Microwave-Improved Polymerization of ϵ-Caprolactone Initiated by Carboxylic Acids

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ABSTRACT: The ring-opening polymerization of ε-caprolactone (ε-CL), initiated by carboxylic acids such as benzoic acid and chlorinated acetic acids under microwave irradiation, was investigated; with this method, no metal catalyst was necessary. The product was characterized as poly(ε-caprolactone) (PCL) by ^{1}H NMR spectroscopy, Fourier transform infrared spectroscopy, ultraviolet spectroscopy, and gel permeation chromatography. The polymerization was significantly improved under microwave irradiation. The weight-average molecular weight (M_w) of PCL reached 44,800 g/mol, with a polydispersity index [weight-average molecular weight/number-average molecular weight ($M_\mathrm{w}/M_\mathrm{n}$)] of 1.6, when a mixture of ε-CL and benzoic acid (25/1 molar ratio) was irradiated at 680 W for 240 min, whereas PCL with $M_\mathrm{w} = 12,100$ and $M_\mathrm{w}/M_\mathrm{n} = 4.2$ was obtained from the same mixture by a conventional heating method at 210 °C for 240 min. A degradation of the resultant PCL was observed during microwave polymerization with chlorinated acetic acids as initiators, and this induced a decrease in M_w of PCL. However, the degradation was hindered by benzoic acid at low concentrations. © 2002 Wiley Periodicals, Inc. J Polym Sci Part A: Polym Chem 41: 13–21, 2003

Keywords: microwave; ring-opening polymerization; polyesters; poly(ε-caprolactone); biodegradable; benzoic acid

INTRODUCTION

Poly(ε-caprolactone) (PCL) is well known for its biocompatibility, biodegradability, and drug permeability and has been used as a biomedical material and as a commodity packing plastic.[1–3] PCL can be readily synthesized from ε-caprolactone (ε-CL) by cationic,[4,5] anionic,[6,7] coordination,[8–10] and free-radical polymerization.[11] Among these catalyzed ring-opening polymerizations (ROPs) of ε-CL, metal catalysts, including compounds containing aluminum,[8] tin,[8,9] or rare-earth metals,[10] were intensively investigated and proven effec-

tive. However, the complete removal of the catalyst residue from the polymerization product is difficult, and the residue may be harmful to human bodies. It is highly preferable to avoid metal catalysts in the synthesis of PCL for biomedical and pharmaceutical applications, although it is commercially prepared by stannous octanoate-catalyzed polymerization. Bixler et al.[12] reported that ROP of ε-CL could be induced by carboxylic acid but the weight-average molecular weight (M_w) of PCL was lower than 5500 g/mol. Zhang et al.[13] synthesized PCL with two terminated carboxylic groups by the polymerization of ε-CL in the presence of succinic acid, and its number-average molecular weight (M_n) was below 3000 g/mol.

More recently, there has been growing interest in the microwave synthesis of macromole-

cules.[14–19] For monomers containing polar groups that favor the absorption of microwaves,[20] microwave polymerization has been proven to be more rapid and efficient than conventional polymerization. We synthesized some biodegradable polyesters such as poly(L-2-hydroxy-3-phenylpropanoic acid),[17] poly(lactic acid),[18] and PCL[19] by microwave-assisted polymerization in a previous study. It was revealed that ROP of ε-CL was carried out smoothly under microwave irradiation at a constant power with a frequency of 2.45 GHz, with stannous octanoate and zinc powder as catalysts.[19] Compared with the conventional heating method, the microwave polymerization of ε-CL was greatly accelerated and enhanced.

In this article, the results are presented for the microwave-assisted polymerization of ε-CL initiated by carboxylic acids such as chloroacetic acid, dichloroacetic acid, trichloroacetic acid, and benzoic acid.

EXPERIMENTAL

Materials

Commercial ε-CL (99%; Aldrich) was used without further purification. Chloroacetic acid, dichloroacetic acid, and trichloroacetic acid (analytical-reagent-grade) were purified by vacuum distillation, and benzoic acid (analytical-reagent-grade) was purified by recrystallization just before use.

