A thermo-, photo- and chemo-responsive shape-memory material is successfully prepared by introducing \(\alpha\)-cyclodextrin \((\alpha\mathrm{CD})\) and azobenzene \((\text{Azo})\) into a poly(acrylate acid)/alginate \((\text{PAA}/\text{Alg})\) network. The tri-stimuli-responsive formation/dissociation of \(\alpha\mathrm{CD}\)-Azo acts as molecular switches freezing or increasing the molecular mobility. The resulting film herein can be processed into temporary shapes as needed and recovers its initial shape upon the application of light irradiation, heating, or chemical agent independently. Furthermore, the agar diffusion test suggests that the \(\alpha\)-CD-Alg/Azo-PAA has good biocompatibility for L929 fibroblast-like cells.

1. Introduction

In nature, shape deformation in response to environmental conditions is often found.\(^1\) For example, the morning glory flower blooms in the morning and closes around noon; the Venus flytrap closes after capturing prey.\(^2\) Shape-memory materials are a kind of responsive material, mimicking the systems found in nature, which have the capability to memorize one or many temporary shapes, while spontaneously recovering their original shapes upon the application of an external stimulus.\(^3,4\)

In principle, polymeric materials are endowed with shape-memory properties by two approaches. The first, and most common way is based on phase transition.\(^5-11\) A material having one or more reversible phase transitions can switch off or on the molecular mobility so as to freeze or release the temporary shape. The phase transitions are largely related to a thermal effect, therefore, the shape memory effect of these materials is triggered by direct or indirect heat (such as light, magnetic field, moisture, ultrasound, etc.).\(^12-15\) The second approach is to design molecular switches. Various reversible bonds (including reversible covalent bonding and supramolecular interaction) in response to different stimuli have been utilized for the construction of shape materials, bringing more options in terms of triggering stimulus.\(^16-20\)

So far, direct heating is the most common trigger, while other stimuli, like light, have attracted more and more interest due to the advantage of remote activation, as well as spatial and precise control. Generally, light-induced shape-memory effect is achieved via photothermal effect or photochemical reactions.\(^21\) The use of the photothermal effect requires the introduction of light-sensitive components, such as nanotubes, graphene oxide, gold particles, dyes and metal-ligand complexes
into the polymer matrix\textsuperscript{[22–24]} These fillers or additives are able to strongly absorb light and covert optical energy to heat. By choosing the appropriate light-absorbing filler, the light sensitive shape memory can be realized by light with different wavelengths. The main disadvantage of these methods is that high operating temperature is still unavoidable, although it is adverse in some applications. Constructing molecular switches based on reversible photochemical reactions is an efficient way to realized light-induced shape changes independent of heat.\textsuperscript{[25–27]} However, the number of utilized photo-induced reversible reaction for the design of shape memory materials is limited. Up to now, most related work is based on [2+2] cycloaddition of cinnamamide or cinnamate pendant groups. Almost all of these materials only respond to a single stimulus.

In this study, we explore a supramolecular interaction, host–guest interaction between α-cyclodextrin (α-CD) and azobenene (Azo) units, as a molecular switch for the construction of light-induced shape-memory material. A supramolecular material composed of Azo grafted on poly(acrylate acid) (Azo-PAA) and α-CD modified on Alginate (α-CD-Alg) was prepared using calcium chloride as crosslinking agent. It has been proven that the complexation between α-CD and Azo can be modulated by temperature, light or chemicals respectively.\textsuperscript{[28,29]} Therefore, the α-CD-Alg/Azo-PAA can be processed into a temporary shape as needed and recover its initial shape not only under UV irradiation, but also by heating, or the addition of competitive molecules. This capacity to respond to multiple stimuli independently expands the application potential of the material. Furthermore, the agar diffusion test suggested that the α-CD-Alg/Azo-PAA has good biocompatibility for L929 fibroblast-like cells.

