Polymers

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Control of the Coil-to-Globule Transition and Ultrahigh Mechanical Properties of PNIPA in Nanocomposite Hydrogels**

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The coil-to-globule transition of polymer chains caused by external stimuli, such as temperature, pH, pressure, solute, or solvent, is one of the most interesting properties in polymer science, and a polymer that undergoes this transition is referred to as a stimuli-responsive polymer. For example, poly(*N*-isopropylacrylamide) (PNIPA) is the most typical stimuli-responsive polymer and exhibits a well-defined coil-to-globule transition in aqueous media at its lower critical solution temperature (LCST $\approx$ 32 °C).[1] To utilize the coil-to-globule transition effectively, PNIPA is mainly used in the form of polymeric hydrogels, which consist of three-dimensional polymer networks highly swollen with large quantities of water. As PNIPA hydrogels can exhibit many characteristic changes in their properties owing to the coil-to-globule transition, such as swelling/deswelling, absorption/desorption, transparency (transparent/opaque), and surface hydrophilicity (hydrophilic/hydrophobic),[2–5] they have increased importance as advanced soft materials, such as smart gels (e.g. photoresponsive gels),[6] enzyme carriers,[7] colloid crystals,[8] separation devices,[9] drug-delivery systems (e.g. glucose-responsive insulin-releasing gels),[10] and biocompatible materials in tissue engineering (e.g. cell-cultivation substrates, scaffolds).[11] So far, it has been desired to control the stimuli-sensitivity of PNIPA hydrogels over a wide range. However, substantial control of the coil-to-globule transition of PNIPA has not been reported.

In previous studies, the inherent mechanical weakness of polymeric, including PNIPA, hydrogels was an unavoidable problem and there were constant efforts to overcome this.[12] Recently, we proposed a new type of hydrogel, nanocomposite hydrogels (NC gels), which consist of poly(*N*-alkylacrylamides) and inorganic clay.[13] As a result of their unique organic–inorganic network structure, which consists of exfoliated clay platelets uniformly dispersed in an aqueous medium with a number of flexible polymer chains linking them together, NC gels simultaneously solved all of the problems concerning the optical, mechanical, and swelling/deswelling properties associated with conventional, chemi-

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PNIPA = poly(*N*-isopropylacrylamide).

cally cross-linked PNIPA hydrogels (OR gels).[14–17] NC gels are anticipated to be promising hydrogels with possibly the most extensive control over both mechanical properties and stimuli-sensitivity. By using NC gels, reversible force generation as a result of the coil-to-globule transition of PNIPA chains was observed for the first time in response to alternating the temperature across the LCST.[18] Additionally, NC gels exhibit many interesting functions such as the formation of unique porous morphologies with a three-layered structure in the freeze-dried state,[19] characteristic sliding frictional behavior with remarkable changes in the coefficient of friction at the surface of the NC gel,[20] and biocompatibility (including implantation, antithrombogenicity, etc).[21] Herein, we report the first observation of total control over the coil-to-globule transition of PNIPA chains by inorganic (clay) nanoparticles and the achievement of strikingly ultrahigh mechanical properties such as the strength, elongation, and fracture energies of NC gels.

Synthetic hectorite ($[Mg_{5.34}Li_{0.66}Si_8O_{20}(OH)_4]Na_{0.66}$; layer size $\approx 30\,nm \varnothing \times 1\,nm$, cation-exchange capacity: 104 meq/100 g) was used as the inorganic clay after washing and freeze-drying. Sample codes for NC gels (NC*c*)are defined by the concentration of clay (c_{clay}) on a molar basis in their as-prepared states: for example, NC5 gel indicates 5×10^{-2} moles of clay (38.1 g) in 1 L of H_2O. Here, c_{clay} was varied over a wide range from 1×10^{-2} mole (NC1) to 20×10^{-2} mole (NC20), while the concentration of the monomer, NIPA, was fixed at 1 mol L^{-1} in H_2O. The synthetic procedure for formation of the NC gels is almost the same as that reported previously,[17] except for the mixing process used to prepare the reaction solution. In the present study, mixing by combined rotation and revolution was used to overcome difficulties in forming uniform dispersions of clay, initiator, and catalyst at high contents of clay. Thus, throughout the range of c_{clay} used, uniform dispersion was achieved by controlling the mixing conditions, including the temperature (1–35 °C). Next, free-radical polymerization in situ was performed at 20 °C for 20 h. As yields for polymerization were almost 100 % for all NC gels, the composition of the NC gel was virtually the same as that of the corresponding initial solution.