Measurements

^{1}H NMR spectra of the polymers were recorded on a Mercury VX-300 (300-MHz) apparatus with tetramethylsilane as an internal standard and with $CDCl_3$ as a solvent. Fourier transform infrared (FTIR) spectra were recorded on a 2000 FTIR apparatus with KBr discs. Ultraviolet (UV) spectroscopy analysis was carried out on a Lambda Bio40 ultraviolet–visible spectrometer with CH_2Cl_2 as a solvent. Gel permeation chromatography measurements were performed at 35°C with $CHCl_3$ as the eluent (1.0 mL min^{-1}) with a Waters high-performance liquid chromatography system equipped with a model 2690D separation module, a model 2410 refractive-index detector, and Shodex K803 columns in series. Calibration was effected with polystyrene standards in a narrow molecular weight distribution.

Microwave-Assisted Polymerization of ε-CL

The microwave-assisted polymerization was carried out in a 2.45-GHz microwave oven. A representative experimental procedure was as follows. A mixture of ε-CL with a certain amount of an initiator in a vacuum-sealed ampule (50 Pa) was irradiated at a certain microwave power for a predetermined period of time. After the ampule was quenched in an ice–water bath, the crude product was dissolved in tetrahydrofuran and precipitated by cold petroleum ether. The precipitate was filtrated and dried *in vacuo* at ambient temperature.

Polymerization of ε-CL by the Conventional Heating Method

The thermal polymerization was carried out with an oil bath at 210 °C for 240 min. The selected initiator was benzoic acid, and the monomer/initiator (M/I) molar ratio was 25. The procedure was the same as that of the microwave method.

Degradation of PCL under Microwave Irradiation

The degradation of PCL was carried out with a microwave power of 680 W. PCL, mixed with dichloroacetic acid or trichloroacetic acid at a molar ratio of 0.05 (PCL/acid) in a sealed ampule (50 Pa), was irradiated for 30 min. A control test was performed under the same conditions, but no acid was added.

RESULTS AND DISCUSSION

Characterization

Pulverous products were obtained when ε-CL was irradiated by microwaves in the presence of chloroacetic acid, dichloroacetic acid, or benzoic acid. The M_w values of the products ranged from 2400 to 12,600 g/mol with a polydispersity index (M_w/M_n) of 1.3–2.8 by chloroacetic acid, from 3700 to 11,800 with M_w/M_n = 1.2–3.3 by dichloroacetic acid, and from 2200 to 44,800 with M_w/M_n = 1.2–2.6 by benzoic acid. However, the product by trichloroacetic acid was semisolid, with M_w = 1000–2000 and M_w/M_n = 2.0–3.8. The results indicated that the polymerization of ε-CL was initiated by any of the four carboxylic acids under microwave irradiation.

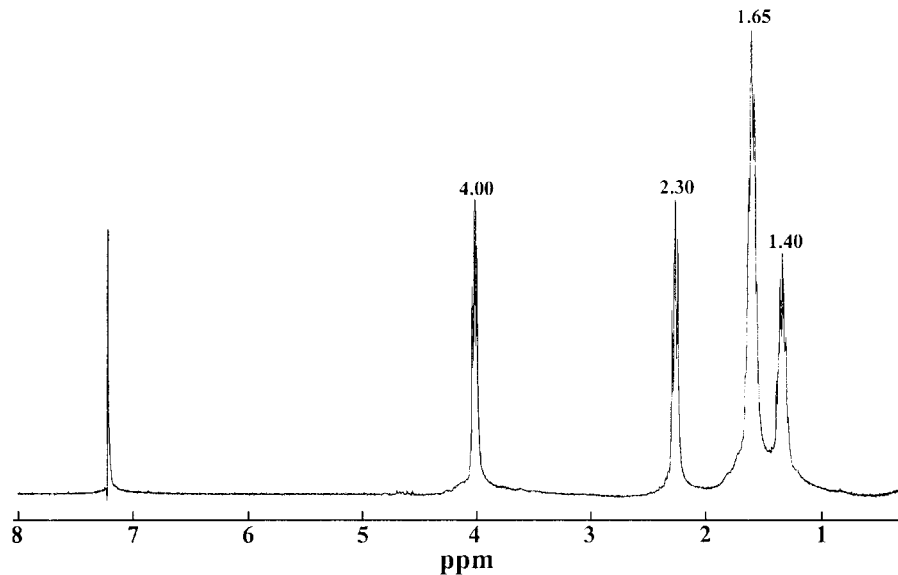The ^{1}H NMR and FTIR spectra of the product (Figs. 1 and 2) were similar to those of an author-

Figure 1. Typical ^{1}H NMR spectra of PCL by chloroacetic acid (M_w = 12,600).