2. Results and Discussion

2.1. Preparation of αCD-Alg/Azo-PAA Film

In principle, shape memory polymer should consist of two phases: a stable fixing phase determining the permanent shape, and a switching phase for temporary shape fixing and recovery. Normally, the fixing phase can be a molecular entanglement, crosslinked network, crystalline phase, or interpenetrated network and the switching transition can be an amorphous/glass transition, crystallization/melting transition, reversible molecular crosslinking, and supramolecular association/disassociation.\textsuperscript{[12,16,17,30–33]} In this study, we designed an αCD-Alg/Azo-PAA film which contained two kinds of phases: crosslinking between carboxyl groups and Ca\textsuperscript{2+} as the fixing phase and crosslinking between αCD and Azo as switching phase.

αCD-Alg and Azo-PAA were synthesized separately. Figure S1 (Supporting Information) shows the \textsuperscript{1}H NMR spectrum of αCD-Alg. Characteristic chemical shifts of both CD and Alg can be found. From the integrated peak area (S1) of H-1 of CD and the integrated peak area (S2) from 3.95 to 3.45, the degree of substitution (DS) could be calculated by the following relationship: DS = (S1/6)/[(S2 − 6S1)/4] = 35.5%. Figure S2 (Supporting Information) shows the \textsuperscript{1}H NMR spectrum of Azo-PAA. As the product was difficult to dissolve in water, we adjusted the pH value of D\textsubscript{2}O to alkaline pH before measurement. From the integrated peak area (S1) of H of Azo and the integrated peak area (S2) from 2.6 to 1.2, the DS could be calculated by the following relationship: DS = (S1/9)/(S2/3) = 17.6%.

It has been reported that αCD could form an inclusion complex with trans-Azo in visible light.\textsuperscript{[34,35]} In order to confirm that αCD and Azo could perform in the same way after grafted onto polymer, the 2D \textsuperscript{1}H NOESY NMR was measured to explore the interaction of αCD and Azo moieties in the supramolecular film. As shown in Figure 1, αCD-Alg/Azo-PAA showed obvious correlation between Azo and αCD protons, suggesting that the trans-Azo threaded through the cavity of αCD indeed. To further confirm that the correlation was due to interactions of αCD-Azo, we also performed 2D \textsuperscript{1}H NOESY NMR of αCD-Alg/Azo-PAA after the irradiation of UV light. It is known that Azo derivatives are isomerized from trans to cis under UV irradiation, as a result, αCD-Azo dissociates because of the mismatch between the αCD and cis-Azo.\textsuperscript{[36–38]} As shown in Figure S3 (Supporting Information), the related signal disappeared completely, indicating the dissociation of αCD-Azo.

2.2. The Swelling Behavior and the Mechanical Property

In order to further confirm that the existence of the αCD-Azo switches, we investigated the swelling ability and mechanical properties of the αCD-Alg/Azo-PAA film after treated with ultraviolet irradiation or visible light.

2.2.1. The Swelling Behavior

Table 1 showed the swelling degree of the αCD-Alg/Azo-PAA film in different conditions. The swelling degree of film under ultraviolet light irradiation was obviously higher than that under visible light irradiation. It is known that the swelling degree of hydrogel is closely related to its crosslink density. These results indicated that the UV irradiation resulted in a decreased crosslink density of αCD-Alg/Azo-PAA film, which attributed to the dissociation of αCD-Azo. It has been reported that
the CD could act as competitive molecules, causing the dissociation of the host–guest inclusion complexes in polymer matrix. It can be seen that immersing the αCD-Alg/Azo-PAA film in the aqueous solution of αCD resulted in higher swelling indeed. The swelling degree was even higher than that under UV irradiation (reaching 193 %), which may be owed to good permeability of small molecules resulting in the completely dissociation of αCD-Azo.

2.2.2. The Mechanical Property

The mechanical properties of αCD-Alg/Azo-PAA film were also different before and after UV irradiation. As shown in Figure S4 (Supporting Information), the elastic modulus and the elongation at break of the film treated with ultraviolet irradiation for 1h were 3.85 MPa and 36.96%, respectively. Nevertheless, the corresponding values for the film under visible light were 6.11 MPa and 24.92%, respectively. These results indicated that UV irradiation reduced the elastic modulus and increased the elongation at break of the αCD-Alg/Azo-PAA film, which suggested that the formation of αCD-Azo served as crosslinking and reinforced the material.

