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Smart Hydrogels

Supramolecular Controlled Water Uptake of Macroscopic Materials by a Cyclodextrin-Induced Hydrophobic-to-Hydrophilic Transition

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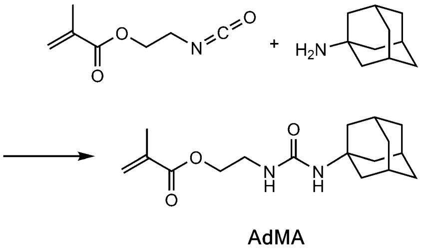
The noncovalent dynamic interactions of double-helical DNA are the basis of human life.[1] Furthermore, supramolecular connected structures of, for example, hyaluronic acids are the origin of the elasticity of human tissue and of the vitreous of the eye.[2–4] Thus, bioinspired developments of artificial soft materials, such as gels, are of increasing interest for medical applications and hygiene items. Of great importance in this field are covalently cross-linked polyacrylic acids which are the basic material of the widely used superabsorbent polymers for water.[5] The water uptake of hydrophilic synthetic materials is dependent on the cross-linking density and the chemical structure of the polymer. The degree of swelling is a function of different external parameters, such as temperature, pH value, light or foreign salt. These parameters are the basis for the development of so called smart materials.[6,7] Note that noncovalently cross-linked gels, cross-linked through van der Waals interactions, are also known. In some cases, this type of physical cross-linking can be decreased by complexation with cyclodextrin.[8–11]

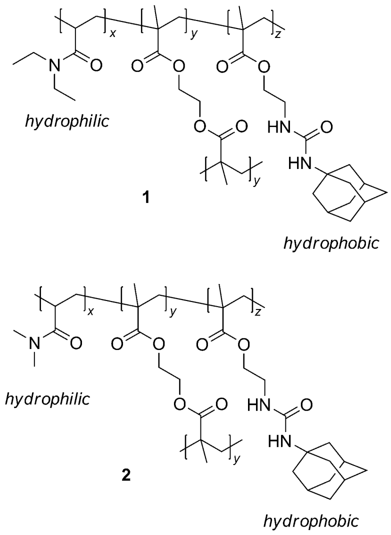
The supramolecular interaction of macromolecules with cyclodextrin is the subject of numerous of papers that appeared in recent decades describing the use of cyclodextrin in polymer chemistry for example, for gel-to-gel attraction in the mm scale[12] or for the transition of nanogel-like micelles to nanovesicles.[13]

To date, the control of swelling of macroscopic soft materials on the cm scale by use of cyclodextrin has not been investigated. Herein we describe for the first time a novel and simple way to create smart gels that are triggered by cyclodextrin-based host–guest effects. Moreover, we describe the swelling behavior and a shape-memory effect of a switchable hydrophilic material of unlimited dimensions, preferentially in the cm region.

We began with the preparation of 2-(*N'*-(adamantan-1-yl)ureido)ethyl methacrylate (AdMA) which served as a hydrophobic co-monomer and as a potential guest moiety to prepare water swellable polymer networks (Scheme 1). Subsequently, disc-shaped samples consisting of the polymer network **1**, with different molar ratios (Scheme 2) were prepared by free radical polymerization. The molar fraction of the cross-linker ethylene glycol dimethacrylate was kept constant at 0.5 mol% throughout this study.



Scheme 1. Synthesis of the adamantyl-bearing monomer AdMA.



Scheme 2. Adamantyl-modified water-swellable polymer networks.

The samples were swollen in water or aqueous solutions of randomly methylated β-CD (CD) to examine the dependence of the equilibrium swelling ratio on the molar fraction of the incorporated hydrophobic AdMA-co-monomer and the influence of CD on the covalently cross-linked systems (Figure 1). As expected, the samples showed a decreasing swelling ratio in water with an increasing amount of incorporated hydrophobic AdMA. Up to a molar fraction of about 10 mol%, this hydrophobic effect of incorporated AdMA was successfully suppressed by using an aqueous CD solution ($c = 50\ \mathrm{g\,L^{-1}}$) instead of pure water (Figure 2).