itative sample of PCL,[21] but no proton signal of the terminal carboxylic acid group was observed in the ^{1}H NMR spectrum in this work, although it was recorded from PCL with M_n = 2200.[13]

With benzoic acid as an initiator, PCL must contain a terminated benzoate group at the end of its backbone chain. To identify the end group, we measured and compared the UV spectrum of the resultant PCL with that from a sample of PCL

initiated by a diol (PCL diol). As shown in Figure 3, only one absorption band at 233 nm was recorded in the UV spectrum of the PCL diol, which was attributed to the absorption of ester bonds in the PCL main chain. However, there were two absorption bands (242 and 274 nm) in the UV spectrum of PCL by benzoic acid. The terminated benzoate group was characterized by the middle strong band at 274 nm,[22] although no signals of
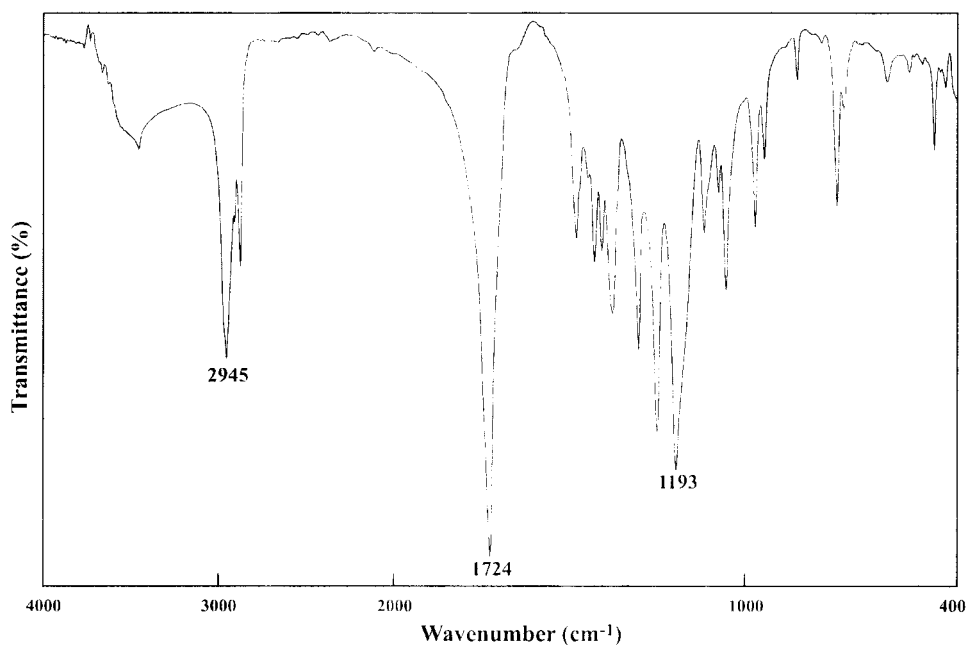

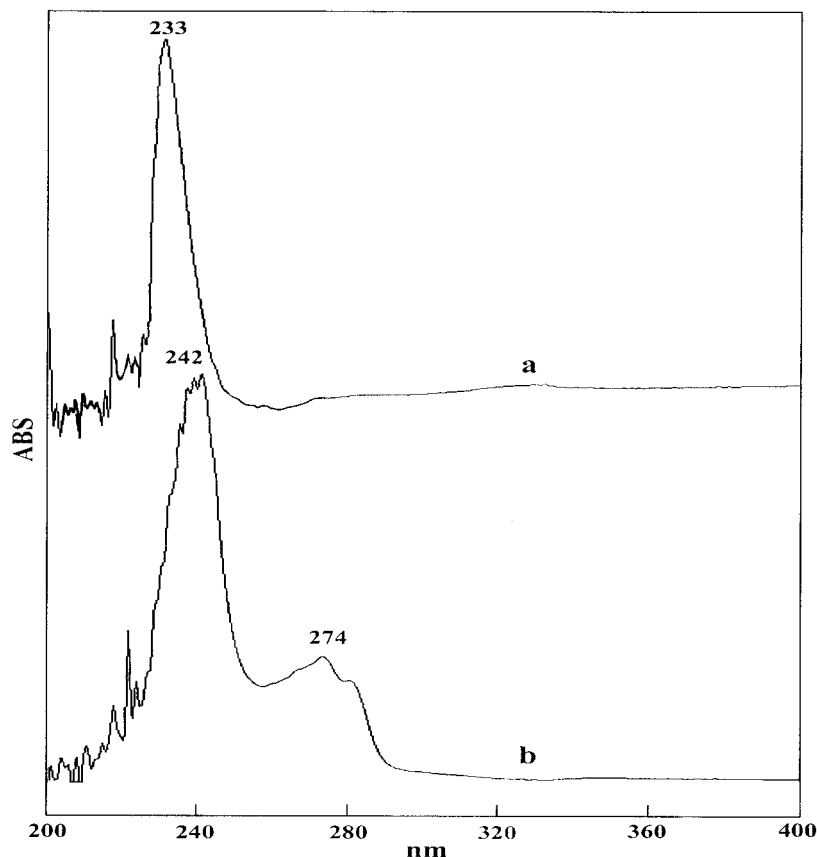**Figure 2.** Typical FTIR spectra of PCL by chloroacetic acid (M_w = 12,600).

