Zinc Glutarate Catalyzed Synthesis and Biodegradability of Poly(carbonate-*co*-ester)s from CO_2, Propylene Oxide, and ε-Caprolactone

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Summary: A zinc glutarate (ZnGA) catalyst was prepared from the reaction of zinc oxide and glutaric acid in dry toluene. ZnGA was found to exhibit a catalytic activity for the copolymerization of carbon dioxide (CO_2) and propylene oxide (PO) and the homopolymerization of PO but to reveal no catalytic activity for the homopolymerization of ε-caprolactone (CL). The ZnGA-catalyzed polymerization was extended for the terpolymerization of CO_2 with PO and CL, producing poly(propylene carbonate-*co*-ε-caprolactone)s (PPCCLs) with a reasonably high molecular weight in high yields. In the terpolymerization, PO and CL were used as both co-monomers and reaction media, after the reaction completed, the excess co-monomers were easily recovered and reused in the next terpolymerization batch. For the synthesized polymers, enzymatic and biological degradability were investigated.

Keywords: biodegradation; carbon dioxide; terpolymerization; zinc glutarate

Introduction

Aliphatic polycarbonates can be produced from the copolymerization of oxirane and CO_2;[1-16] CO_2 is the cheapest and most abundant raw material source of carbon.[17] However, the major drawback of this copolymerization is the relatively high stability of CO_2, which means that its copolymerization with alkylene oxide requires a highly active catalyst. Among various catalysts reported to date, zinc glutarate (ZnGA), which is prepared from zinc oxide and glutaric acid, is thought to be the most effective catalyst for the production of polycarbonate from CO_2 and oxirane.[1-3] On the other hand, aliphatic polyesters are presently thought to be the most attractive class of artificial polymers from the environmental standpoint, in that they degrade in contact with living tissues and in

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outdoor conditions.[18-21] In particular, poly(ε-caprolactone) (PCL) is biodegradable and of commercial interest because of its remarkable compatibility with a number of polymers.[18-21]

In this study we have attempted to terpolymerize CO_2, propylene oxide (PO: an oxirane), and ε-caprolactone (CL) using a ZnGA catalyst in order to meld the advantageous properties of polycarbonate and PCL into one polymeric system. In the polymerization, PO and CL were used as both co-monomers and reaction media, respectively; thus no organic solvent was involved in the copolymerization and the process did not produce organic solvent waste. For the synthesized polymers, enzymatic and biological degradability were additionally investigated.

Experimental

Materials. Carbon dioxide was obtained from BOC Gases Company (Korea), and propylene oxide (PO) was supplied by SK Oxichemical Company (Korea). All other chemicals used in this study were purchased from Aldrich. PO was purified by distillation over calcium hydride under dry nitrogen gas before use. Toluene was purified by the usual method before use. All the other chemicals were used as received without further purification.

ZnGA was synthesized from zinc oxide (ZnO) and glutaric acid (GA) as described elsewhere.[1] GA (100 mmol) was dissolved in 150 mL of toluene in a round bottom flask equipped with a Dean-Stark trap and a reflux condenser with a drying tube. Then, ZnO (100 mmol) was added into the GA in toluene. After the addition was complete, the slurried mixture was stirred vigorously at 55 °C for 4 h. After cooled to room temperature, the reaction mixture was filtered off and washed with acetone several times, giving ZnGA in powder form. The powdered ZnGA was dried in a vacuum of 1 x 10-5 torr at 100 °C for 2 days.

Polymerization. All polymerizations of our study were conducted using an autoclave reactor (500 mL) system equipped with a mechanical stirrer and a programmable temperature controller. ZnGA (1.00 g) was added into the reactor, followed by adding desired amounts of monomers. Then the reactor was heated at 30-100 °C with stirring. After 5-60 h, the reactor was cooled to room temperature. The polymer product was taken out and dried further in a vacuum oven at room temperature, followed by weighing to

determine gross yield. The dried product was dissolved in methylene chloride and transferred to a separating funnel. The catalyst residue was extracted from the product solution by adding a diluted hydrochloric acid. The extraction was repeated three times. The product solution was subsequently washed two times with distilled water. The product solution was concentrated to a proper volume using a rotary evaporator. Then the product solution was poured into methanol in excess. The polymer precipitate was filtered off, followed by drying at room temperature in a vacuum oven.