The resulting NC gels were all uniform and mostly transparent regardless of the concentration of clay (Figure 1 a), although conventional OR gels became totally opaque when the concentration of organic cross-linker (*N*,*N*′-methylenebis(acrylamide); BIS) exceeded 5 mol % relative to NIPA (Figure 1 b). All NC gels were mechanically very tough, although they differed greatly in softness depending on the content of clay. Figure 1 a shows a soft NC5 hydrogel which was readily deformed on compression, while the NC20 gel could hardly be deformed by hand. Here, the deformation of NC5 gel was almost totally reversible, and all NC gels including NC5 and NC20 gels did not break during the compression tests. Figure 2 a shows tensile stress versus strain curves for NC5, NC10, NC15, NC18, and NC20 gels. It is seen that both the initial modulus of elasticity (E_i) and the tensile strength (σ) increase monotonically with increasing values of c_{clay}. NC20 gel exhibits a tensile strength of nearly 1000 kPa, an E_i value of 400 kPa, and approximately 1000 % elongation at break—these are the highest tensile properties by far ever reported for polymeric hydrogels and are comparable to those of pristine styrene–butadiene rubber.[22]

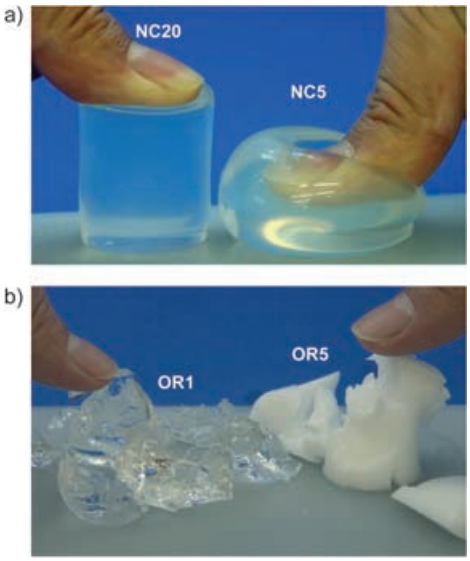

Figure 1. a) NC5 and NC20 gels with high transparencies exhibit differing degrees of softness. Both NC gels did not rupture under repeated compressions by hand. b) OR gels with different transparencies, transparent OR1 and opaque OR5, are both very brittle under compression.

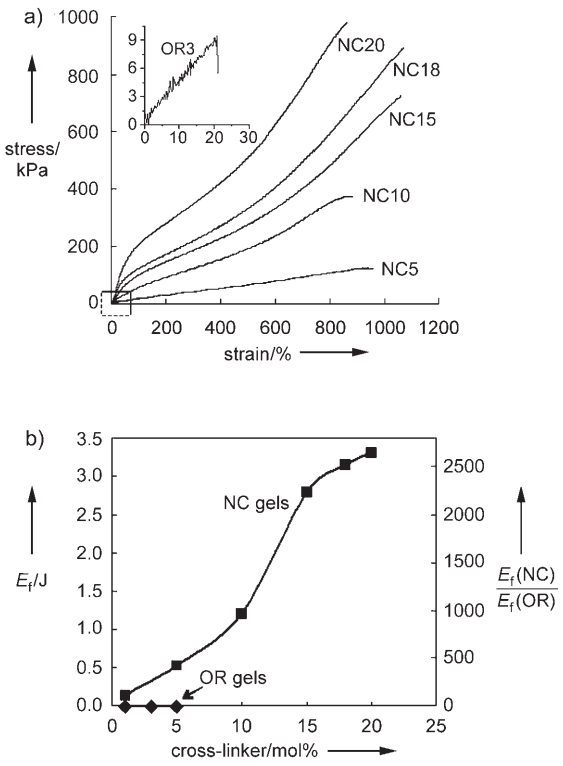

Figure 2. a) Tensile stress versus strain curves for NC gels with different contents of clay (NC5–NC20). The inset shows a magnified view of the dotted box at the origin, with the curve for OR3 gel. b) Fracture energies (E_f) for the gels and ratios of E_f for NC/OR gels as functions of the amount of cross-linker.