Figure 3. UV spectra of (a) PCL diol (M_w = 7700) and (b) PCL by benzoic acid (M_w = 8500).

the benzoate group were detected by ^{1}H NMR and FTIR. The strong band at 242 nm was due to the absorption of ester bonds in PCL overlapping with the K absorption band caused by a conjugation of phenyl and carbonyl groups. The results indicated that benzoic acid was incorporated into PCL.

Polymerization of ε-CL by Chlorinated Acetic Acids

The influences of reaction conditions, including the M/I molar ratio, the level of microwave power, and the time of microwave irradiation, on the ROP of ε-CL initiated by chloroacetic acids were investigated. In our study, M/I was 5, 15, or 25, the microwave power was 340, 510, or 680 W, and the irradiation time was 5–240 min.

For the three M/I ratios, M_w of PCL first increased to a maximum and then decreased when the ROP was carried out at 680 W for 240 min [Fig. 4(a)]. The greatest M_w values were 7200

g/mol for M/I = 5, 10,500 for M/I = 15, and 12,600 for M/I = 25, whereas the times to obtain them were 20, 60, and 150 min, respectively. It seems that the larger the M/I ratio was, the greater the M_w maximum was and the longer the time was to reach it.

To understand the change in M_w, we plotted the monomer conversion against the irradiation time. As shown in Figure 4(b), the monomer conversion at 20 min was 98.3% for M/I = 5, at which a maximum of M_w was measured. However, at the same time, the monomer conversion was 34.9% for M/I = 15 and 26.1% for M/I = 25. The order of monomer conversion (M/I = 5 > M/I = 15 > M/I = 25) was the same as that in M_w. Also, at 60 min, the monomer conversion for M/I = 15 was 98.0%, which was greater than that of M/I = 25 (84%). Correspondingly, the maximum of M_w for M/I = 15 was found at this moment. However, the maximum of M_w for M/I = 25 was determined at 150 min with a monomer conversion of 98.1%.
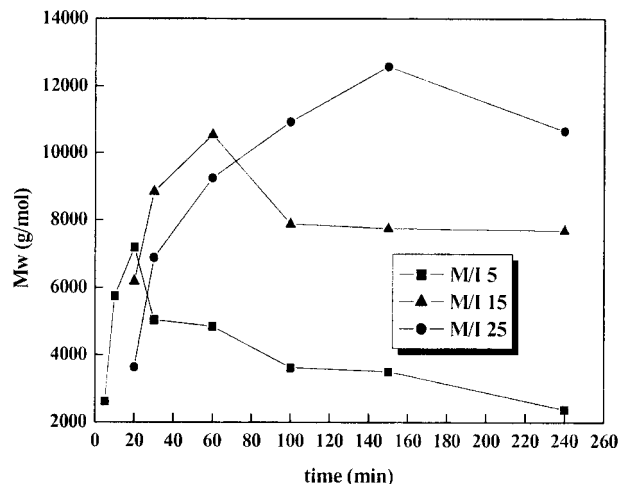
(a)
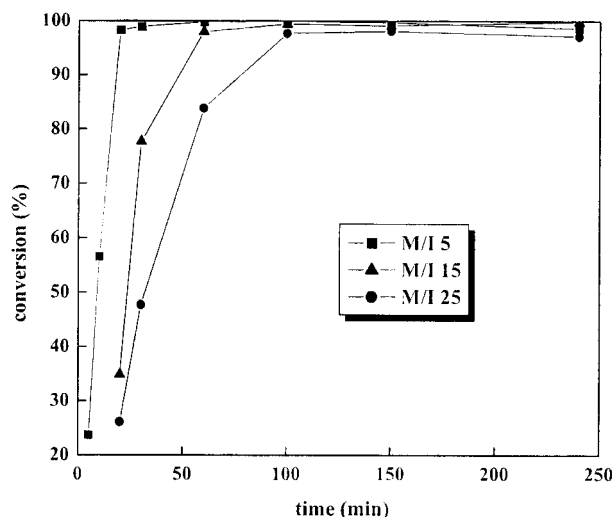
(b)

