

Polytetrahydrofuran Amphiphilic Networks. III. Synthesis and Characterization of pH-sensitive Poly(methacrylic acid)-*l*-Polytetrahydrofuran Networks

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ABSTRACT: A series of pH-sensitive amphiphilic poly(methacrylic acid)-*l*-polytetrahydrofuran (PMAA-*l*-PTHF) networks were prepared by free radical copolymerization of hydrophobic telechelic polytetrahydrofuran diacrylates (PTHFDA) with hydrophilic methacrylic acid(MAA). Network composition was characterized. The networks are amphiphilic, namely, that swell both in organic solvents and in water. The swelling of the networks in organic solvents or in water is composition dependent. Swelling dynamics of networks indicates a non-Fickian process in cyclohexane as well as in water. According to swelling experiments, four solubility parameters of PMAA-*l*-PTHF networks were obtained, which correspond to the hydrophilic and hydrophobic segments, and the interaction between these two segments and solvents. The networks are pH sensitive in aqueous media. These results indicate that PMAA-*l*-PTHF networks exhibit not only the properties of PMAA and PTHF segments but also the combined properties of them. © 2002 Wiley Periodicals, Inc. *J Appl Polym Sci* 85: 351–357, 2002

Key words: telechelic; stimuli-sensitive polymers; networks; swelling

INTRODUCTION

Recently, amphiphilic networks have received increasing attention on account of their interesting properties and potential applications,^{1–4} such as blood- and biocompatibility materials and drug release carrier. Amphiphilic networks are cross-linked random assemblages of hydrophilic and hydrophobic polymer segments.^{5–10} In such networks two immiscible polymers are combined to form a microphase-separated structure. These materials are able to swell in both water and organic solvents.

In the previous article of this series^{11,12} we reported the synthesis and characterization of polyacrylamide-*l*-polytetrahydrofuran (PAm-*l*-PTHF) networks. Because of their hydrophilic/hydrophobic heterophase structure, they exhibited not only the properties of PAm and PTHF segments but also the combined properties of them. In addition, their properties could be adjusted by changing the content of the two segments of the networks.

Environmentally sensitive polymers,^{13–16} called intelligent polymers, show a phase transition in response to external stimuli, such as pH, temperature, ionic strength, electric potential. Among them, pH- and temperature-sensitive polymers have been studied intensively because of their scientific and technological importance. If environmentally sensitive polymers are included into the amphiphilic polymer networks, these networks may be intelli-

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gent. In this research, we chose polymethacrylic acid as hydrophilic segments to synthesize a series of novel poly(methacrylic acid)-*l*-polytetrahydrofuran(PMAA-*l*-PTHF) networks. Polymethacrylic acid is pH-sensitive in aqueous solution. We hope these novel networks will combine this advantage and will become potentially important materials. The preparation of PMAA-*l*-PTHF networks are described and the swelling behavior studied.

EXPERIMENTAL

Materials

All reagents used received from Shanghai First Reagent Factory. Methacrylic acid (MAA) was distilled before use under vacuum in the presence of 0.1% (wt %) hydroquinone. Tetrahydrofuran (THF) was treated with calcium hydride for a week, and then refluxed with sodium wire in the presence of a trace of benzophenone until a blue color was obtained. It was distilled before use. 2,2'-Azo-bis-isobutyronitrile (AIBN) was recrystallized twice from alcohol, then dried under vacuum at room temperature. Other reagents were used without pretreatment.

All solvents were analytically pure and used without pretreatment. The solubility parameters (δ) of the solvents are in ref. 17.

The different buffers were used as ref. 18. Ionic strength was adjusted with potassium chloride to 0.10 in all cases.

Synthesis of PMAA-*l*-PTHF Networks

Polytetrahydrofuran diacrylates (PTHFDA) were prepared as before.¹¹ The free radical copolymerization of PTHFDA with MAA was carried out in a cylindrical flask equipped with a condenser, an electromagnetic stirring bar, and a nitrogen inlet. AIBN was used as initiator and THF as solvent. The charge was kept at 60°C for 24 h. Stirring was stopped when gelation began and the charge solidified. The product was cut into cubes.

To remove unreacted monomers and PMAA, the product was extracted sequentially with cyclohexane for 24 h, ethanol for 24 h, and distilled water for 48 h.

Analysis

FTIR spectra were measured on a Nicolet MX-1 FTIR spectrometer. Pellets made of mixtures of

pulverized products and dry potassium bromide were used.