If the high water content (ca. 80–90 wt %) of NC gels is taken into account, this is quite a striking result. Also, in most solid polymers, whether they are linear or cross-linked, it is a common feature that the fracture strain ε_f decreases inversely in proportion to E_i.[23] However, in the case of NC gels, ε_f was maintained at a high value (ca. 1000 %) despite large increases in the initial modulus of elasticity, E_i. Contrary to this, as shown in Figure 1b (under compression) and Figure 2a (under elongation), OR gels show a very brittle mechanical nature and the brittleness changes little with a varying content of cross-linker. Note that OR gels have the same composition (water and PNIPA) as NC gels except for the difference in cross-linker. The fracture energy for each NC and OR gel was calculated from the areas under the stress–strain curves. The fracture energies (E_f) of NC gels and their dependence on c_{clay} are shown in Figure 2b relative to those of OR gels. The fracture energies of OR gels are almost the same, regardless of the content of BIS cross-linker (the average value for OR1, OR3, and OR5 gels is used in Figure 2b). It is also striking that the fracture energy of NC20 gel could be as much as 2650-times higher than that of the OR gel. All these advantageous results may be ascribed to the unique organic–inorganic network structure[13–15] of NC gels in which the density of cross-links was controlled without sacrificing the large extensional capability of its constituent polymer chains.

We previously reported that NC gels show a distinct change in transparency across the LCST as a result of the coil-to-globule transition.[13,14] In the present study, we found that decreases in transparency at the LCST varied dramatically with the concentration of clay, as shown in Figure 3a; that is, the loss in transparency gradually decreased as c_{clay} increased until, finally, at c_{clay} values greater than 15×10^{-2} mol L^{-1}, there was no loss in transparency and gels remained transparent regardless of the temperature. Figure 3b shows NC5 and NC15 gels that exhibit different transparency behaviors at ambient temperature (upper, 20 °C) and in hot water (lower, 50 °C). The NC15 gel did not change its transparency but retained a high transmittance regardless of the surrounding temperature. In contrast, NC5 gel showed an abrupt change, as previously reported, between transparent and opaque by alternating the temperature across the LCST. The results shown in Figure 3a,b indicate that the thermal molecular motion of PNIPA chains was completely restricted in NC gels with c_{clay} greater than 15×10^{-2} mol L^{-1}, and, consequently, the thermosensitivity was totally depressed in NC gels with such high concentrations of clay. The molecular restriction of PNIPA chains in NC gels was attributed to restriction by exfoliated clay platelets incorporated in NC gels. As the clay platelets (hectorite) are strongly hydrophilic, the conformational change from coil (hydrophilic) to globular (hydrophobic) form may be hindered in PNIPA chains attached to clay surfaces or lying close to them. This is the first observation of complete control over the coil-to-globule transition of PNIPA chains by inorganic nanoparticles. Note that through interactions with clay platelets, the thermal molecular motions (associated with the transition between random-coil and globular forms) of PNIPA chains towards the globular form are hindered despite the increasing temperature. At the same time, PNIPA chains adopt random conformations amongst the clay platelets so that large reversible deformations are possible on applying external stresses as shown in Figure 2a.

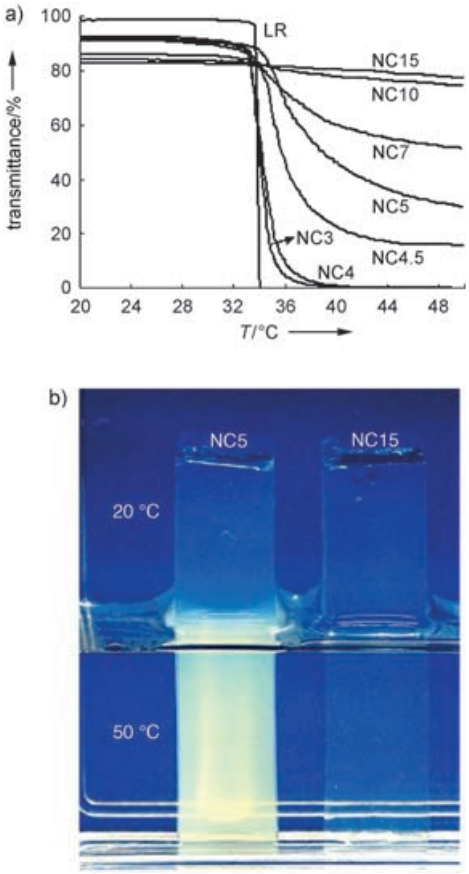

Figure 3. a) Temperature dependence of the optical transmittance for a linear polymer (LR) and NC gels with different c_{clay}. b) Transparency of NC5 and NC15 gels below (in air: upper) and above the LCST (in water: lower). The observed change in transparency for NC5 gel was not observed for NC15 gel (its transparency was maintained upon heating).

