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Synthesis of Polymers Containing Herbicides and Their Release Behavior

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Abstract : In order to prepare the controlled-release type herbicides of 2,4-dichlorophenoxyacetic acid (2,4-D) and its analogues, 2,4,5-trichlorophenoxyacetic acid, 2-methyl-4-chlorophenoxyacetic acid, and 2-(2,4-dichlorophenoxy) propionic acid, the herbicidal monomers were synthesized by reacting chloromethylstyrene with the sodium salts of 2,4-D and its analogues in chlorobenzene in the presence of triethylamine at 90 ℃. The herbicidal polymers were prepared by radically copolymerizing acrylamide as hydrophilic monomer with the herbicidal monomers in dimethylformamide at 70 ℃. Then, the amounts of the herbicides released through the hydrolysis of the copolymers were measured. As a result, the release rates of the herbicides from the copolymers with about 10 mol% of the herbicidal monomers were controlled more effectively with respect to the herbicides than those of the herbicides from the copolymers with about 5 mol% of the herbicidal monomers. This result could be explained in terms of the contents and the hydrophobicity of the herbicidal monomers in the copolymers.

Introduction

One of the effective and economical methods of delivery, which is especially important for herbicides with high activity, is to synthesize herbicidal polymers which can release the herbicides through hydrolysis.[1] Recently, such studies have been reported. For examples, the herbicidal polymers of metribuzin were synthesized by the copolymerization of metribuzin-containing momomer with acrylamide as hydrophilic monomer[1] and by the reaction of metribuzin with biodegradable polymers such as starch, cellulose and poly(vinyl alcohol).[2,3] Also, the herbicidal polymer of 2,4-dichlorophenoxyacetic acid (2,4-D) was prepared by the reaction of 2,4-D with poly[oligo(oxyethylene methacrylate)].[4] The fungicidal polymer of 8-hydroxyquinoline, which was not a herbicide but a fungicide, was prepared by the copolymerization of 8-hydroxyquinoline-containing monomer with acrylamide.[5] The release rates of the low molecular compounds from the polymers through the hydrolysis were affected by the type of hydrolyzing bonds and the backbone of polymers.[1-5]

Due to the complexity of reactions on polymers, it is difficult to regulate herbicidal compositions in the polymers during the polymeric reactions to synthesize herbicidal polymers.[1] On the other hand, it is easy to control herbicidal compositions of herbicidal polymers when they are prepared by the copolymerization of herbicidal monomers with hydrophilic monomers. Accordingly, we synthesized the herbicidal polymer for 2,4-D, which has not only the high herbicidal activity but also the very high toxic side effect, by the copolymerization of 2,4-D-containing monomer with acrylamide and reported the result in the communication.[6]

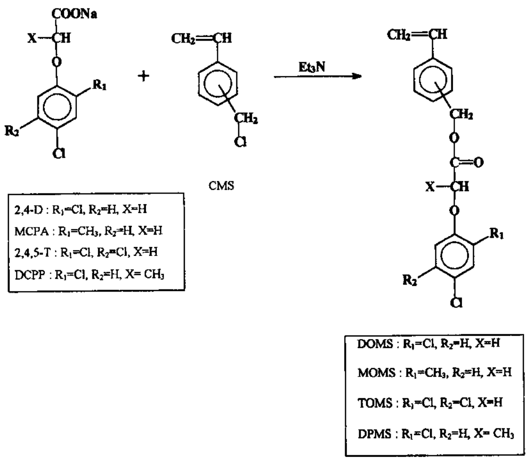
In this study, to make controlled-release type herbicides of 2,4-D and its analogues, their herbicidal monomers were synthesized and then were radically copolymerized with acrylamide. Also, the release rates of the herbicides from the copolymers through hydrolysis were investigated and the result was discussed in terms of the composition and the hydrophobicity of the herbicidal monomers in the copolymers.