Elemental analyses of PMAA and PMAA-*l*-PTHF networks were carried out by an CARLO ERBA 1106 (Italy) elemental analysis instrument.

Swelling Measurements

Swelling measurements were performed at 37°C. Preweighed strips of the samples (about 100 mg) were immersed in a large excess of solvent. Samples were periodically removed from the solution and weighed after the excess liquid was blotted off with laboratory tissue paper. The equilibrium-swelling ratio (SR) in solvents with different solubility parameters was obtained until the weight of samples unchanged.

The swelling ratio (SR) was measured as the ratio of the weight of the absorbed solvent and the dried networks. The calculated formula was as follows:

$$SR = \frac{W_s - W_o}{W_o} \quad (1)$$

where W_s is the weight of the swollen gel, W_o is the weight of the original dry gel.

RESULTS AND DISCUSSION

Synthesis of PMAA-*l*-PTHF Networks

The synthesis conditions and compositions of amphiphilic networks are summarized in Table I. The network abbreviation code indicates the hydrophilic segments, the number-average molecular weight of the starting PTHFDA, and the percent of PTHFDA in the networks. For example, MAA-2-50 indicates a network prepared with MAA, and the number-average molecular weight of PTHFDA is about 2000, and the weight fraction of PTHFDA in network is 50% (wt %).

The FTIR spectra of PMAA, PTHFDA, and PMAA-*l*-PTHF networks are shown in Figure 1. Comparing with the spectra of PMAA and PTHFDA, the peak at 1112 cm^{-1} is due to C—O—C bond of PTHF, and indicates the PTHF segment in the networks. The peaks at 1720 cm^{-1} characteristic of C=O stretching indicate the presence of PMAA segments in the networks. The increasing intensity of C—O—C bond stretching signal at 1110 cm^{-1} from MAA-2-13 to MAA-2-85 corre-

Table I PMAA-*l*-PTHF Network Synthesis Conditions^a and Compositions

Networks Sample ^b	In Feed		Network Characterization		
	PTHFDA g	MAA g	Yield %	PTHF ^c wt %	$\bar{M}_{c, \text{PMAA}}$ ^c
MAA-2-85	0.9	0.1	80.28	85.09	195
MAA-2-64	0.7	0.3	82.95	63.63	653
MAA-2-45	0.6	0.4	90.10	44.82	1414
MAA-2-36	0.5	0.5	89.86	36.08	2085
MAA-2-13	0.4	0.6	90.17	12.97	4741

^a Copolymerization in 2.0 mL THF with 15 mg AIBN at 60°C.

^b MAA-2-X indicates that the hydrophilic segment is PMAA, the molecular weight of PTHFDA is about 2000, and the weight percent of PTHF segment is X%.

^c Calculated values.

lates with the increasing PTHF content in the networks.

In this system, the PTHFDA is an end-functionalized macromolecular crosslinker of the free-radical polymerization of MAA. The copolymer network contains PMAA and PTHF segments. The average molecular weights of PMAA and PTHF segments between two crosslinks in the network are represented as $\bar{M}_{c, \text{PMAA}}$ and $\bar{M}_{c, \text{PTHF}}$. Because the mol fraction of PTHF in the networks is much less than that of MAA, it is reasonable to consider that the $\bar{M}_{c, \text{PTHF}}$ is equal to the number-average molecular weight (M_n) of the PTHFDA. Hence, the values of $\bar{M}_{c, \text{PMAA}}$ can be estimated

according to the elemental analysis.¹¹ The calculated results are listed in Table I.

Solubility Parameters of PMAA-*l*-PTHF Networks

Polymer networks cannot dissolve in solvents but can swell in some solvents. When the solubility parameters (δ) of the solvent approaches to that of the polymer networks, the equilibrium swelling ratio (SRe) of networks reaches a maximum, which shows a peak in the SR- δ plot. The solubility parameter corresponding to this peak is considered the solubility parameter of the network.¹⁹ Amphiphilic networks contain hydrophilic and hydrophobic segments, and their swelling behavior¹² differ from those of homopolymer networks.

The solubility parameters of PTHF and PMMA homopolymer is calculated from the equation as follows:

$$\delta^2 = \frac{U}{V}$$

where U is the cohesive energy and V is the molar volume. It is assumed that the cohesive energy of polymers are additive, namely, the interaction of a pair of groups, is not influenced by the presence of other groups. According to this rule, the δ of polymers can be estimated. The calculated δ of PTHF is 17.6 and that of PMMA is 28.4 J^{1/2} cm^{-3/2}. Because the assumption is applicable for nonpolar and dissociation systems, the calculated solubility parameter of PMAA has some deviation.