Figure 4. Results of ROP by chloroacetic acid (680 W): (a) M_w–time curve and (b) monomer conversion/time curve.

The decrease in M_w of PCL [Fig. 4(a)] was thought to be induced by an acid/ester interchange reaction (transesterification) because the acid was partially consumed as an initiator.[12,13] Therefore, it was deduced that within 240 min, there were at least two chemical reactions, the ROP of ε-CL and the transesterification of PCL that formed. The dominative reaction was ROP in
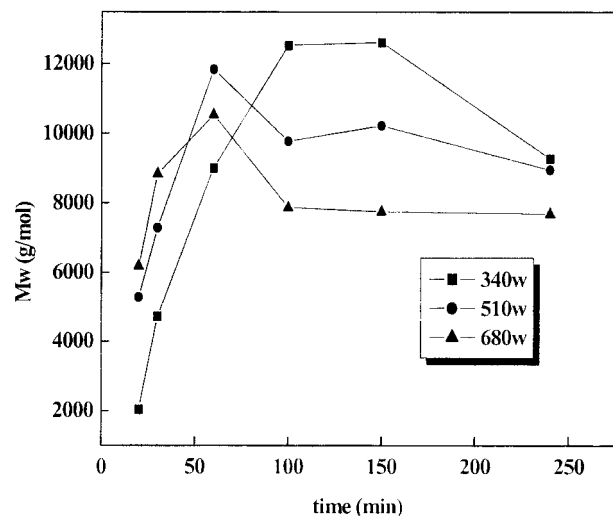
the presence of the monomer, but transesterification occurred significantly after the monomer was mostly consumed.

The microwave power also had great influence on the ROP. For the three microwave power levels (340, 510, and 680 W), M_w–time curves were parabola-like, that is, increasing first and then decreasing [Fig. 5(a)]. The greatest M_w values were 12,600 g/mol at 150 min for 340 W and 11,800 and 10,500 g/mol at 60 min for 510 and 680 W, respectively. Before 30 min, the order of M_w was 340 W $<$ 510 W $<$ 680 W, but after 100 min, the order was reversed (340 W $>$ 510 W $>$ 680 W). It seems that with a stronger microwave power, the ROP took place faster, but the maximum of M_w was smaller and the degradation occurred earlier.
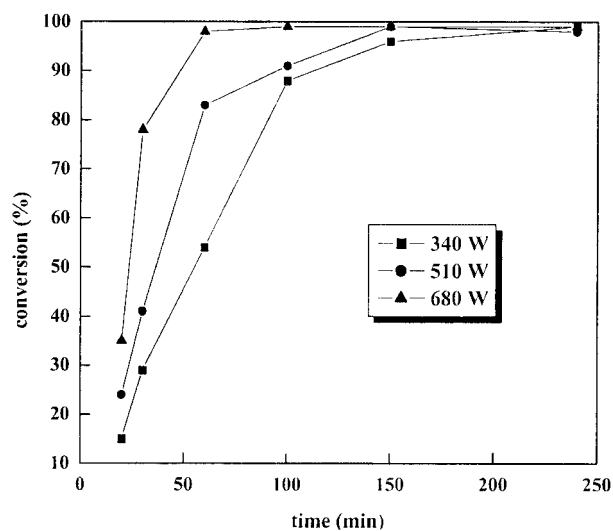
The relationships between M_w and monomer conversion [Fig. 5(b)] with various microwave powers were somewhat different. Under the condition of 510 W, the greatest M_w (11,800 g/mol) appeared at 60 min, but the monomer conversion was only 83%. However, for 340 and 680 W, the greatest M_w was obtained when the monomer conversion was greater than 95% [Fig. 5(a,b)]. The results indicated that the competition between the ROP and degradation was influenced by the microwave power. With 680 W of power, the ROP went much faster than the degradation, which took place 60 min after the ROP ended. When the microwave power was 510 W, the ROP went slower than it did at 680 W, but the degradation did not, also taking place at 60 min but before the ROP was finished. The ROP and degradation were both low-speed at 340 W, and the degradation still followed the ROP.