Experimental

Materials. Chloromethylstyrene (CMS) which has 3 and 4 isomers of the benzene, 2,4-D, 2,4,5-trichlorophenoxyacetic acid (2,4,5-T), 2-methyl-4-chlorophenoxyacetic acid (MCPA), and 2-(2,4-dichlorophenoxy) propionic acid (DCPP) from Aldrich Chemical Co. were used as received. Acrylamide (AM) as a reagent grade was recrystallized twice from benzene. Azobisisobutyronitrile (AIBN) as a reagent grade was also recrystallized from methanol. Dimethylformamide as a reagent grade was distilled. All other reagents including triethylamine and chlorobenzene were used without further purification. Cellulose tubing membrane (Spectrum Medical Co., molecular weight cut-off 1,000) was used for the release experiments.

Synthesis of Herbicidal Monomers. Synthesis of the herbicidal monomers (DOMS, MOMS, TOMS, and DPMS) from the sodium salts of the herbicides (2,4-D, MCPA, 2,4,5-T, and DCPP) and chloromethylstyrene (CMS) is shown in Scheme I. It is similar to the synthetic route of benzyl benzoate.[7]

2,4-Dichlorophenoxyacetyloxy methylstyrene (DOMS)[5]. The sodium salt of 2,4-D (5 g, 0.021 mol), and triethylamine (2.9 mL, 0.021 mol) were added to CMS (2.9 mL, 0.021 mol) in chlorobenzene (3 mL). A trace amount of *p*-benzoquinone was also added to inhibit the polymerization of DOMS and CMS. After the reaction mixture was stirred for 10 h at 90℃, the solution was filtered to remove the precipitated sodium chloride salt of triethylamine. The solvent and the unreacted CMS were evaporated. The product was washed with water and dried under vacuum at room temperature. The yield was 84% (6.9 g) and the melting point was 27-28℃.



Scheme I. Synthesis of herbicidal monomers.

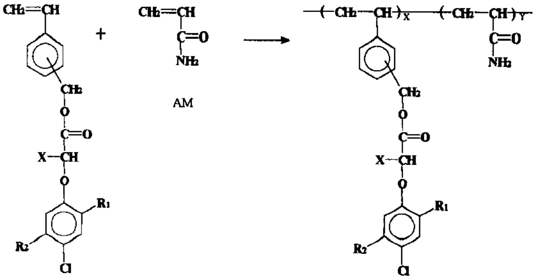
2-Methyl-4-chlorophenoxyacetyloxy methylstyrene (MOMS). MOMS was synthesized using the sodium salt of MCPA (5 g, 0.023 mol), CMS (3.2 mL, 0.023 mol), triethylamine (3.2 mL, 0.023 mol), and chlorobenzene (3 mL) under the same condition as the synthesis of DOMS. The yield was 71% (5.2 g) and the melting point was 19-20℃.

2,4,5-Trichlorophenoxyacetyloxy methylstyrene (TOMS). TOMS was synthesized using the sodium salt of 2,4,5-T (5 g, 0.018 mol), CMS (2.5 mL, 0.018 mol), triethylamine (2.5 mL, 0.018 mol) and chlorobenzene (3 mL) by the same way as the synthesis of DOMS. The yield was 61% (4.1 g) and the melting point was 47-48℃.

2-(2,4-Dichlorophenoxy) propionyloxy methylstyrene (DPMS). DPMS was synthesized using the sodium salt of DCPP (5 g, 0.019 mol), CMS (2.6 mL, 0.019 mol), triethylamine (2.6 mL, 0.019 mol), and chlorobenzene (3 mL) by the same way as described above. The yield was 73% (5.0 g) and the melting point was 34-35℃.

Copolymerizations of Herbicidal Monomers with AM. Synthesis of the hydrophilic polymers bearing the herbicidal moieties by the radical copolymerizations of the herbicidal monomers with AM is shown in Scheme II.