Characterization. For the catalysts, a FT-IR spectroscopic analysis was carried out with a resolution of 2 cm^{-1} using an ATI Mattson FT-IR spectrometer (Research Series). Thermogravimetric analysis (TGA) was conducted using a Seiko TG/DT analyzer (EXSTAR 6000 TG/DT). During the measurement, dry nitrogen gas was purged at a flow rate of 100 mL/min and a ramping rate of 5.0 °C/min was employed. For the polymer products, spectroscopic analysis was performed using a Bruker NMR spectrometer (ASPECT 300 MHz) with ^{1}H and ^{13}C probes. In the NMR spectroscopic measurements, chemical shifts were calibrated with the chemical shifts of the solvents used: chloroform-d_1 and benzene-d_6. The number average molecular weight ($\overline{Mn}$)and the polydispersity of the polymer product were estimated using a gel permeation chromatography (GPC) system (Polymer Labs Model PL-GPC 210) The GPC system was calibrated by a series of polystyrene standards. Tetrahydrofuran (THF, HPLC grade) was used as an eluent. Thermal stability was measured in a nitrogen atmosphere by TGA. Glass transition temperature (T_g) was measured using a Seiko differential scanning calorimeter (DSC-220CU). During the measurement, dry nitrogen gas was purged with a flow rate of 100 mL/min and a ramping rate of 10.0 °C/min was employed.

For the polymers, enzymatic degradation was carried out at 37 °C in a 0.02 M phosphate buffer solution (pH 7) containing *Pseudomonas* lipase (Sigma Aldrich). The biodegradability was additionally tested at 25 °C for 30 days in an inorganic salt solution containing one of three fungi: *Aspergillus fumigatus*, *Aspergillus terreus*, and *Penicillium olonii*. For these tests, film samples of the polymers were prepared in a size of 0.3 × 10 × 10 mm^3 and then dried in a vacuum at room temperature for 2 days before use. The films and buffer solution were incubated in a test tube and were shaken in a shaker. After a determined period of time, the films were picked out and washed with distilled water, and then dried in a vacuum at 25 °C to a constant weight. Surface morphologies of films were

recorded with a scanning electron microscope (SEM, Hitachi S-570) after coating with gold.

Results and Discussion

Polymerizations. As seen in Figure 1, CO_2 reveals its melting point at -78 °C at 1 atm, triple point at -56.6 °C and 5.1 atm, and critical point at 31 °C and 72.8 atm.[22] Taking this information into account, the ZnGA-catalyzed terpolymerization of CO_2 with PO and CL was conducted in various reaction conditions. Among the terpolymerization trials, a reaction condition, 60 °C/27 atm CO_2/40 h, gave the highest product yield. In this condition, the terpolymerizations of CO_2, PO and CL in various compositions were conducted in an autoclave reactor. Here PO and CL were used as co-monomers as well as reaction media, so no additional organic solvent was used in the terpolymerization, resulting in no organic solvent waste. The polymer products of this terpolymerization process were further found to be highly soluble in PO and CL, confirming the appropriateness of the use of PO and CL as both co-monomers and reaction media. The