The ROP initiated by dichloroacetic acid and trichloroacetic acid was also investigated with a microwave power at 680 W, which was chosen because the ROP went much faster than at 340 and 510 W and PCL degraded at that power level.

By dichloroacetic acid, the M_w–time curves of ROP with M/I = 5, 15, and 25 were still parabola-like [Fig. 6(a)], but the time to reach the greatest M_w (10 min for M/I = 5, 20 min for M/I = 15, and 60 min for M/I = 25) was shorter than that by chloroacetic acid [20, 60, and 150 min, respectively; see Fig. 4(a)]. The conversion of ε-CL was 96.4% for M/I = 5 at 10 min, 95.0% for M/I = 15 at 20 min, and 98.8% for M/I = 25 at 60 min [Fig. 6(b)], but the times for monomer conversions over 95% by chloroacetic acid were 20, 60, and 150 min, respectively. Meanwhile, the following order of M_w—M/I = 5 (3700 g/mol) $<$ M/I = 15 (9700 g/mol) $<$ M/I = 25 (10,600 g/mol)—appeared at 30
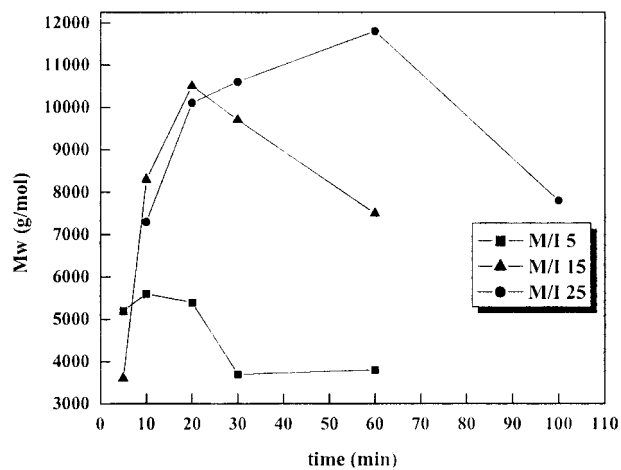
(a)

on both the ROP and degradation was stronger than that of chloroacetic acid, but the degradation still followed the ROP with dichloroacetic acid as an initiator.

The M_w of the resultant product by trichloroacetic acid was lower than 2000 g/mol at M/I

(a)

(b)

Figure 5. Results of ROP by chloroacetic acid (M/I = 15): (a) M_w–time curve and (b) monomer conversion/time curve.

(b)

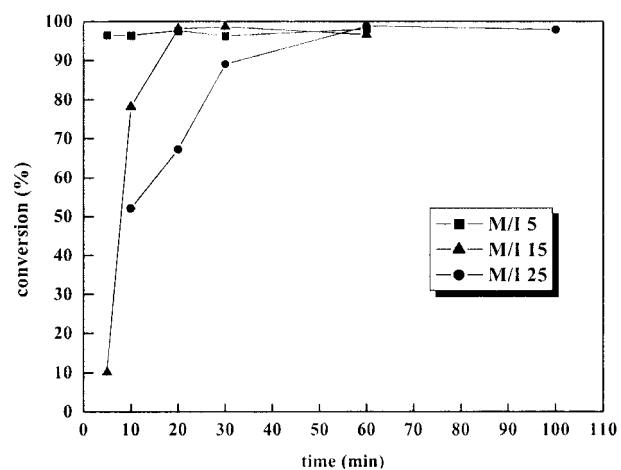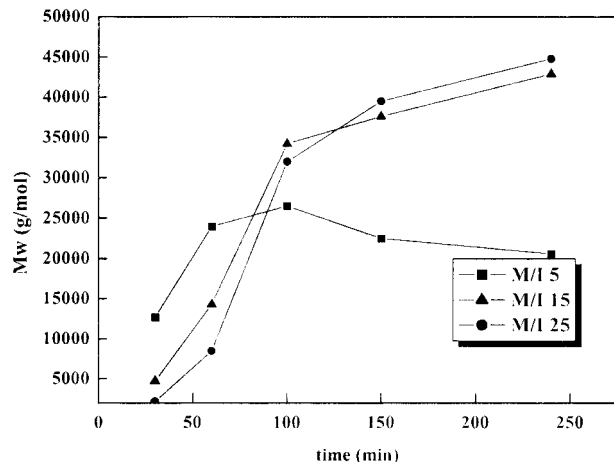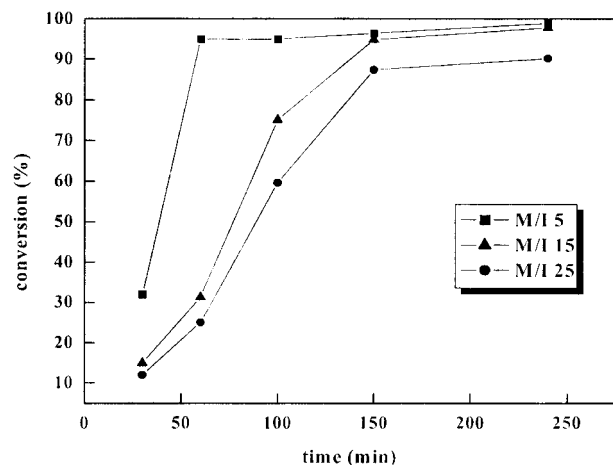**Figure 6.** Results of ROP by dichloroacetic acid (680 W): (a) M_w–time curve and (b) monomer conversion/time curve.

