Macromolecules **1998,** *31,* 3383−3384 **3383**

Hydrophobic Site-Specific Control of the Volume Phase Transition of Hydrogels

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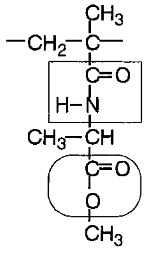
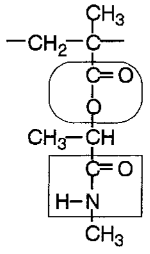
Received November 25, 1997
Revised Manuscript Received March 23, 1998

Hydrogels consisting of nonionic polymer networks with a hydrophobic and a hydrophilic domain in the side chains swell at a low temperature by absorbing water and collapse at a high temperature.[1−6] The volume phase transition temperature from the swollen to the collapsed state is controlled by a hydrophobic−hydrophilic balance in the structure of the polymer.[7−10] Polymers with the same ratio of hydrophobic and hydrophilic residues should then exhibit the same volume phase transition profile. We found, however, that the volume phase transition of such polymers depends strongly on the location of the hydrophobic domain in the side chains.

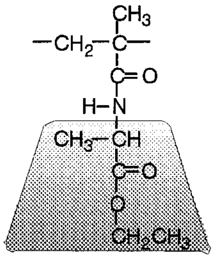
First we compared the networks consisting of methacryloyl-L-alanine methyl ester (MA-Ala-OMe) and methacryloyl-L-lactic acid *N*-methylamide (MA-Lac-NMe) residues. Since these polymers contain the same functional groups in the side chain, single amide and ester groups, single methyl side chain in L-alanine and L-lactic acid, and terminal methyl group, they should exhibit an identical hydrophobic−hydrophilic balance. These polymer structures differ, however, in the location of the amide and ester groups in the side chains: in MA-Ala-OMe the strongly hydrophilic amide lies close to and the strongly hydrophobic ester at some distance from the main chain, while the amide and ester are in the opposite location in MA-Lac-NMe.[11]



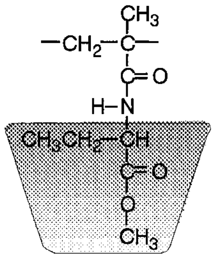
MA-Ala-OMe



MA-Lac-NMe



MA-Ala-OEt



MA-Abu-OMe

Figure 1 illustrates a dramatic difference of volume phase transition with temperature for these polymer networks.[12] The hydrogel of poly(MA-Ala-OMe) is highly swollen from 0 to 10 °C and collapsed above 30 °C. The midpoint of transition from a swollen to a collapsed phase occurs at 20 °C.

On the other hand, the poly(MA-Lac-NMe) gel swells slightly at 0 °C and the swelling is depressed with rising temperature to form a collapsed phase above 25 °C. The midpoint of the transition temperature is 15 °C.

We also compared networks of copolymers of MA-Ala-OMe with methacryloyl-L-alanine ethyl ester (MA-Ala-OEt) or methacryloyl-L-2-aminobutanoic acid methyl ester (MA-Abu-OMe), respectively. Here the volume phase transition occurs for network gels at a given temperature on varying the copolymer composition.[7] MA-Ala-OEt and MA-Abu-OMe are structural isomers having the same groups in the side chains but differ in the location of the more hydrophobic ethyl group: the former has the ethyl group far from and the latter close to the main chain.

The volume phase transition profile of these copolymers changes strongly on varying the composition of comonomer residues, as shown in Figure 2. The swelling of the poly(MA-Ala-OMe-*co*-MA-Ala-OEt) hydrogel first gradually decreases with an increasing MA-Ala-OEt content and then abruptly decreases at very high contents of MA-Ala-OEt.[13] The transition occurs at 0 °C for a copolymer containing 30 mol % MA-Ala-OMe. On the other hand, the swelling of the poly(MA-Ala-OMe-*co*-MA-Abu-OMe) gel decreases with a small increase of the MA-Abu-OMe content and the transition occurs at 0 °C for a gel containing 60 mol % MA-Ala-OMe. A different transition midpoint for these copolymer gels was observed at higher temperatures: for example 65 mol % MA-Ala-OMe for poly(MA-Ala-OMe-*co*-MA-Ala-OEt) and 70 mol % for poly(MA-Ala-OMe-*co*-MA-Abu-OMe) at 10 °C.