To synthesize poly(DOMS-*co*-AM)s with two different molar ratios of DOMS to AM according to Scheme II, the copolymerization of DOMS with AM was conducted for 48 h at 70℃ in 20 mL of dimethylformamide using AIBN as the initiator. The concentration of initiator was 0.1 mol% based on total amount of comonomers in the mixture. The reaction mixture was poured in a large excess of ethyl ether. The precipitated



poly(DOMS-*co*-AM): R_1=Cl, R_2=H, X=H
poly(MOMS-*co*-AM): R_1=CH_3, R_2=H, X=H
poly(TOMS-*co*-AM): R_1=Cl, R_2=Cl, X=H
poly(DPMS-*co*-AM): R_1=Cl, R_2=H, X=CH_3

Scheme II. Synthesis of hydrophilic polymers containing herbicidal moieties.

copolymer was filtered and dried under reduced pressure at 50 ℃. Poly(MOMS-*co*-AM)s, poly(TOMS-*co*-AM)s, and poly(DPMS-*co*-AM)s with two different molar ratios of herbicidal monomers to AM were also synthesized by the same way as described in the synthesis of poly(DOMS-*co*-AM).

Measurements. IR spectra of the herbicidal monomers and the copolymers were recorded on a Nicolet Magna-IR 550 spectrophotometer. ^{1}H-NMR spectra of the herbicidal monomers were measured in $CDCl_3$ with a Varian T-60A NMR spectrometer. Molar absorptivities (ε) of the herbicides in the buffer solutions of pH 7 and pH 9 were measured with a Shimadzu UV spectrophotometer. The buffer solutions were prepared from potassium hydrogen phosphate and potassium dihydrogen phosphate. Molar absorptivities of the herbicidal monomers in dimethyl sulfoxide were measured with the same spectrophotometer. Intrinsic viscosities of the copolymers were measured in trifluoroacetic acid at 30 ℃ with an Ubbelohde viscometer. Swelling degrees of the copolymers were measured as the percent of weight of absorbed water per weight of the dry copolymer after soaking the copolymers in the buffer solutions of pH 7 and pH 9 at 30 ℃ for 24 h.

Release Experiments. The copolymers were ground and sieved (100 mesh, U.S. standard testing sieve). About 10 mg of each copolymer sample was weighed and placed in 5 cm cellulose dialysis membrane. After addition of 3 mL of the buffer solution, the membrane was placed in a tube with 30 mL of the solution and the tube was shaken at constant speed at 30 ℃. Periodically, 1 mL of the solution was withdrawn and analyzed by UV spectrometry to determine the amount of the herbicide released from the copolymer sample.

Results and Discussion

Synthesis of Herbicidal Monomers. Since the herbicidal monomers (DOMS, MOMS, TOMS, and DPMS) were precipitated by pouring the reaction mixtures in excess of water, they could be separated from the unreacted reagents, the solvent and the sodium chloride salt of triethylamine. However, the monomers were not recrystallized probably due to their high molecular weight and low melting point. The yields of the herbicidal monomers were in the range of 61% to 84%.

Typical IR spectrum of DOMS among the herbicidal monomers is given in Figure 1. DOMS exhibited the peaks of carbonyl group of the ester bond at 1757 cm^{-1} and the vinyl group of styrene at 1583 cm^{-1}. Even though IR spectra of the other herbicidal monomers are not shown here, MOMS had the peaks of the carbonyl group at 1751 cm^{-1} and the vinyl group at 1583 cm^{-1}, and TOMS showed the carbonyl group at

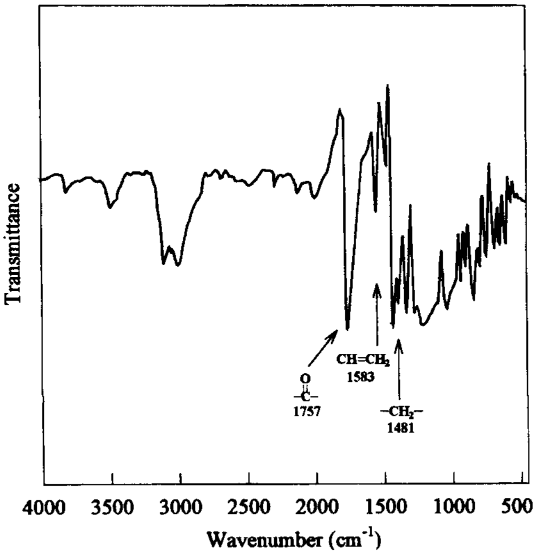


Figure 1. IR spectrum of DOMS.