min, and the time to have the same order by chloroacetic acid was 100 min [Fig. 4(a)]. It was deduced that the influence of dichloroacetic acid

(a)

(b)

Figure 7. Results of ROP by benzoic acid (680 W): (a) M_w–time curve and (b) monomer conversion/time curve.

ratios of 5–25 and power levels of 85–850 W, possibly because of its strong acidity.

However, no polymeric product was obtained when ε-CL alone was irradiated under microwaves, by which the initiation effect of organic acid on the ROP of ε-CL was supported.
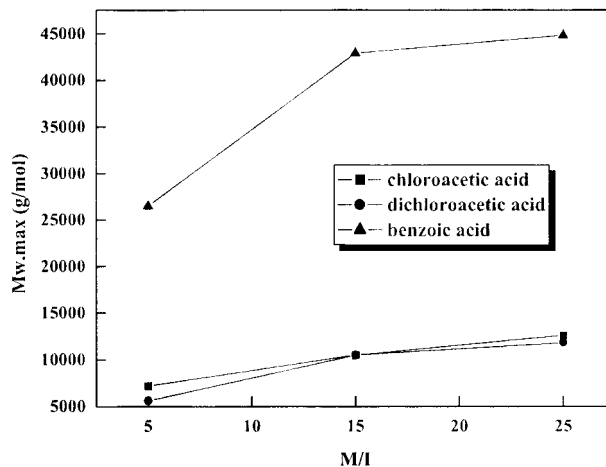

Figure 8. $M_{w\ max}$–M/I curve of ROP of ε-CL at 680 W.

Polymerization of ε-CL by Benzoic Acid

As previously shown, the greatest M_w by chloroacetic acid for M/I = 25 at 680 W was 12,600 g/mol, which was greater than those by dichloroacetic acid (11,800 g/mol) and trichloroacetic acid (<2000 g/mol). However, the decrease of M_w corresponded to the strengthened acidity of the initiators (pK_a: chloroacetic acid, 2.86; dichloroacetic acid, 1.30; and trichloroacetic acid, 0.64[23]). The effect of the initiator's acidity was different from the results in the literature, which indicted that the acidity of the initiator had no impact on the thermal polymerization of ε-CL by carboxylic acids with pK_a = 4.37–4.83.[12] It was expected that M_w might be improved with a weaker acid as an initiator, although a longer irradiation time was necessary.
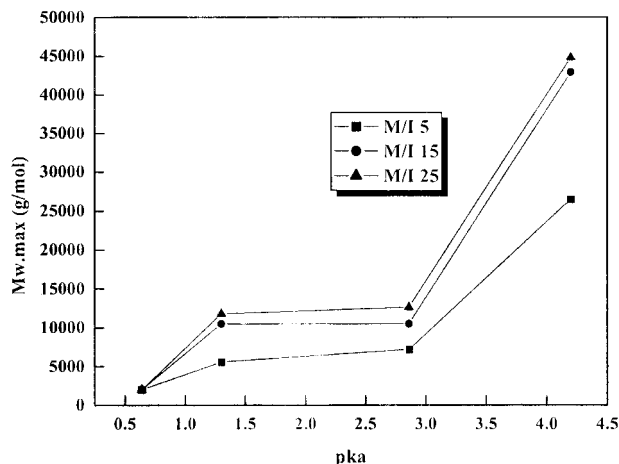

Figure 9. $M_{w\ max}$–pK_a curve of ROP of ε-CL at 680 W (trichloroacetic acid, 0.64; dichloroacetic acid, 1.30; chloroacetic acid, 2.86; and benzoic acid, 4.21).