2.3. Shape Memory Behavior

2.3.1. Photoresponsive Shape Memory Properties

The association/dissociation of αCD-Azo in response to light endows the αCD-Alg/Azo-PAA film light-induced shape memory effect. As shown in Figure 2, the film was a straight strip before it was deformed (Figure 2a). It was deformed into a circle in a mould and irradiated by UV

Table 1. The swelling degree of αCD-Alg/Azo-PAA film in different conditions.

|                         | In visible light | After irradiation of UV | In aqueous solution of αCD |
|-------------------------|-----------------|-------------------------|---------------------------|
| Swelling degree [%]     | 103             | 124                     | 193                       |

Figure 1. 2D 1H NOESY NMR spectrum of the mixture of αCD-Alg and Azo-PAA in D₂O after the irradiation of visible light.
light for 1 h, and then irradiated by visible light for 3 h to fix the deformed shape (Figure 2b). After removing from the mould, the film recovered its shape to some extent and eventually formed its temporary shape (Figure 2c). The fixity ratio ($R_f$) was (57.75 ± 5.55)%. When the deformed film was irradiated by UV again, it recovered its original shape (Figure 2d). The shape recovery ratio ($R_r$) was (90.25 ± 3.05)% $R_f$ was relative low, which probably be due to the incomplete reformation of $\alpha$CD-Azo. This phenomenon was also observed in other light-induced shape memory materials based on reversible molecular switches.\cite{25}

2.3.2. Temperature Responsive Shape Memory Behavior

Figure 3e showed the dynamic mechanical analysis (DMA) results of $\alpha$CD-Alg/Azo-PAA film. Intriguingly, two transitions were present. In 2012, Voit etc. reported a system of acrylic shape memory polymers comprised of both permanent covalent crosslinks and supramolecular hydrogen bonding crosslinks, which also showed similar two thermal transitions.\cite{39} The glass transition temperature ($T_g$) of polymer chains and dissociation of hydrogen bonding moieties were supposed to contribute to these thermal transitions. In our case, the dissociation of $\alpha$CD-Azo could be triggered not only by light but heating too.\cite{29} Therefore, combination of glass transition of polymeric chains and the dissociation of $\alpha$CD-Azo can endow multithermal transitions and broaden the application area of the material. The $\alpha$CD-Alg/Azo-PAA film showed thermo-induced shape memory behavior like that light-induced behavior. As shown in Figure 3a, the original shape of the $\alpha$CD-Alg/Azo-PAA film was straight strip. After being immersed in water at 80 °C for 10 min, it was bent to a “U” shape by external stress and moved in water at 4 °C (Figure 3b) for 30 min. When the external stress was released, the sample kept the “U” shape to a large extent, 30 min later (Figure 3c). The $R_f$ was (70.34 ± 4.8)%. When the sample was immersed in water at 80 °C again, it recovered its original shape in 30 min (Figure 3d). The $R_r$ measured was (74.82 ± 2.18)%. 

Figure 2. The photoresponsive shape memory effect of $\alpha$CD-Alg/Azo-PAA film. a) Original shape. b) Deformed shape. c) Temporary shape. d) Recovered shape.

Figure 3. The temperature-responsive shape memory effect of $\alpha$CD-Alg/Azo-PAA film. a) Original shape. b) Deformed shape. c) Temporary shape. d) Recovered shape. e) DMA curve of the $\alpha$CD-Alg/Azo-PAA film.
The $R_s$ of thermo-induced shape memory effect was a little lower than that of photo-induced effect, which may be due to the incomplete dissociation of $\alpha$CD-Azo at high temperature. It should be noted that the $\alpha$CD-Alg/Azo-PAA film did not show triple shape memory effect as we expected although it had two thermal transitions, which was probably because two transition temperatures were too close.