SRe of PMAA-*l*-PTHF networks were measured in different solvents. The solubility parameters of solvents are in ref. 17. As shown in Figure

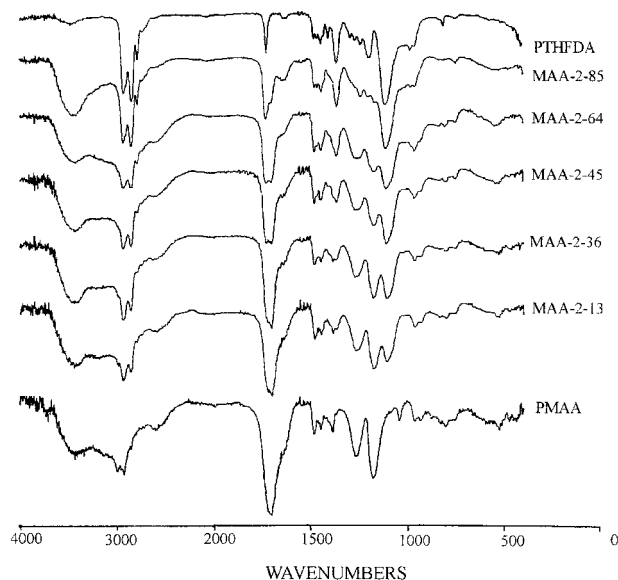


Figure 1 IR spectra of the homopolymers and PMAA-*l*-PTHF networks.

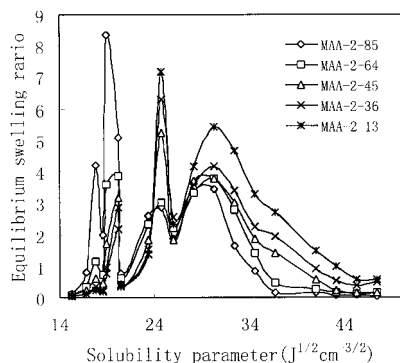


Figure 2 The swelling behavior of PMAA-*l*-PTHF networks in different solvents.

2, despite the fact that the network composition varies, the PMAA-*l*-PTHF networks give maximum swelling ratios at four solubility parameters, which indicates that PMAA-*l*-PTHF networks have four solubility parameters. The corresponding solubility parameters and swelling ratios of PMAA-*l*-PTHF networks are summarized in Figure 3.

As shown in Figure 3, the four solubility parameters are 17.7, 20.2, 24.7, and 30.2 $J^{1/2} \cdot cm^{-3/2}$. 17.7 $J^{1/2} \cdot cm^{-3/2}$ approaches the solubility parameter of PTHF, 17.6 $J^{1/2} \cdot cm^{-3/2}$, 30.2 $J^{1/2} \cdot cm^{-3/2}$ approaches the solubility parameter of PMAA, 28.4 $J^{1/2} \cdot cm^{-3/2}$. These two solubility parameters indicate the interaction of PTHF and PMAA segments with solvents, respectively. When the solubility parameter is 17.7 and 20.2 $J^{1/2} \cdot cm^{-3/2}$, the SRe of networks increases with increasing the PTHF content in networks. While the solubility parameter is 24.7 and 30.2 $J^{1/2} \cdot cm^{-3/2}$, the SRe of networks decrease with increasing the PTHF content in network. These facts

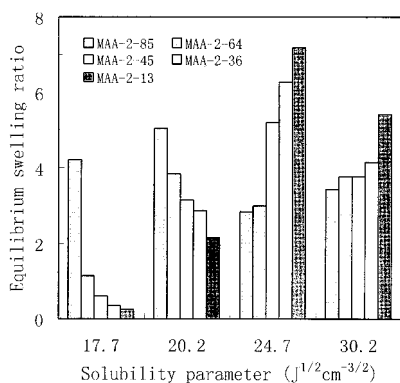


Figure 3 Plot of equilibrium swelling ratio of PMAA-*l*-PTHF networks against solubility parameters.