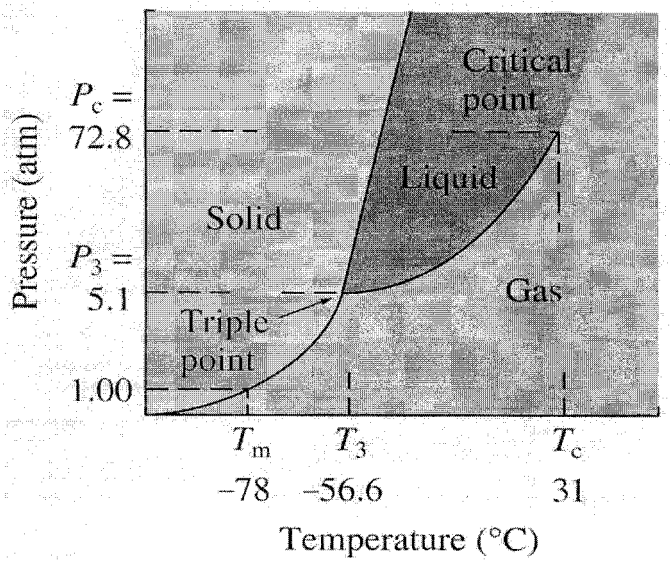


Figure 1. The phase diagram of carbon dioxide.[22]

use of an excess of PO and CL as the reaction solvent plays an important role in this terpolymerization because it ensures the efficient mixing of the reactants during the reaction. After the terpolymerization is complete, the excess amounts of PO and CL are easily recovered and reused in the next terpolymerization batch. The results of the terpolymerizations are summarized in Table 1.

As shown in Table 1, the terpolymerizations produced polymer products with reasonably highly molecular weights; their yields ranged from 20.2 to 59.8 g per gram of catalyst, depending on the molar feed ratio of PO and CL. In particular, the product yield decreased when the CL was loaded more than 50 mol-% with respect to the total mole of PO and CL. The copolymerization of CO_2 and PO also gave a polymer product with high molecular weight in a yield of 50.3 g per gram of catalyst.

In addition, homopolymerizations of the used monomers were performed. The PO monomer was found to undergo ZnGA-catalyzed homopolymerization, producing poly(propylene oxide). This indicates that ZnGA is a good catalyst to initiate the ring-opening polymerization of PO. In contrast, the CL monomer was found not to undergo ZnGA-catalyzed homopolymerization. This suggests that the catalytic activity of ZnGA is

Table 1. Results for the ZnGA-catalyzed terpolymerizations of CO_2, PO, and CL.

PO:CL [a] (molar ratio)	PO : CL (mL)	Yield [b] (g/g cat)	$\overline{Mn}$ / $\overline{Mw}$ / PDI [c]	[η] [d] (dL/g)	T_g / T_m [e] (°C)
10 / 0	100 : 0	50.3	226k / 673k / 2.97	0.992	38.6 / -
7 / 3	60 : 40	47.7	137k / 381k / 2.79	0.903	17.7 / 51.0
6 /4	49 : 51	59.8	215k / 363k / 1.69	0.921	16.6 / 52.5
5 / 5	39 : 61	47.0	243k / 369k / 1.52	0.936	17.6 / 51.1
4 / 6	30 : 60	38.7	275k / 423k / 1.54	0.988	19.2 / 50.6
3 / 7	21 : 79	33.0	180k / 271k / 1.50	0.877	5.9 / 52.1
2 / 8	14 : 86	20.2	17k / 69k / 4.08	0.674	5.4 / 57.2
0 /10	0 : 100	0	- [f]	-	-

[a] Feed molar ratio.
[b] Yield of polymer product insoluble in methanol.
[c] Measured by GPC: $\overline{Mn}$, number-average molecular weight; $\overline{Mw}$, weight-average molecular weight; PDI, polydispersity.
[d] Intrinsic viscosity was measured in THF at 25.0 °C.
[e] Measured with a heating rate of 10.0 °C/min under a nitrogen atmosphere by DSC.
[f] No product was synthesized.

not enough to open the ring of the CL monomer that is essential for the homopolymerization of CL.