2.3.3. Chemoresponsive Shape Recovery Behavior

The reversible association/dissociation between $\alpha$CD and Azo was critical for the shape memory effect of $\alpha$CD-Alg/Azo-PAA film. Conceptually any chemical that can dissociate $\alpha$CD-Azo could be used to induce shape memory properties.

Harada’s group has demonstrated that, the addition of competitive host or guest molecules could hinder the formation of inclusion complexes between guest and CD moieties in polymer chains due to the good mobility of small molecules.\(^{[38]}\) Therefore, we selected $\alpha$CD as competitive hosts to investigate the chemoresponsive shape memory behavior of $\alpha$CD-Alg/Azo-PAA film in this study. Figure S5 (Supporting Information) shows the shape memory behavior of $\alpha$CD-Alg/Azo-PAA film in the present of $\alpha$CD. The original permanent shape was straight as shown in Figure S5a (Supporting Information). It was fixed into a temporary shape U as shown in Figure S5c (Supporting Information) after exposure to ultraviolet light and visible light in sequence. Then, the deformed sample was put into aqueous solution containing $\alpha$CD. It can be seen that the shape recovered nearly 100% (Figure S5d, Supporting Information). This shape recovery process was much faster than that in the condition of ultraviolet light irradiation due to good permeability of small molecules into the polymer matrix.

2.3.4. Proposed Mechanism

The mechanism of the shape memory behavior of $\alpha$CD-Alg/Azo-PAA film was proposed to be as follows (Figure 4). In molecular level, $\alpha$CD-Alg/Azo-PAA film consists of two phases: crosslinking between carboxyl groups and Ca\(^{2+}\) as the fixing phase and $\alpha$CD-Azo inclusion complexes as the switching phase. When the $\alpha$CD-Azo switched off (Azo included in $\alpha$CD cavity forming inclusion complexes), the material was rigid and hard to be deformed. As the $\alpha$CD-Azo switched on (Azo excluded in $\alpha$CD cavity) in response to UV light, heat or competitive small molecules, the material became soft and readily deformable by application of an external stress. On switching off the $\alpha$CD-Azo (reformation of $\alpha$CD-Azo) under external stress, the deformed shape was fixed partially. Once the $\alpha$CD-Azo was switched on under stimulus again, disappearance of the strength of the “frozen deformation” resulted in the shape recovery. As the switch on/off of the $\alpha$CD-Azo could be modulated by light, temperature or chemicals respectively, the $\alpha$CD-Alg/Azo-PAA film showed shape-memory effect in response to these stimuli independently.
2.4. In Vitro Evaluation of the Biocompatibility of the Shape Memory Membrane

As the biocompatibility is very important for the biomedical and biotechnological applications, the biocompatibility of the shape memory film was investigated. We test the cytotoxicity by using the classic method of agar diffusion test. The result is shown in Figure S6 (Supporting Information), cells under the film (Figure S6c, Supporting Information) showed a well-spread morphology and were uniformly stained, like the cells cultured under the negative control (Figure S6b, Supporting Information). However, the positive control tests (Figure S6a, Supporting Information) showed clearly lysis and a decolorizing zone. These results indicated that the film has good biocompatibility for L929 fibroblast-like cells.

3. Conclusions

In summary, we developed a thermo-, photo-, and chemoresponsive shape-memory material by introducing αCD and Azo into the PAA/Alg network. The stimuli-responsive formation/dissociation of αCD-Azo acted as switches, freezing or increasing the molecular mobility; therefore, the α-CD-Alg/Azo-PAA film can be processed into temporary shapes as needed and recovers its initial shape upon the application of stimulus. Unlike other shape-memory effects based on photothermal or photochemical reactions, the shape memory behavior of α-CD-Alg/Azo-PAA film can be activated not only by heating but also by irradiation with light at ambient temperatures. This ability to respond to multistimuli independently shows great potential for biomedical and biotechnological applications.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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