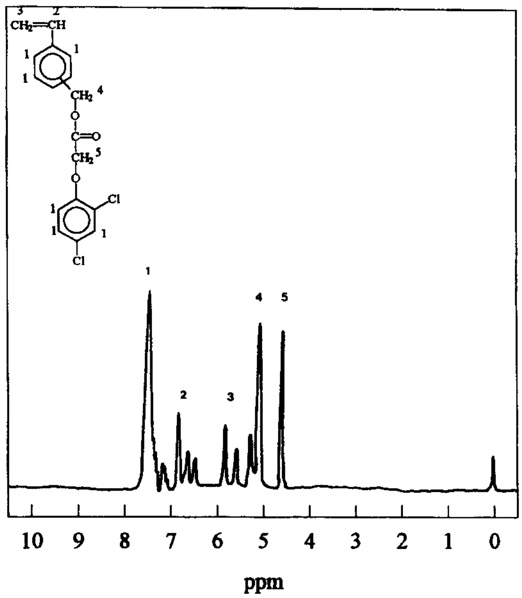


Figure 2. ^{1}H-NMR spectrum of DOMS.

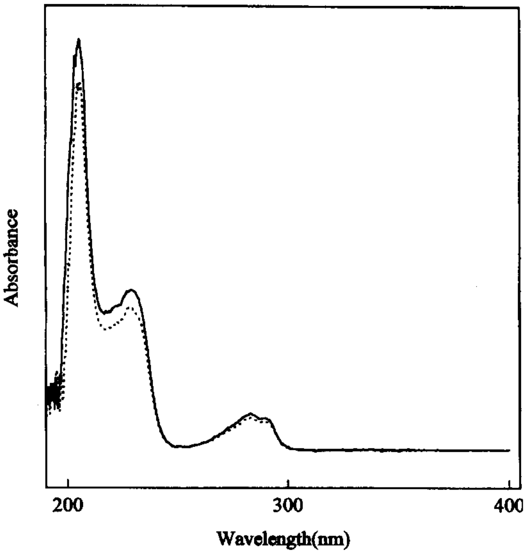


Figure 3. UV spectra of 2,4-D(—) and 2,4-D(······) released from poly(DOMS-*co*-AM)-1 in the buffer solution of pH 7.

1758 cm^{-1} and the vinyl group at 1586 cm^{-1}. Also, DPMS showed them at 1755 cm^{-1} and 1585 cm^{-1}. The NMR spectrum of DOMS is shown in Figure 2. The peaks were assigned by referring to the spectra of chloromethylstyrene and parent herbicides. Among the assignments, the hydrogens of the methylene in the vinyl group at 3 position must exhibit 4 peaks. However, only three peaks were shown as given here. The remaining peak might be overlapped with the methylene peak at 4 position. The hydrogen of methine in the vinyl group at 2 posiotion exhibited stronger intensity than expected. It can be due to the duplication of the peaks of benzoquinone which was used as the polymerization inhibitor because benzoquinone was scarcely soluble in water and was not separated from the herbicidal monomer.

Molar Absorptivities of Herbicides and Herbicidal Monomers. To know whether the compound released from poly(DOMS-*co*-AM) with about 5 mol% of the herbicidal monomer is 2,4-D or not, its UV spectrum is shown together with the spectrum of 2,4-D in Figure 3. The former spectrum is identical with the latter one. Therefore, the compound released from the copolymer was identified as 2,4-D.

To use in measuring the concentrations of the herbicides released from the copolymers, the molar absorptivities of the herbicides in the buffer solutions of pH 7 and pH 9 were determined. As shown in Table I, their maximum wavelengths were in the range of 280 nm to 290 nm. The wavelengths were not affected by the pH. But the molar absorptivities at pH 9 were a little higher than those at pH 7.

