahedron 1990, 46, 503-512.
- (52) Kricheldorf, H. R. J. Polym. Sci., Part A: Polym. Chem. 2004, 42, 4723-4742.
- (53) Kricheldorf, H. R.; Schwarz, G. Macromol. Rapid Commun. 2003, 24, 359-381.
- (54) Isono, T.; Kondo, Y.; Ozawa, S.; Chen, Y.; Sakai, R.; Sato, S.-i.;
- Tajima, K.; Kakuchi, T.; Satoh, T. *Macromolecules* **2014**, *47*, 7118–7128.
- (55) Zhang, C.-X.; Wang, B.; Chen, Y.; Cheng, F.; Jiang, S.-C. Polymer **2012**, 53, 3900–3909.

- 54, 846–859.
 (57) Li, H.; Jéröme, R.; Lecomte, P. Polymer 2006, 47, 8406–8413.
 (58) Schäler, K.; Ostas, E.; Schröter, K.; Thurn-Albrecht, T.; Binder,
- W. H.; Saalwächter, K. *Macromolecules* **2011**, *44*, 2743–2754. (59) Pérez, R. A.; Córdova, M. E.; López, J. V.; Hoskins, J. N.; Zhang,
- (39) Felez, K. A.; Cordova, M. E.; Lopez, J. V.; Hoskins, J. N.; Zhang,
 B.; Grayson, S. M.; Müller, A. J. *React. Funct. Polym.* 2014, 80, 71–82.
 (60) Córdova, M. E.; Lorenzo, A. T.; Müller, A. J.; Hoskins, J. N.;
 Grayson, S. M. *Macromolecules* 2011, 44, 1742–1746.
- (61) Ponting, M.; Lin, Y.; Keum, J. K.; Hiltner, A.; Baer, E. Macromolecules **2010**, 43, 8619–8627.
- (62) Holzwarth, U.; Gibson, N. Nat. Nanotechnol. 2011, 6, 534-534.