Taking these results into account, the observation, that the product yield decreased when the CL was loaded more than 50 mol-% with respect to the total mole of PO and CL, is attributed to the relatively low reactivity of CL to the ZnGA catalyst, compared to PO. Further we found that ZnGA could not initiate the homopolymerization of CO_2. This result is supported by our recent near-edge X-ray absorption fine structure spectroscopy study: ZnGA was found to reversibly react with CO_2 and readily react with PO via adsorption onto the catalyst surface and to insert into the Zn-O bond.[5]

It is known that the copolymerization of CO_2 and PO is accompanied by the formation of cyclic propylene carbonate as a byproduct.[1-3,8-15] However, the characteristic chemical shifts of such cyclization byproducts were not detected in any of the nuclear magnetic resonance (NMR) spectra obtained from the terpolymerization and copolymerization products of our study. Taking all polymerization results of our study into account, we propose an anionic mechanism for the terpolymerization as follows. The nucleophilic oxygen atom of the PO monomer, which has a higher reactivity due to its high ring strain, is first drawn towards the electrophilic zinc metal center of the ZnGA catalyst and then is inserted into the zinc-carboxyl bond, activating the zinc metal center. In the next step, the two co-monomers, CO_2 and CL, competitively interact with the activated zinc metal center and are inserted into the growing chain. Then, PO, CO_2 and CL are all competitively added to the ZnGA catalyst and thus to the growing chain throughout the terpolymerization process. Conclusively, the PO monomer is found to play the most critical role in the ZnGA-catalyzed terpolymerization of CO_2 with PO and CL as well as in the ZnGA-catalyzed copolymerization of CO_2 and PO.

The chemical compositions of the terpolymer products were characterized by proton (^1H) and carbon (^{13}C) NMR spectroscopy. Figure 2 shows representative ^1H-NMR and ^{13}C-NMR spectra for the product obtained by terpolymerization with 5:5 feed mole ratio of PO/CL. : ^1H-NMR (δ, $CDCl_3$), 5.0 (1H, C<u>H</u>(a)), 4.1-4.34 (2H, C<u>H</u>$_2$(b)), 1.3 (3H, C<u>H</u>$_3$(c)), 4.0 (2H, C<u>H</u>$_2$(h)), 2.3 (2H, C<u>H</u>$_2$(d)), 1.6-1.7 (4H, C<u>H</u>$_2$(g) and C<u>H</u>$_2$(f)), 1.4 (2H, C<u>H</u>$_2$(e)). ^{13}C-NMR (δ, $CDCl_3$), 154-155 (O<u>C</u>OO(A)), 72 (<u>C</u>H$_2$(C)), 69 (<u>C</u>H(B)), 16 (<u>C</u>H$_3$(D)), 174 (O<u>C</u>O(E)), 64.5 (CH_2(J)), 34.5 (CH_2(F)), 28.7 (<u>C</u>H$_2$(I)), 25.9 (<u>C</u>H$_2$(G)), 24.9(<u>C</u>H$_2$(H)). In the ^1H NMR spectrum (Figure 2), a number of additional weak peaks (marked by asterisks) also appear, while in the ^{13}C NMR spectrum each carbon peak appears with

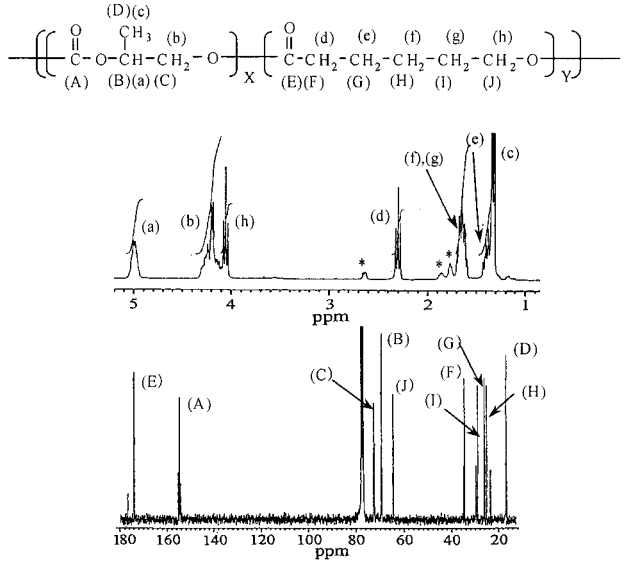


Figure 2. ^{1}H- and ^{13}C-NMR spectra of a terpolymer prepared by the terpolymerization of CO_2 with PO and CL in 5:5 feed mole ratio.