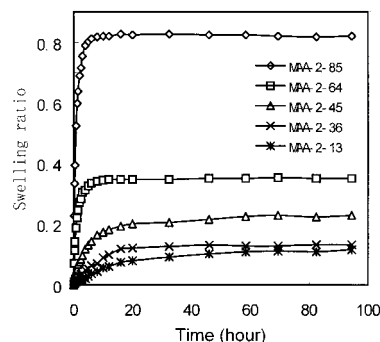


Figure 4 Swelling curves of PMAA-*l*-PTHF networks in cyclohexane at 37°C.

give further information that 17.7 and 30.2 $J^{1/2} \cdot cm^{-3/2}$ correspond to the solubility parameters of PTHF and PMAA segments, respectively. The other two solubility parameters, 20.2 and 24.7 $J^{1/2} \cdot cm^{-3/2}$, indicate the interaction of PTHF and PMAA segments with solvents. PMAA-*l*-PTHF networks exhibit not only the properties of both hydrophilic and hydrophobic segments but also the combined properties of two segments.

Swelling Dynamics of Networks in Different Solvents

PMAA-*l*-PTHF networks are amphiphilic. Cyclohexane is hydrophobic solvent and water is a hydrophilic. Cyclohexane and water were chosen to study the dynamic swelling kinetics of these networks. Figures 4 and 5 show the swelling curves of networks in cyclohexane and water, respectively.

The swelling dynamics of networks was studied by the well-known relationship:²⁰

$$SR(t) = kt^n \quad (2)$$

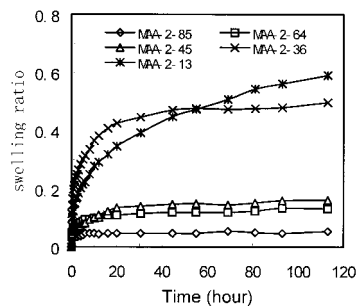


Figure 5 Swelling curves of PMAA-*l*-PTHF networks in water at 37°C.

where $SR(t)$ is the measured swelling ratio at time t , k is a constant, and n is the kinetic exponent. The exponent n provides insight into the type of the sorption mechanism.²¹ For a Fickian I rate-limiting diffusion process, n is 0.5, for Fickian II diffusion, n is 1, whereas when n is between 0.5 and 1, diffusion is non-Fickian process, namely, the solvent diffusion rate and the polymer relaxation rate are about the same order of magnitude. The values of n of PMAA-*l*-PTHF networks obtained from the slope of a log-log plot of swelling ratio vs. time are summarized in Table II.

As shown in Table II, the n values of PMAA-*l*-PTHF networks are lower than 0.5, indicating a non-Fickian I or II diffusion. According to the unique properties of these networks, we think that the diffusion is non-Fickian diffusion process. When PMAA-*l*-PTHF networks swell in water or in cyclohexane, the relaxation of PMAA and PTHF segments are always different. Cyclohexane is a good solvent for PTHF and a poor solvent for PMAA. The PMAA segment expands relatively in water and contracts in cyclohexane, while the PTHF segment expands in cyclohexane and contracts in water. In addition, the testing temperature is higher than the glass-transition temperature (T_g) of the PTHF segment and lower than the T_g of the PMAA segment. The PTHF segment is in the rubbery state, which allows an easier penetration of the solvent. The PMAA segment is in the glass state, so the PMAA chains are not sufficiently mobile to permit immediate solvent penetration in the polymer. There are always two opposite effects whenever we consider the swelling of two segments or the mechanical states of them. Hence, the n values are different from normal non-Fickian diffusion.

Due to the presence of the —COOH groups, the dynamic swelling is different in an organic solvent from those in water. Because n for cyclohex-

Table II The Swelling Exponent (n) of PMAA-*l*-PTHF Amphiphilic Networks in Cyclohexane and Water

Sample	Swelling Exponent (n)	
	Cyclohexane	Water
MA-2-85	0.4150	0.1745
MA-2-64	0.4971	0.2052
MA-2-45	0.4836	0.1773
MA-2-36	0.4132	0.2679
MA-2-13	0.4725	0.3110

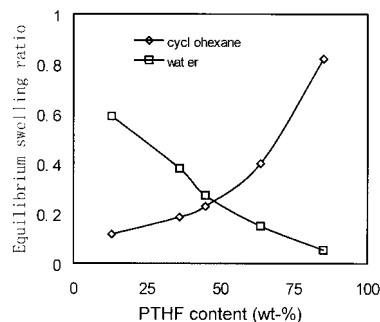


Figure 6 Equilibrium swelling ratios of PMAA-*l*-PTHF networks in different solvents as the function of PTHF content.

ane was 0.4–0.5 but somewhat higher than for water, the non-Fickian swelling behavior in water is caused in part by ion transport and not by network chain relaxation.

