Dependence of Volume Phase Transition Temperature of Poly(acryloyl-L-proline methyl ester) Gel on Hydrophobic Tail Length of Anionic Surfactants

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Since from the early works of Tanaka,[1] who found that partially hydrolyzed polyacrylamide gels display discontinuous volume change as a function of temperature and solvent composition, hydrogels that respond to environmental stimuli have been much investigated. The inverse volume phase transition that is induced by changes in temperature is especially of great interest due to its relevance to biological systems. One of the better known examples of such a gel is the cross-linked poly(*N*-isopropylacrylamide). Our interest in thermoreversible hydrogels originates in their proposed use as controlled drug delivery devices, and we are synthesizing such hydrogels from polymers with α-amino acids in their side chains.[2−5]

The temperature-induced inverse volume phase transition of a gel in aqueous solution is an entropy-driven phenomenon.[6−8] The entropy gain originates from the breakdown of the highly ordered, icelike water that exists around the polymer chains as the temperature increases. This water structuring occurs at low temperature as a result of hydrogen bonding between water and hydrophilic groups of the polymer. At high temperature, this structured water is released, and the interactions between the hydrophobic groups of the polymer prevails, thus causing the shrinking of the gel.[9−11] Since the volume phase transition temperature depends on the balance of hydrophobic and hydrophilic groups of the polymer, it can be influenced by either changing the hydrophobicity or the charge of the polymer itself,[12−14] or by the addition of salts[15,16] or surfactants[17−20] to the solution that contains the gel.

In our previous work,[21] the swelling equilibrium of poly(acryloyl-L-proline alkyl esters) gels was studied as a function of temperature in aqueous solutions of such different surfactants as anionic sodium dodecyl sulfate, cationic cetyltrimethylammonium chloride, zwitterionic dimethylalkyllaurylbetaine, and nonionic dodecyl octaoxyethylene ether.

At low surfactant concentration, addition of anionic or cationic surfactant to the solution raised the transition temperature as well as the swelling. On the other hand, the nonionic surfactant did not affect neither the transition temperature or the volume change. These results were interpreted in terms of preferential uptake of the surfactants by the gels and the formation of mixed micelles. The driving force for the surfactant−gel interaction is the hydrophobic one between the surfactant tail and the hydrophobic groups on the gel. When the surfactant head groups are ionic, the otherwise neutral gel is converted to a polyelectrolyte gel, and the introduction of this additional osmotic pressure due to ionization elevates the transition temperature. On the other hand, when the head groups are nonionic, at low surfactant concentration there are no measurable changes in the swelling behavior. Here, we summarized the study of the influence of the hydrophobic tail length of anionic sodium alkane sulfonate surfactants on the swelling behavior of the gels. The changes in the volume phase transition are correlated to the critical micelle formation and to number of the methylene units in the tails of these surfactants.

The synthesis of poly(acryloyl-L-proline methyl ester) (poly(A-Pro-OMe)) gel was as follows. A-Pro-OMe monomer (2.5 g) was mixed into a glass vial filled with distilled water (7.5 g) to obtain the homogeneous solution, and then nitrogen was bubbled into the solution for 10 min at 25 °C After the solution was pipetted into a 5 mm inner diameter glass ampoule, the irradiation was carried out up to 30 kGy (dose rate of 10 kGy/h) at 25 °C in nitrogen atmosphere. The gels obtained were refluxed in a Soxhlet's apparatus with boiling ethanol for 24 h to remove the unreacted monomer and oilgomers and then were dried *in vacuo* to constant weight. The resulting degree of cross-linking, 100 (*W*/Wo), where *W* is the weight of dry sample after reflux and Wo is the weight of the feed monomer before irradiation, was approximately 92%.

In the swelling experiments, the gels treated with boiling ethanol were immersed in distilled water at 0 °C (ice-water bath) to replace the medium with water and were lyophilized. The lyophilized sample, cut in a rodlike shape of 5 mm in diameter and 10 mm length, was immersed in aqueous surfactant solutions at 0 °C, until the swelling equilibrium was reached. In order to measure the degree of swelling, the vials with sample and 50 mL of aqueous surfactant solutions (one sample per vial, five vials per group) were put in a water bath (in the range of 0−60 °C) or in a windy oven (in the range of 60−100 °C) for 48 h. The samples were then removed from their respective vials, wiped to remove the excess surface solution, and weighed. The dry weights were measured after desiccating the same sample *in vacuo*. The resulting degree of swelling was calculated as follows: $(W - Wo)/Wo$, where *W* is the wet weight of the gel and Wo is the dry weight of the gel, respectively. The anionic sodium alkane sulfonates are those having chemical structures $CH_3(CH_2)_nSO_3Na$ [n = 6(C_7), 7(C_8), 9(C_{10}), 11(C_{12}), 13(C_{14}), and 15(C_{16})] whose properties in water are well established.[22−25]