another weak peak nearby. To determine the origins of these weak peaks, a two dimensional (2D) proton-carbon correlation NMR spectral analysis was performed. As a result, the asterisk-marked proton peaks, as well as the weak carbon peaks near those of the carbons (F, G, H, I and J), were found to originate from the CL units in the polymer backbone. These NMR results collectively indicate that there exist two environmentally different CL units in the polymer backbone, namely CL units directly linked to PC units (i.e. PC-linked CL units), and blocked CL units.

In the 2D NMR analysis, one may further expect to have signals from PC units directly linked to the CL blocks in the proton and carbon NMR spectra. However, the intensities of the signals from such PC units are too small to be detectable in the ^{1}H- and ^{13}C-NMR spectra. This result suggests that the population of the PC unit directly linked to the single or CL blocks in the terpolymer is so small that signals associated with this unit cannot be detected in the NMR spectra. The 2D NMR analysis therefore concludes that in the terpolymer the PC units appear mainly in blocks whereas the CL units appear as longer blocks, short blocks and single units. The chemical compositions of all polymer products were estimated from the integrations of the assigned proton NMR peaks, including the asterisk-marked proton peaks. The results are summarized in Table 2. Taking into

consideration the chemical compositions of the terpolymers as listed in Table 2, in the ZnGA-catalyzed terpolymerization, the addition of PO seems more favorable than that of CL immediately after CO_2 insertion, while the addition of CL is more favorable than that of CO_2 or PO immediately after CL insertion. This situation is due to the different reactivities of the co-monomers and produces the formation of blocky PC and CL units in the growing polymer chain.

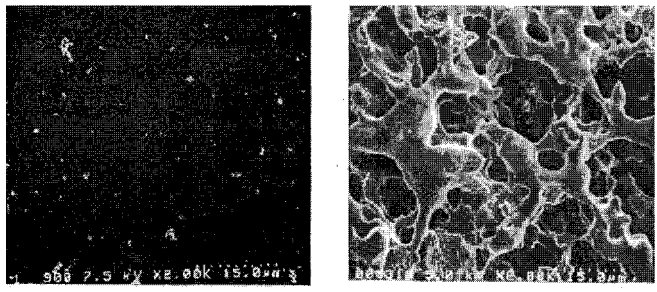
Glass transition temperatures T_g and melting points T_m of the terpolymer products were measured by DSC. As can be seen in Table 1, the PPC polymer containing no CL units reveals only a single T_g, 38.6 °C, indicating that the PPC polymer is amorphous. A PCL polymer is a crystalline polymer, thus showing -63.2 °C T_g and 57.9 °C T_m (data not shown in Table 1). Taking these results and the determined compositions into account, terpolymers are expected to reveal two T_gs (one from the PC blocks and another from the CL blocks) and a single T_m (from the CL blocks). All the terpolymers show a single T_m, which originates from the CL blocks, but only a single T_g, which originates from the PC blocks; another T_g originated from the CL blocks could not be determined due to the very weak glass transition in the DSC measurements.

Biodegradation. The terpolymers were treated with a lipase (*Pseudomonas cepacia*) in a phosphate buffer solution of pH 7.0 at 37 °C for 10 days, exhibiting a 18~67% weight loss

Table 2. Compositions of the terpolymers prepared by terpolymerizations of CO_2, PO, and CL.