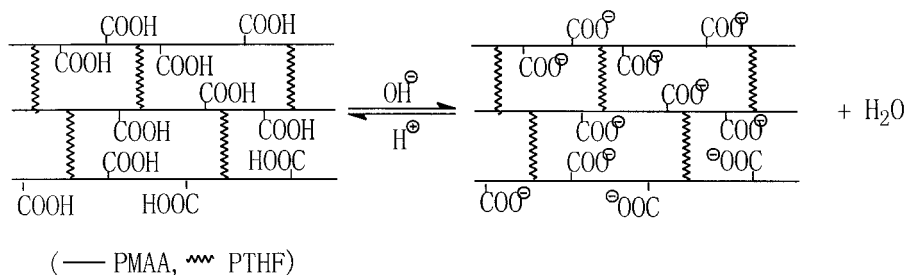
All the samples were tested three times and got similar results as shown in Figure 5. We noticed that although the equilibrium swelling ratio of MAA-2-36 was lower than MAA-2-13, at the initial stage the swelling of MAA-2-36 sample was faster than that of MAA-2-13. We could not explain this phenomenon at this stage. We think it may due to the defect of the network structure of MAA-2-36, which cause the fast diffusion of water from the outside to the inside of network. More research is needed to fully understand this phenomenon, which will be carried out in our laboratory.

Both in organic solvents and in water, the swelling of PMAA-*l*-PTHF networks is composition dependent. As shown in Figure 6, the equilibrium swelling ratio (SRe) in water increases with decreasing PTHF content in the networks, whereas in cyclohexane it decreases with decreasing PTHF content. When the PTHF content decreases from 85 to 13%, the SRe in water increases from 5.4 to 59.0%, and it decreases from 82.0 to 11.6% in cyclohexane. Hence, the ratio of hydrophilic and hydrophobic segments controls the swelling behavior of these amphiphilic networks.

pH-Sensitive Behavior

PMAA is pH-sensitive¹⁶ and PMAA-*l*-PTHF networks may retain this advantage. pH-response of these networks was studied in different buffers. The results are shown in Figure 7.

Due to the presence of the —COOH group in PMAA-*l*-PTHF networks, when the pH of the system was increased, the —COOH groups may ionize:



This reaction is reversible in response to increasing or decreasing the pH. The dissociation constant (pK_a) of $-\text{COOH}$ is about 5.²² When $\text{pH} < 5$, the nonionic form is dominating, whereas at $\text{pH} > 5$, the $-\text{COOH}$ group ionizes. Because of the electrostatic repulsion between ionized groups, the osmotic pressure caused by the presence of the mobile counter ions increases the swelling ratio of networks. As shown in Figure 7, the swelling ratio of the networks increased significantly when $\text{pH} > 5.2$. The pK_a of networks approaches to the pK_a of $-\text{COOH}$ group. With increasing PMAA content, the swelling ratio increases, indicating the contribution of PMAA segments. These experimental facts coincide with the expected theoretical results. Hence, PMAA-*l*-PTHF networks are pH sensitive, caused by the PMAA segment. In line with this, other environmentally sensitive amphiphilic networks could be designed and synthesized.

CONCLUSIONS

The copolymerization of MAA and PTHFDA leads to a series of pH-sensitive amphiphilic PMAA-*l*-PTHF networks.

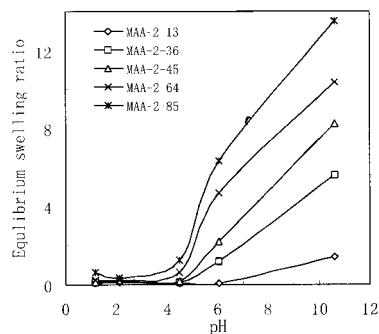


Figure 7 Effect of pH on the swelling of PMAA-*l*-PTHF networks.

These networks swell both in organic solvents and in water. The swelling of networks is composition dependent.

PMAA-*l*-PTHF networks are pH sensitive in aqueous solution; the pK_a of the networks is about 5, close to those of $-\text{COOH}$ groups.

Swelling dynamics of the networks indicate a non-Fickian process in cyclohexane as well as in water.

These networks exhibit not only the properties of PMAA and PTHF segments, but also the combined properties of these two segments.

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