To use in determining the compositions of herbicidal monomers in the copolymers spectrophotometrically, the molar absorptivities of herbicidal monomers at the maximum wavelengths in dimethyl sulfoxide were determined. In this case, dimethyl sulfoxide was used as the solvent. The molar absorptivities are given in Table II. The maximum wavelengths of herbicides were in the range of 280 nm to 293 nm. The maximum

Table I. Wavelength of Maximum Absorption (λ_{max}) and Malar Absorptivity (ε) of the Herbicides in the Buffer Solutions

Herbicide	λ_{max}(nm)	ε(pH 7)	ε(pH 9)
2,4-D	290.4	22600	22800
MCPA	277.9	15860	15880
2,4,5-T	288.0	22640	22800
DCPP	283.8	14510	14930

Table II. Wavelength of Maximum Absorption (λ_{max}) and Molar Absorptivity (ε) of the Herbicidal Monomers in Dimethyl Sulfoxide

Monomer	λ_{max}(nm)	ε
DOMS	290	2930
MOMS	288	2680
TOMS	293	3200
DPMS	280	2900

wavelengths of herbicidal monomers in dimethyl sulfoxide were similar to those of herbicides in the buffer solutions of pH 7 and pH 9. However, the molar absorptivities of the former were much smaller than those of the latter. This might be due to the differences in properties between the dimethyl sulfoxide and the buffer solutions.

Synthesis and Characterization of the Copolymers. IR spectra of poly(DOMS-*co*-AM), poly(MOMS-*co*-AM), poly(TOMS-*co*-AM), and poly(DPMS-*co*-AM) showed a broad peak of amino group in AM unit at 3360 cm^{-1}, and a shoulder of carbonyl group of the ester bond in herbicidal monomer unit at about 1760 cm^{-1}, and a strong peak of carbonyl group in AM unit at 1665 cm^{-1}.

The yields, contents, and intrinsic viscosities of the copolymers are shown in Table III. The yields ranged from 71% to 94%. The yields of copolymers prepared with 5 mol% of the herbicidal monomers in the feeds were higher than those of copolymers prepared with 10 mol% of the herbicidal monomers. This result might be due to a chain transfer of the herbicidal monomers when they were copolymerized with acrylamide. Even though their yields are high, the contents of the herbicidal monomers in the copolymers were a little higher than those of the herbicidal monomers in the feeds. It has been reported that the monomer reactivity of styrene was higher than that of AM in the copolymerization of styrene and AM.[8,9] The intrinsic viscosities of the copolymers were in the range of 0.20 to 0.62. The viscosities of the copolymers prepared with 5 mol% of the herbicidal monomers were higher than those of the copolymers prepared with 10 mol% of the herbicidal monomers in the feeds. The result might be due to a chain transfer of the herbicidal monomers as described in the yields of the copolymers.

To estimate the hydrophobicity or the hydrophilicity of the copolymers, their swelling degrees measured in the buffer solutions of pH 7 and pH 9 are shown in Table IV. The swelling degrees at pH 9 were larger than those at pH 7. This can be due to the easy hydrolysis of herbicidal monomers and acrylamide[10] in the copolymers at high pH. The swelling degrees of copolymers with about 10 mol% of the herbicidal monomers were lower than those of copolymers with about 5 mol% of herbicidal monomers. This result means that the herbicidal monomers are more hydrophobic than acrylamide.