Through the formation of hydrophilic adamantyl–CD complexes, the original hydrophobic domains disappeared (Figure 1) which means that a hydrophobic-to-hydrophilic transition of the gel took place. Accordingly, the materials were able to absorb water and to expand drastically. At higher

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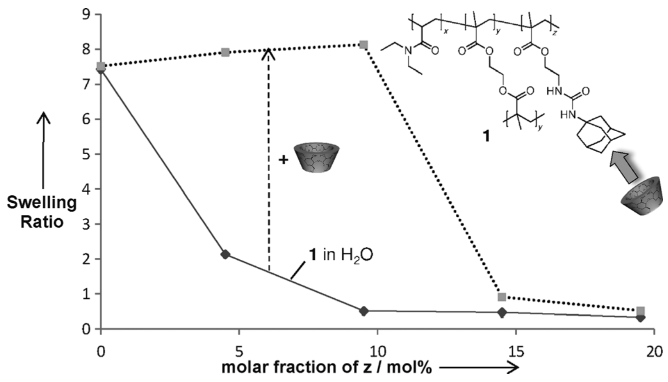

Figure 1. Swelling ratios of disc-shaped samples of **1** at different molar fractions of the adamantyl-bearing co-monomer AdMA with a constant fraction of $y=0.5$ mol% at room temperature in water and in aqueous CD solution ($c=50\,\mathrm{g\,L^{-1}}$). The swelling ratio is the ratio of the weight of the absorbed water to the weight of the dry polymer.

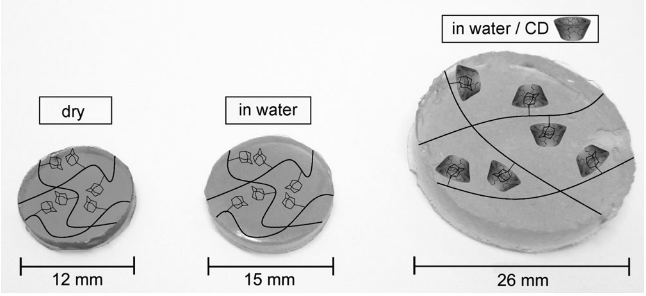

Figure 2. Photographs and scheme of the swelling in water and aqueous CD solution of the disc-shaped polymer samples. For visualization, a spatula tip of copper phthalocyanine was added to the monomer mixture before the polymerization to give the blue color. The polymer samples consist of network **1** with a molar ratio $x/y/z$ of 90/0.5/9.5.

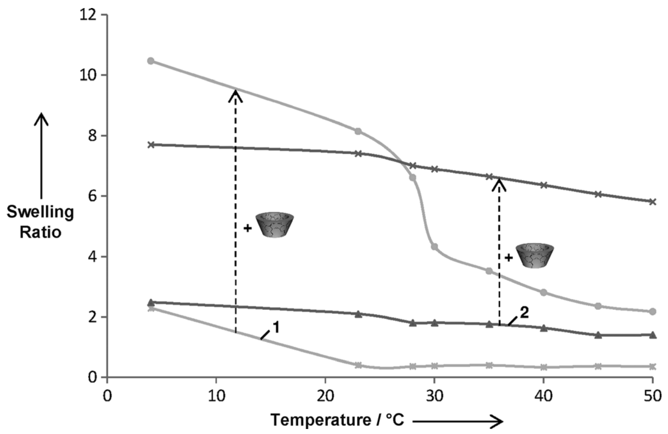

Figure 3. Swelling ratios of polymer samples of **1** and **2** in water and CD solution at temperatures from 4 to 50 °C.

molar fractions of the hydrophobic co-monomer AdMA the hydrophobic-to-hydrophilic transition could not be observed. The swelling in α-cyclodextrin solution showed no significant enhancement compared to the swelling in water (see Supporting Information). Accordingly, in this case the physical cross-linking of the hydrophobic adamantyl-groups is not influenced by the smaller α-cyclodextrin.

In addition to the determination of the swelling ratios of the samples of **1** with the different molar ratios that are shown in Figure 1, we measured their rheological behavior in the linear viscoelastic region (see Supporting Information). In all the samples the elastic character dominated over the viscous character ($G' > G''$) which complies with gel-like structures. The results of the rheological experiments show the addition of CD causes an increase in the elastic character and thus a decrease in the physical cross-link density. This confirms the results obtained by the swelling experiments.

We evaluated the temperature dependence of the swelling ratio caused by host–guest interactions. Since the host–guest equilibrium constant depends on temperature, an increased loss of CD from the polymer-bound hydrophobic adamantyl moieties was expected with increasing temperature. Disc shaped samples consisting of polymers **1** and **2** with constant molar ratios were prepared and immersed into water or aqueous CD solutions at different temperatures. All the samples showed an exothermic swelling behavior, which means that less swelling occurs at higher temperatures (Figure 3).[14] The effect of the inclusion-complex-driven swelling changes also appeared in a temperature range from 4 °C to 50 °C for all the samples. The swelling ratio of **1** in CD solution was far superior compared to the swelling in water. This observation is consistent with the previous results (Figure 1). In addition, poly(*N,N*-diethylacrylamide) shows a lower critical solution temperature (LCST) in water which results in a phase transition at temperatures between 25 and 36 °C.[15] Accordingly, a transition in the swelling behavior of a cross-linked material consisting of *N,N*-diethylacrylamide, such as **1**, is expected around the LCST value of the corresponding homopolymers. Owing to the hydrophobic effect[16] of the AdMA-co-monomer, the LCST of **1** in water is lowered below room temperature. After immersion in CD solution, not only the swelling ratio is significantly enhanced compared to the swelling in water, but also the LCST is increased to approximately 29 °C. A far superior swelling ratio could also be observed for **2** in CD solution compared to the swelling in water over the whole temperature range. A loss of the inclusion-complex-driven swelling superiority could not be observed at temperatures up to 50 °C.