These results show that the volume phase transition of hydrogels depends strongly on the location of hydrophobic site in the side chains even if the polymers have the same hydrophobic−hydrophilic balance. The formation and decomposition of icelike structures of water molecules around the hydrophobic groups generally account for the formation of the swollen and collapsed states of polymer hydrogels.[14] Hydrogels with a more hydrophobic character thus form the collapsed state associated with the decomposition of icelike structures at lower temperatures.[7] For the polymer network of poly(MA-Lac-NMe) having a hydrophobic domain consisting of an ester group and a lactyl residue close to the main chain, the hydrophobic domains tend to associate strongly because of easy arrangement of the side chains by the restricted rotational angle ϕ between the ester bond and the α-carbon with the methyl side group of the lactyl residue to −70°.[15] The association of the side chains promotes cooperative association of the main chains even at a lower temperature. On the other hand, the hydrophobic domain in the poly(MA-

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S0024-9297(97)01727-0 CCC: $15.00

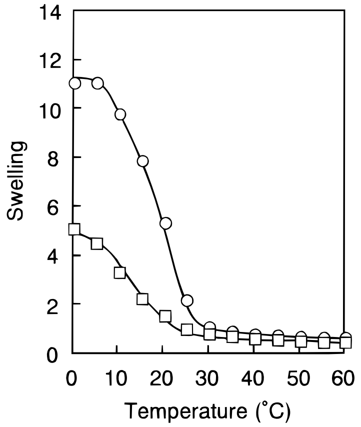

Figure 1. Dependence of the degree of swelling of hydrogels consisting of poly(MA-Ala-OMe) (○) and poly(MA-Lac-NMe) (□) on temperature.

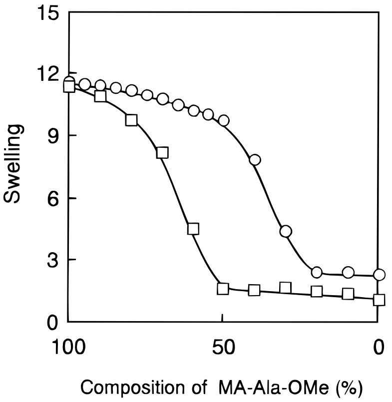

Figure 2. Dependence of the degree of swelling of hydrogels consisting of poly(MA-Ala-OMe-*co*-MA-Ala-OEt) (○) and poly(MA-Ala-OMe-*co*-MA-Abu-OMe) (□) on the composition of comonomers at 0 °C.

Ala-OMe) consisting of the alanyl residue and the terminal methyl ester is separated from the main chain by the hydrophilic amide group. The hydrophobic domains then cannot promote the cooperative association of the chain backbones. For this polymer network, the main chains associate on release of water molecules at an elevated temperature. This explains the different behavior of the copolymers of MA-Ala-OMe with MA-Abu-OMe or MA-Ala-OEt. The hydrogels of the former with the more hydrophobic ethyl group in the side chain close to the main chain form the collapsed phase at a lower MA-Abu-OMe content, because the strongly hydrophobic domain near the main chains promotes association even though the hydrophilic amide group lies between the main and side chains. Since the MA-Ala-OEt copolymer has the less hydrophobic methyl group in the side chain close to the main chain, a higher MA-Ala-OEt content is required for the collapse of the gel.

References and Notes

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(11) For example, dielectric constants of *N*-methylacetamide, methyl acetate, and 1,2-dichloroethane are 179.0 at 30 °C, 7.07 at 25 °C, and 10.42 at 20 °C, respectively.
(12) The polymer gels were prepared by the procedure reported.[7] The gels thus obtained in an ethanol solution were completely rinsed with acetone, and allowed to stand in water to give hydrogels. The swelling values were determined by the same procedure as reported.[7]
(13) The volume phase transition profile of this copolymer has been reported.[7] The profile reported is somewhat different from that in this study. The difference is caused by the preparation of hydrogels. The hydrogel in the former work[7] was prepared by the substitution of solvent for the polymer gel from ethanol to water. In this work, the hydrogel was obtained from an acetone solution. We have found that the hydrogel obtained from an ethanol solution contains a very small amount of ethanol molecules that can affect the volume phase transition profile.
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