Release of Herbicides from the Copolymers. In order to discuss the effect of hydrophobic

Table III. Characterization of the Copolymers

Copolymer	Feed Composition[a] [M_H] (mol%)	Feed Composition[a] [M_A] (mol%)	Conversion[b] (%)	Copolymer Composition[c] [M_H] (mol%)	Copolymer Composition[c] [M_A] (mol%)	Intrinsic Viscosity[d]
Poly(DOMS)-*co*-AM)-1	5	95	94.1	5.1	94.9	0.31
Poly(DOMS)-*co*-AM)-2	10	90	76.4	10.6	89.4	0.20
Poly(MOMS)-*co*-AM)-1	5	95	83.7	5.9	94.1	0.32
Poly(MOMS)-*co*-AM)-2	10	90	71.3	12.2	87.8	0.24
Poly(TOMS)-*co*-AM)-1	5	95	88.2	5.2	94.8	0.61
Poly(TOMS)-*co*-AM)-2	10	90	74.9	10.7	89.3	0.53
Poly(DOMS)-*co*-AM)-1	5	95	84.1	5.3	94.7	0.54
Poly(DOMS)-*co*-AM)-2	10	90	71.3	11.5	88.5	0.36

[a] [M_H] and [M_A]: mol% of herbicidal monomers and acrylamide.

[b] Measured by gravimetry.

[c] Measured with UV spectrophotometer.

[d] Measured in trifluoroacetic acid at 30 ℃.

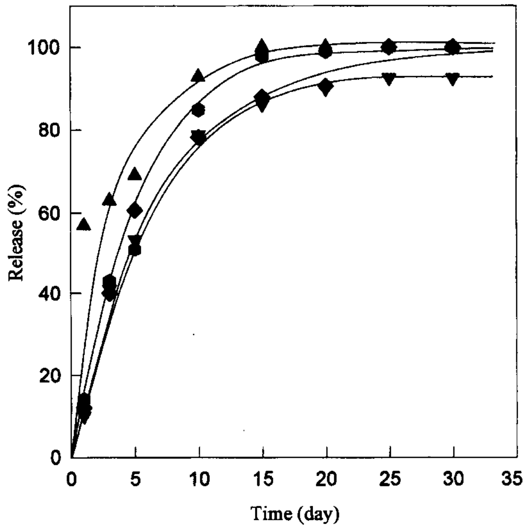


Figure 4. Release of 2,4-D, MCPA, 2,4,5-T, and DCPP from the copolymers in the buffer solution of pH 7 at 30 ℃ as a function of hydrolysis time: ▲ Poly(DOMS-*co*-AM)-1, ▼ Poly(MOMS-*co*-AM)-1, ◆ Poly(TOMS-*co*-AM)-1, ● Poly (DPMS-*co*-AM)-1.

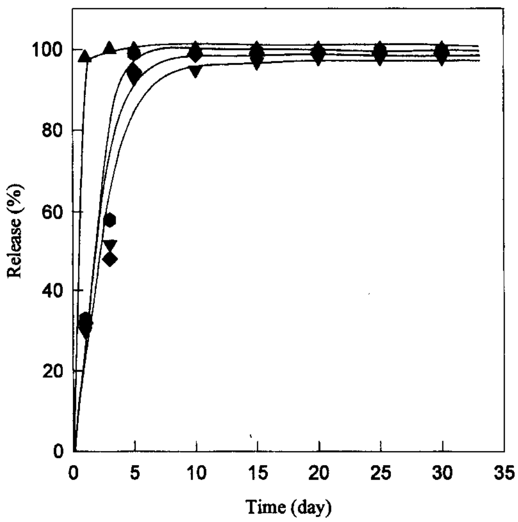


Figure 5. Release of 2,4-D, MCPA, 2,4,5-T, and DCPP from the copolymers in the buffer solution of pH 9 at 30 ℃ as a function of hydrolysis time: ▲ Poly(DOMS-*co*-AM)-1, ▼ Poly(MOMS-*co*-AM)-1, ◆ Poly(TOMS-*co*-AM)-1, ● Poly (DPMS-*co*-AM)-1.

difference among the herbicides on the release rate of the herbicides from the copolymers, the relation between the ratios of the herbicides released from the copolymers with about 5 mol% of the herbicidal monomers in the buffer solution at pH 7 and the hydrolysis time is shown in Figure 4. The ratios of poly(MOMS-*co*-AM)-1, poly(TOMS-*co*-AM)-1, poly(DPMS-*co*-AM)-1, and poly(DOMS-*co*-AM)-1 were around 86%, 88%, 96%, and 98% up to 15 days. The values exhibited only small differences with respect to the release of herbicides. This result is similar to the small difference among the swelling degrees of the copolymers with about 5 mol% of herbicidal monomers at pH 7. This fact suggests that the copolymers can not have large hydrophobic differences among the herbicidal monomers because the copolymers have about 19 times of AM as the hydrophilic monomer.