Figure 1 illustrates the temperature dependence of the swelling of poly(A-Pro-OMe) gel in pure water and in aqueous solution of sodium decanesulfonate (C_{10}). In pure water, the gel shows the inverse volume phase transition at around 14 °C (determined from the inflection point at the swelling vs temperature curve), accompanied by a volume change (defined as the ratio of gel volume at 0 and at 80 °C) of 25. When the gel is immersed in a solution of the surfactant, with increase in the concentration of the surfactant, the volume phase transition temperature (VPTT) increases as expected. On the other hand, the volume change remains almost same.

When a gel is placed in aqueous solutions of surfactants, the surfactants tend to preferentially absorbed

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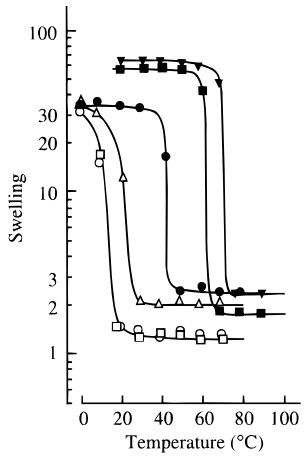

Figure 1. Temperature dependence of the swelling of poly(A-Pro-OMe) gel in aqueous solutions of sodium decanesulfonate (C_{10}) with concentrations of (○) 0 mM, (□) 17.3 mM, (△) 27.7 mM, (●) 34.7 mM, (■) 69.3 mM, and (▼) 104 mM.

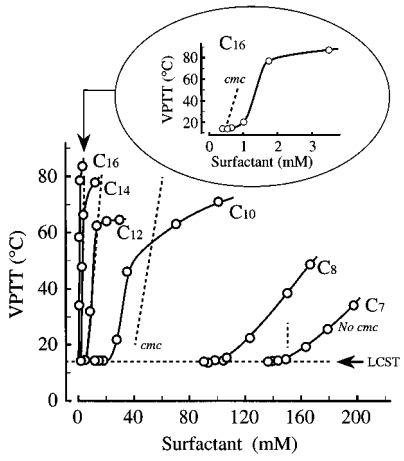

Figure 2. Changes in VPTT of poly(A-Pro-OMe) gel with variation of the concentration of the surfactants having different hydrophobic tail lengths.

by the gel.[19,21,26−28] By the uptake of the surfactant into the poly(A-Pro-OMe) gel, mixed micelles are formed, the center of each micelle being the proline and alkyl side groups, onto which the hydrophobic tail of the surfactant adsorbs.[21] When the surfactants are ionic, like the alkane sulfonates, the formation of mixed micelles converts the originally natural gel to a polyelectrolyte. These charges introduce an additional osmotic pressure on the gel, and since additional energy is needed to counter the electrostatic interactions between the surfactant head groups, the VPTT increases.

In the case of anionic surfactants, mixed micelles usually form at a critical aggregation concentration (cac), that is lower than the critical micelle concentration (cmc).[22] It should be very interesting to investigate how the relationship between the cac and cmc depends on the hydrophobic tail length of sodium alkane sulfonates. Figure 2 illustrates the changes in VPTT of poly(A-Pro-OMe) gel with variation of the concentration of the surfactants having different hydrophobic tail lengths. Sodium heptanesulfonate (C_7) shows no micelle formation in pure aqueous solution. At high surfactant concentration above 150 mM, however, it also induces an elevation of the VPTT, indicating that, when the surfactant is inside the gel, even this surfactant could form mixed micelles. In sodium octanesulfonate (C_8) with cmc of 150 mM, the elevation of the VPTT starts at a lower surfactant concentration (cac) of 100 mM than the cmc. This fact suggests that the mixed micelle formation of the surfactant having a rather short tail length with the polymer side chains predominates over the micelle formation with the surfactant molecules. In the surfactants having longer tail length (C_{10}−C_{15}) where the cac's are still lower than the cmc's, the surfactant molecules are preferentially absorbed into the gel at lower concentrations than the cmc's to give abrupt elevation of the VPTT of the gel. Above the cmc's of the surfactants, an equilibrium between the mixed micelle formation and the micelle formation should be established, resulting in the depression of elevation of the VPTT. In the surfactant having longest tail length (C_{16}), the cac is very close to the cmc. In this system, the elevation of the VPTT of the gel starts at the same concentration of 0.5 mM as the cmc.

The results mentioned above clearly show that it depends on the hydrophobic tail length of the surfactant and the hydrophobicity of the side chains of the polymer whether the mixed micelle formation predominates over the micelle formation.

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