Table 1. Degradation of PCL under Microwave Irradiation

Sample	Polymer/Acid (Molar Ratio)	Power (W)	Time (min)	M_w	M_w/M_n	Decreasing in M_w (%)
PCL-b				44,800	1.6	0
PCL-b-0		680	30	36,700	1.6	18.1
PCL-b-d	0.05	680	30	29,000	1.8	35.3
PCL-b-t	0.05	680	30	19,700	1.9	56.0

The ROP of ε-CL with benzoic acid ($pK_a = 4.21^{23}$) as an initiator was, therefore, investigated. The microwave power was 680 W, and the M/I ratios were 5, 15, and 25. The results showed that after a mixture of ε-CL and benzoic acid was irradiated for 100 min, PCL with $M_w > 25,000$ g/mol was obtained for every M/I [Fig. 7(a)]. By the conventional method at 210 °C for 240 min, M_w of PCL was only 12,000 g/mol. The M_w–time curves for M/I = 15 and 25 were no longer parabola-like as those by chloroacetic and dichloroacetic acids, and M_w of PCL kept increasing during 240 min. Obviously, its degradation did not take place under the conditions. The M_w–time curve for M/I = 5 showed that the degradation occurred at this M/I ratio after 100 min. Correspondingly, the monomer conversion for M/I = 5 reached 95% at 60 min [Fig. 7(b)]. The results showed that the degradation of PCL by benzoic acid started not only after the ROP but also later than that by chloroacetic acid (20 min). The monomer conversions at 60 min for M/I = 15 and 25 were only 31 and 25%. At 100 min, they were 75 and 60%, which increased to 97.8 and 90.2% at 240 min. It was noted that ε-CL was not consumed completely for M/I = 25 at 240 min.

Furthermore, the M_w values of PCL reached 42,900 and 44,800 g/mol for M/I = 15 and 25 at 240 min, but the greatest value of M_w by chloroacetic acid was only 12,600 g/mol (Fig. 8).

It is concluded that benzoic acid is a more efficient initiator than any of the three chlorinated acetic acids and that the ROP by benzoic acid can be enhanced and improved by the microwave method.

Degradation of PCL under Microwave Irradiation

As mentioned previously, the ROP of ε-CL and the degradation of the PCL formed were both influenced by the concentration and acidity of the initiator (Figs. 4, 6, and 7). However, the greatest M_w of PCL ($M_{w\ max}$) was directly controlled by the concentration and acidity of the initiator as well (Fig. 9).

In general, an increase in $M_{w\ max}$ was hindered by stronger acidity, and the optimum pK_a value was 4.21. Therefore, the degradation behavior of PCL under microwave irradiation was investigated. PCL ($M_w = 44,800$ g/mol), prepared by benzoic acid, was used as a starting sample and was named PCL-b (see Table 1). When PCL was irradiated by microwaves without any acid, the sample was called PCL-b-0. Dichloroacetic and trichloroacetic acid-catalyzed degradation tests were presented as PCL-b-d and PCL-b-t, respectively. The PCL/acid molar ratio was 0.05. PCL-b itself degraded under microwave irradiation (680 W) for 30 min, and M_w decreased from 44,800 to 36,700 g/mol (Table 1). In the presence of dichloroacetic acid and trichloroacetic acid, M_w decreased to 29,000 and 19,700 g/mol, respectively. Obviously, the stronger the acidity was of the reaction system, the lower M_w was. However, M_w/M_n changed little.

CONCLUSIONS

The ROP of ε-CL can be initiated effectively by carboxylic acid under microwave irradiation, and PCL with $M_w > 40,000$ g/mol can be prepared without any metal catalyst. The initiator is incorporated into the polymer chain. The M_w value of the resultant PCL and the monomer conversion are affected by the M/I ratio, irradiation time, microwave power, and initiator acidity.

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