The relation between the ratios of the herbicides released from the copolymers with about 5 mol% of the herbicidal monomers at pH 9 and the hydrolysis time is represented in Figure 5. The values were quickly reached to more than 92% within 5 days and were scarcely changed afterwards with respect to the herbicides. This result can be explained in the same way as the release ratios in Figure 4. The values in this figure were larger than those in Figure 4. This means that the hydrolysis takes place more easily in the alkaline solution of pH 9 than in the

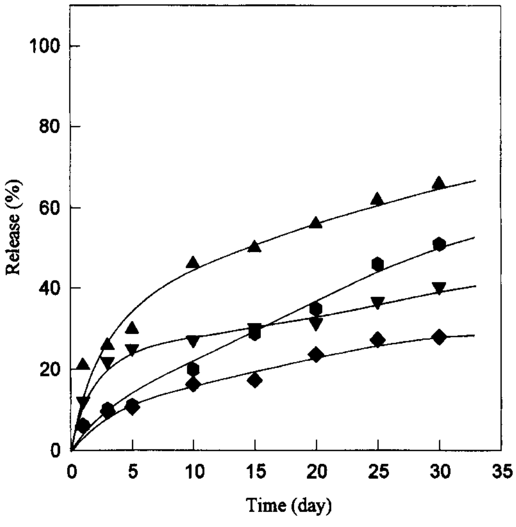


Figure 6. Release of 2,4-D, MCPA, 2,4,5-T, and DCPP from the copolymers in the buffer solution of pH 7 at 20 ℃ as a function of hydrolysis time: ▲ Poly(DOMS-*co*-AM)-2, ▼ Poly(MOMS-*co*-AM)-2, ◆ Poly(TOMS-*co*-AM)-2, ● Poly (DPMS-*co*-AM)-2.

Table IV. Swelling Degree of Copolymers at 30 ℃

Copolymer	pH 7 (%)	pH 9 (%)	Copolymer	pH 7 (%)	pH 9 (%)
Poly(DOMS-*co*-AM)-1	279	444	Poly(DOMS-*co*-AM)-2	182	341
Poly(MOMS-*co*-AM)-1	213	391	Poly(MOMS-*co*-AM)-2	88	124
Poly(TOMS-*co*-AM)-1	243	400	Poly(TOMS-*co*-AM)-2	97	150
Poly(DPMS-*co*-AM)-1	264	426	Poly(DPMS-*co*-AM)-2	105	214

neutral solution of pH 7.

The relation between the ratios of the herbicides released from the copolymers with about 10 mol% of the herbicidal monomers at pH 7 and the hydrolysis time is shown in Figure 6. The values of poly(TOMS-*co*-AM)-2, poly(MOMS-*co*-AM)-2, poly(DPMS-*co*-AM)-2, and poly(DOMS-*co*-AM)-2 are around 28%, 38%, 50%, and 65% until 30 days. The highest value of poly(DOMS-*co*-AM)-2 among the copolymers can be due to the lowest hydrophobicity of the copolymer. The highest swelling degree at pH 7 in Table IV means the lowest hydrophobicity. The herbicides were more slowly released from the copolymers comparing with the copolymers with about 5 mol% of the herbicidal monomers, and the values were effectively controlled with the herbicides. This result can be attributed to the hydrophobic differences among the herbicidal monomers in the copolymers because the copolymers with about 10 mol% of the herbicidal monomers had the differences in the swelling degrees at pH 7.