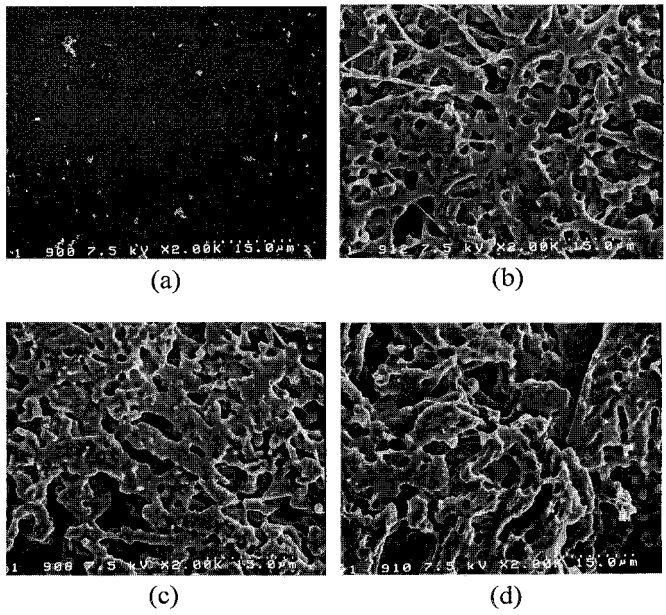
PO:CL (feed molar ratio) [a]	Composition (molar fraction in %) [b]		
	PC unit	PC-linked CL unit	blocked CL unit
7 / 3	78.6	7.7	13.7
6 / 4	61.4	5.7	32.9
5 / 5	67.4	4.6	28.0
4 / 6	68.9	12.2	18.9
3 / 7	36.8	18.4	44.8
2 / 8	17.8	17.7	64.5

[a] Feed mole ratio.
[b] Molar fractions of PPC and PCL units in the terpolymer products were determined by ^{1}H NMR spectroscopy.



(a) (b)

Figure 3. Scanning electron micrographs of the films of a terpolymer (PO/CL = 70/30, feed molar ratio) before and after enzymatic degradation with a lipase (*Pseudomonas cepacia*): (a) before degradation; (b) after enzymatic degradation (18% weight loss).



(a) (b)

(c) (d)

Figure 4. Scanning electron micrographs of films of a terpolymer (PO/CL = 50/50, feed mole ratio) before and after biodegradation with fungi: (a) before degradation, (b) after degradation with *Aspergillus fumigatus* (10% weight loss), (c) after degradation with *Aspergillus terreus* (12% weight loss), (d) after degradation with *Penicillium olonii* (13% weight loss).

depending on the composition; a larger content of the CL component in the terpolymer revealed larger weight loss in the enzymatic degradation. A representative result is shown in Figure 3. The terpolymers also exhibited a 10~15% weight loss as a result of their treatment with three fungi (*Aspergillus fumigatus*, *Aspergillus terreus* or *Penicillium olonii*) in an inorganic buffer solution at 25 °C for 30 days. Figure 4 shows scanning electron microscopic images taken before and after fungi treatments of the terpolymer specimens; surface erosions are clearly observed in the figure. These enzymatic and biological degradabilities are comparable to those of the PCL homopolymer. In conclusion, the terpolymers exhibited excellent enzymatic and biological degradability, suggesting their merit as candidate materials for biomedical applications. In addition we examined the enzymatic and fungal degradations of the copolymer, poly(propylene carbonate). The copolymer films exhibited a 9.5% weight loss in the enzymatic degradation and showed positive signs in the biological degradations.

Conclusion

In the present study, we first successfully carried out the ZnGA-catalyzed terpolymerization of CO_2 with PO and CL, producing aliphatic carbonate-ester terpolymers with reasonably high molecular weights in high yield. For this ZnGA-catalyzed terpolymerization, a reaction mechanism was proposed. The chemical structures and compositions of the obtained terpolymers were determined by ^{1}H- and ^{13}C NMR spectroscopy and their 2D correlation analysis. The terpolymers were found to exhibit excellent enzymatic and fungal degradation properties. The copolymer of CO_2 and PO was also found to reveal enzymatic and fungal degradation properties. In addition, the thermal properties were investigated. Conclusively these polymers are candidate materials for biomedical applications.

Acknowledgements

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