Concerning the swelling in water, all NC gels swell to equilibrium at 20 °C (< LCST) and their swelling markedly decreases with increasing concentrations of clay. These results clearly indicate that clay platelets act as an effective cross-linking agent in NC gels over the whole range of c_{clay}. At temperatures above the LCST, we previously found that NC gels exhibit very rapid deswelling (volume contraction) compared with OR gels; for example, an NC1 gel took less than 10 minutes to reach equilibrium, although an OR1 gel took more than 1 month.[14] This result was attributed to the rapid dehydration of flexible PNIPA chains, including grafts, in organic–inorganic networks of NC gels. For NC gels with high concentrations of clay, as the conformational change of PNIPA chains was substantially restricted as described above, it is expected that the deswelling behavior may also be depressed. As shown in Figure 4a, deswelling was decreased markedly with increasing c_{clay} values, and for NC gels with c_{clay} values greater than that for NC12 no contraction of volume

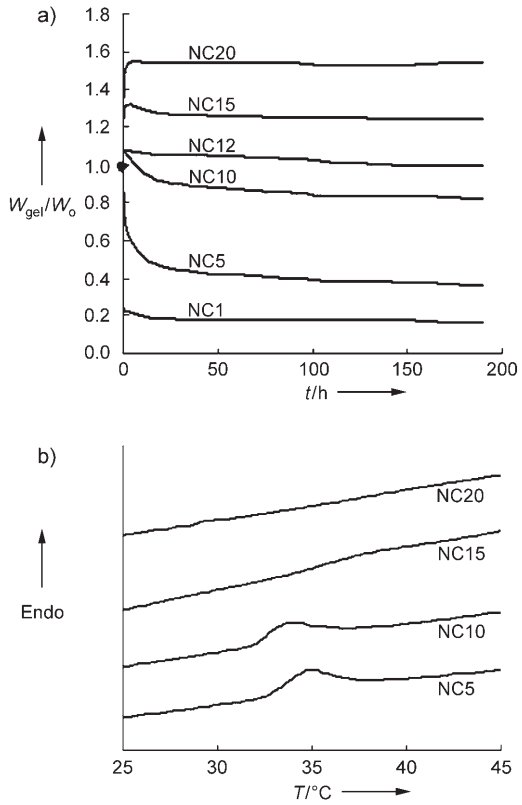

Figure 4. a) Deswelling kinetics (at 50 °C) for NC gels with different c_{clay} values. W_o is the weight of each initial (as-prepared) gel; W_{gel} is the weight of the swollen hydrogel. b) Heats for the coil-to-globule transition measured by DSC for NC gels with different contents of clay. The transition peak disappeared for NC gels with a concentration of clay greater than that for NC15.

was observed. Instead, NC gels simply swelled, even at 50 °C (> LCST). Here, PNIPA behaves like a hydrophilic polymer without exhibiting a thermosensitive transition. Thus, the volume changes (due to either swelling or deswelling) of NC gels can be controlled greatly by altering c_{clay} over a wide range. From the variations in both swelling and deswelling, it is expected that certain NC gels with high concentrations of clay will maintain a stable volume in water regardless of the temperature.

All the results herein, particularly the superior mechanical properties and good transparencies, indicate that the unique organic–inorganic network structure is retained even for NC gels with high concentrations of clay. However, from the results of suppressed thermosensitivities of transparency and swelling/deswelling it was concluded that PNIPA chains are subject to steric hindrance by clay platelets and that finally the coil-to-globule transition is prohibited at sufficiently high c_{clay} values. This conclusion was confirmed by differential scanning calorimetric (DSC) measurements for NC gels with various concentrations of clay (Figure 4b). The heat change associated with the coil-to-globule transition in the gel state decreased with increasing c_{clay} and disappeared at c_{clay} values greater than that for NC15. Also, from measurements on dried NC gels it was found that the change in heat capacity at the glass transition temperature ($\approx$142 °C) decreased with increasing c_{clay} values, and by analogy with the coil-to-globule transition in the gel state the glass transition in the dried state due to the micro Brownian motion of PNIPA disappeared at c_{clay} values greater than that for NC15. These phenomena are specific to NC gels and are totally different from those of OR gels, which become opaque at high contents of BIS as a result of the formation of inhomogeneous networks.