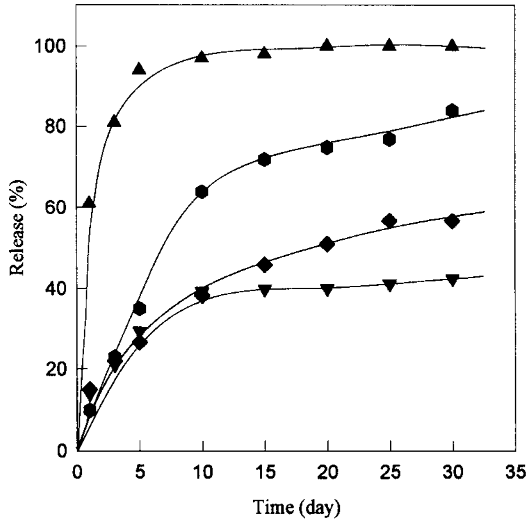


Figure 7. Release of 2,4-D, MCPA, 2,4,5-T, and DCPP from the copolymers in the buffer solution of pH 9 at 20 ℃ as a function of hydrolysis time: ▲ Poly(DOMS-*co*-AM)-2, ▼ Poly(MOMS-*co*-AM)-2, ◆ Poly(TOMS-*co*-AM)-2, ● Poly (DPMS-*co*-AM)-2.

The relation between the ratios of the herbicides released from the copolymers with about 10 mol% of the herbicidal monomers at pH 9 and the hydrolysis time is given in Figure 7. The values of poly(MOMS-*co*-AM)-2, poly(TOMS-*co*-AM)-2, poly(DPMS-*co*-AM)-2, and poly(DOMS-*co*-AM)-2 were around 40%, 55%, 83%, and 100% until 30 days. The rates were more effectively controlled than those of the copolymers with about 5 mol% of the herbicidal monomers at the same pH in Figure 5. The effectively controlled rates can be explained with the swelling degrees of the copolymers in the same way as Figure 6. Therefore, the result suggests that the release rates of the herbicides can be controlled effectively when the copolymers contain about 10 mol% of herbicidal monomers.

Conclusions

DOMS, MOMS, TOMS, and DPMS as the herbicidal monomers were synthesized by the reactions of chloromethylstyrene with the sodium salts of 2,4-D, MCPA, 2,4,5-T and DCPP, respectively and poly(TOMS-*co*-AM), poly(MOMS-*co*-AM), poly(DPMS-*co*-AM), and poly(DOMS-*co*-AM) as the herbicidal polymers were prepared by radically copolymerizing AM with the corresponding herbicidal monomers. The release rates of the herbicides from the copolymers with about 10 mol% of the herbicidal monomers were controlled more effectively than those of the herbicides from the copolymers with about 5 mol% of the herbicidal monomers. This result could be explained in terms of the contents and the hydrophobicity of the herbicidal monomers in the copolymers.

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References

(1) C. L. McCormick, Z. B. Zhang, and K. W. Anderson, *J. Controlled Release*, **4**, 97 (1986).
(2) C. L. McCormick, US Patent 4, 267,280 (1981).
(3) C. L. McCormick, US Patent 4, 267, 281 (1981).
(4) R. Issa, A. Akelah, A. Rehab, R. Solaso, and E. Chiellini, *J. Controlled Release*, **13**, 1 (1990).
(5) W. S. Kim, S. H. Lee, I. K. Kang, and N. K. Park, *J. Controlled Release*, **9**, 281 (1989).
(6) W. S. Kim, S. W. Jung, S. K. Lee, S. I. Moon, and J. K. Lee, *Korea Polymer J.*, **5**, 238 (1997).
(7) I. D. Tharp and H. A. Nottarf, *Ind. Eng. Chem.*, **39**, 1300 (1947).
(8) A. Leonic and S. Franco, *Macromolecules*, **4**, 355 (1971).
(9) G. Saini, A. Seoni, and S. Franco, *Makromol. Chem.*, **144**, 235 (1971).
(10) H. Tanaka and R. Senju, *Kobunshi Ronbunshu*, **33**, 309 (1976).