Thus, in hydrophilic polymer networks, a strong complex dependency of the swelling ratio was realized. The added CD served as a host and the polymer-bound adamantyl moiety as a guest. For comparison, hydrophilic model networks of **1** and **2** without the AdMA-co-monomer were prepared which indicated no influence of CD on their temperature-dependent swelling behavior (see Supporting Information).

A subcategory of smart materials is represented by the shape-memory polymers. Their principles and functionalities have been described thoroughly in literature.[17] Some hydrogels with crystallizable side chains show a thermoresponsive shape-memory effect.[18–22] The results of the swelling experiments with the polymer networks **1** and **2** were extended to realize an inclusion-complex-driven one-way shape-memory effect. Therefore, materials of **1** were prepared on the 5 cm

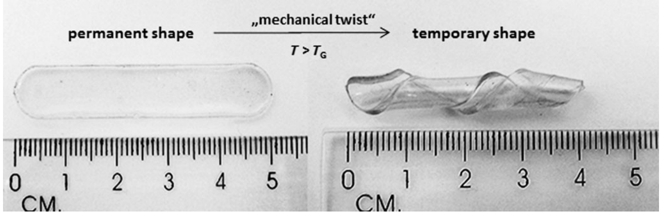

Figure 4. 5 cm samples of **1** in the permanent shape and in the temporary shape after heating above T_G and subsequent mechanical deformation.

scale and "programmed" as shape-memory polymers by heating above the glass-transition temperature (T_G) to 60 °C followed by a mechanical twisting (Figure 4). The twisted samples were cooled to room temperature to keep the temporary shape. After being programmed as a shape-memory polymer and immersion in water and CD solution, a difference in the relaxation progresses of the samples was observed (Figure 5).

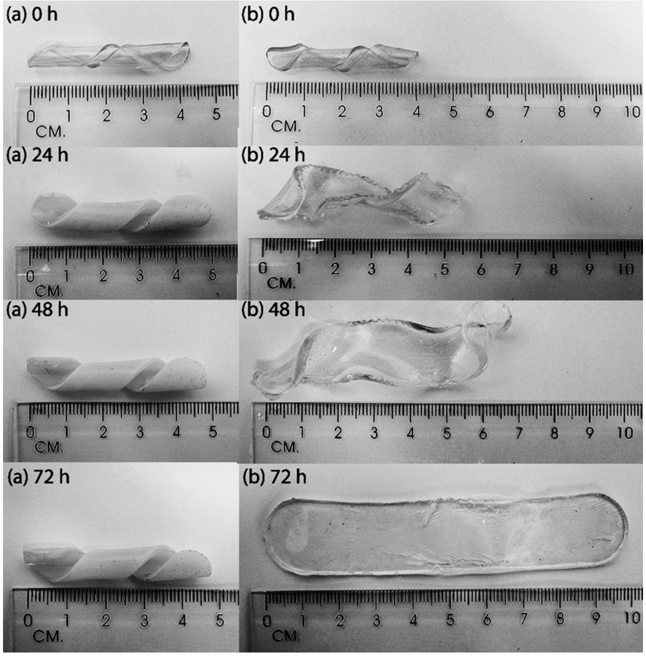

Figure 5. Relaxation of the programmed shape-memory polymer samples in water (a) and aqueous CD solution (b) over 72 h.

In presence of water, the sample largely maintained its twisted, temporary shape while undergoing only a slight swelling and becoming turbid. The slight swelling is complete after one day and the shape of the programmed sample is stable in water over at least 3 months. The turbidity of the sample is to be explained by the lowered LCST below room temperature (compare Figure 3). However, in aqueous CD solution a slow swelling and recovery of the original shape could be observed. This shape-memory effect takes approximately 3 days with the prepared samples. Again, the observed shape-memory effect in CD solution is a result of the formation of inclusion complexes. They allow water uptake into the network which allowed the network to relax and take its original shape in the highly swollen form.

It can be concluded from the results described above that we successfully implemented a new method to control the swelling of networks by the introduction of a hydrophobic guest into the network which can be switched to hydrophilic by a CD-host. Within the concept of "smart polymers" we have enabled a new stimulus to be used to influence the swelling of hydrogels. Possible applications for this concept lie in the field of biomedicine. Through de-/complexation of the non-hazardous CD in aqueous environment, the swelling of inclusion-sensitive polymer networks can be controlled and adjusted to the application.

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