In conclusion, we have presented the extraordinarily high strength and high fracture energy of polymeric hydrogels (NC gels) as well as complete control over the coil-to-globule transition in PNIPA chains, in terms of transparency and swelling/deswelling, by inorganic clay nanoparticles. In comparison with conventional rubbers (e.g. styrene–butadiene rubber) that consist of 100% organic polymers, NC gels comprise mostly water (80—90 wt%) and are also essentially nonflammable without the need for any harmful halogen or phosphorus additives. Thus, NC gels can be referred to as truly environmentally friendly soft materials, from both production and disposal viewpoints. By recognizing the control over mechanical and functional properties as reported here, NC gels may lead to new horizons in the fields of advanced research and technologies.

Experimental Section

Synthesis of NC gels with high clay contents: The inorganic clay "Laponite XLG" (Rockwood Ltd., UK) and NIPA monomer were used after purification. The synthetic procedure for NC gels with low concentrations of clay ($c_{clay} \leq 5 \times 10^{-2}$ mol L^{-1}) is the same as that reported previously.[17] For NC gels with high concentrations of clay ($c_{clay} \geq 10 \times 10^{-2}$ mol L^{-1}), the experimental procedure differed in the preparation of the initial reaction solution: For example, for NC20 gel only a part of the clay was used at first and a transparent aqueous solution consisting of water (19 mL), NIPA (2.26 g), and inorganic clay (0.76 g) was prepared by normal magnetic stirring. Next, the remainder of clay (2.29 g) was added to the aqueous solution while stirring at 1 °C and subsequently heating to 35 °C and then cooling again to 1 °C, to avoid flocculation and to accelerate dispersion. Then, to achieve the exfoliation of clay and the good dispersion of all components, the solution was further mixed at 1–5 °C for 30 minutes by utilizing two combinations of rotation and revolution (800/2000 rpm and 60/2200 rpm). The mixtures were subsequently mixed for further periods of 1 minute each after the addition of initiator and catalyst. The amount of clay was varied from 0.152 g to 3.05 g. The concentration of monomer (NIPA) was fixed at 1 mol L^{-1} in H_2O, and the molar ratios of monomer, initiator (potassium persulfate), and catalyst (*N*,*N*,*N*′,*N*′-tetramethylethylenediamine) were fixed at 100:0.426:0.735, respectively. Then, free-radical polymerization in situ was allowed to proceed in a water bath at 20 °C for 20 h. Throughout all experiments, oxygen was excluded from the system. Meanwhile, OR1 and OR5 gels were prepared using NIPA (2.26 g, 1 mol L^{-1} in H_2O) and the organic cross-linker *N*,*N*′-methylenebis-(acrylamide) (BIS; 0.028 g, 1 mol%, or 0.140 g, 5 mol%, respectively) instead of clay.

Measurements: Swelling and deswelling experiments were performed by immersing as-prepared gels (initial size: 5.5 mm diameter × 30 mm long) in a large excess of water for approximately 200 h at 20 and 50 °C, respectively, and changing the water several times. Swelling and deswelling ratios are represented as the ratios of weights of the swollen hydrogel (W_{gel}) to the corresponding dried gel (W_{dry}). Tensile mechanical measurements were performed on as-prepared NC and OR gels of the same size (5.5 mm diameter × 70 mm long) using a Shimadzu Autograph AGS-H under the following conditions: 25 °C; gauge length: 30 mm; cross-head speed: 100 mm min^{-1}. The initial

cross section (23.75 mm^2) and loads detected between elongations of 10% and 50% were used to calculate the tensile strengths (σ) and the initial modulus of elasticity (E_i). Thermogravimetric analyses were conducted using a TG/DTA 220 (Seiko Denshi Ind. Inc.) instrument, by heating samples from 30°C to 1000°C at a heating rate of 10°C min^{-1} in an air flow. DSC measurements were performed using a Perkin–Elmer DSC-7 apparatus in a nitrogen atmosphere for NC gels and milled dried gels, with heating from −50 to 60°C and from 30 to 250°C, respectively, at a heating rate of 10°C min^{-1}.

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