Electronic Supplementary Material (ESI) for ChemComm.
This journal is © The Royal Society of Chemistry 2016

Light-, pH- and thermal-responsive hydrogel with triple-shape memory effect

Yao-Yu Xiao,[a] Xiao-Lei Gong[a], Yang Kang,[b] Zhi-Chao Jiang,[a] Sheng Zhang*[a] and Bang-Jing Li*[b]

[a] State Key Laboratory of Polymer Materials Engineering, Polymer Research Institute of Sichuan University, Chengdu 610065, China.
[b] Chengdu Institute of Biology, Chinese Academy of Sciences, Chengdu 610041, China.
*Correspondence and requests for materials should be addressed to Sheng Zhang (email: zslbj@163.com) or Bang-Jing Li (email: libj@cib.ac.cn).

Supporting information

Experimental methods

Materials

4-(Phenylazo)benzoic acid, dansyl chloride and methacrylic anhydride were received from J&K Scientific Ltd. N,N′-Methylenediacrylamide, dicyclohexylcarbodiimide (DCC), 4-dimethylaminopyridine, 2-hydroxyethyl methacrylate (HEMA), acrylamide (AAm), acryloyl chloride were purchased from Aladdin Reagent Database Inc. β-Cyclodextrin (β-CD) and the other solvents and reagents, all supplied by Chengdu Kelong Chemical Co., Ltd., were analytical grade and used without further purification.

Instruments and measurements

^{1}H NMR spectra, ^{13}C NMR spectra were obtained on an Advance Bruker AV Ⅱ-400 NMR spectrometer operating at 400 MHz, or on an Advance Bruker AV III 600 NMR spectrometer operating at 600 MHz. High-resolution mass spectroscopy was performed on micrOTOF-QII mass spectrometer (Bruker, Germany). Fourier transform infrared (FTIR) spectra (KBr method) were recorded on a Varian Scimitar1000 Fourier transform IR. The swelling ratio (SR) of the hydrogels was defined as the weight ratio of swollen hydrogel to dried polymer: $SR=(w_{hydrogel} - w_{polymer})/w_{polymer} * 100\%$. Tensile strength measurements were carried out on a INSTRON 5567 universal tensile tester at room temperature, with a strain rate of 5 mm.min^{-1}. Dynamic mechanical analysis (DMA) was performed using a DMA Q800V7.1 in the strain mode at a fixed frequency of 1 Hz with the temperature range from 5 to 50℃, and a heating rate of 1.0 K min^{-1} was employed in these measurements. pH values of aqueous solutions were measured by a Mettler Toledo Delta320 digital pH meter in this study. UV irradiation was carried out on a photochemical reaction apparatus YM-GHX-V with band-pass filters to irradiate UV light at 365 nm, and the power was set as 38 W.

Synthesis and characterization of Dns-EMA

To prepare Dns-EMA, 2-Aminoethyl methacrylamide hydrochloride (AEMA) was firstly synthesized according to the literature.[1] Briefly, ethylenediamine (11 ml, 0.16 mol) and ethylenediamine dihydrochloride (10 g, 0.075 mol) were mixed in 200 ml ultrapure water and stirred for 1h. Then, methanol (230 ml) was added into the mixture before it was cooled down to -30℃, followed by adding another solution, which was prepared by dissolving methacrylic anhydride (22 ml, 0.15 mol) and a small amount of 4-Methylphenol in 30 ml methanol, slowly into this cooled mixture. After reacting for 75 min at -30℃, the pH of the solution was adjusted to ~1 and maintained overnight at room temperature. Finally, the mixture was dried under vacuum, washed with acetone, extracted by hot 2-propanol and kept at -20℃ for crystallization. AEMA was obtained by drying the precipitates (yield: 52.7%). AEMA: ^{1}H NMR (400 MHz, D_2O, ppm): δ=5.7 (s, 1H, olefin), 5.44 (s, 1H, olefin), 3.51 (t, 2H, -NH-CH2-), 3.11 (t, 2H, -CH2-NH2), 1.87 (s, 3H, -CH3) (**Figure S1**).

Procedures used to synthesize Dns-EMA from AEMA are as following: triethylamine (2.08 ml, 0.015 mol) was added in to a suspension of AEMA (1.282 g, 0.01 mol) and 50 ml dichloromethane (DCM) before it was stirred for 1h at room temperature. Subsequently, dansyl chloride (2.695 g, 0.01 mol) / DCM (30 mL) solution was added dropwise in to the suspension under stirring. After reacting for 4 h, the precipitate was removed by the filtration, and the filtrate was concentrated by rotary evaporation and followed by purified by silica gel column chromatography with ethyl acetate and hexane (1/1, v/v) as eluent to give the Dns-EMA (yield: 86.5%).

Dns-EMA: ^{1}H NMR (400 MHz, DMSO-d^6, ppm): δ=8.46 (d, 1H, naphthyl), 8.25 (d, 1H, naphthyl), 8.09 (d, 1H, naphthyl), 8.02 (t, 1H, -NH-CO-), 7.75 (t, 1H, $-SO_2-NH-$), 7.6 (m, 2H, naphthyl), 7.27 (d, 2H, naphthyl), 5.56 (s, 1H, olefin), 5.27 (s, 1H, olefin), 3.10 (t, 2H, $-CH_2$-NH-CO-), 2.81 (t, 2H, $-CH_2-NH-SO_2-$), 2.83 (s, 6H, $-N-(CH_3)_2$), 1.76 (s, 3H, $-CH_3$) (**Figure S2**). ^{13}C NMR (600 MHz, DMSO-d^6, ppm) δ=167.93, 151.85, 140.03, 136.26, 129.94, 129.56, 129.49, 128.78, 128.35, 124.05, 119.71, 119.49, 115.60, 45.50, 42.20, 18.91 (**Figure S3**). MS: Calcd for $[C_{18}H_{23}N_3O_3S+Na]^+$

= 384.4467, found 384.45 (**Figure S4**).

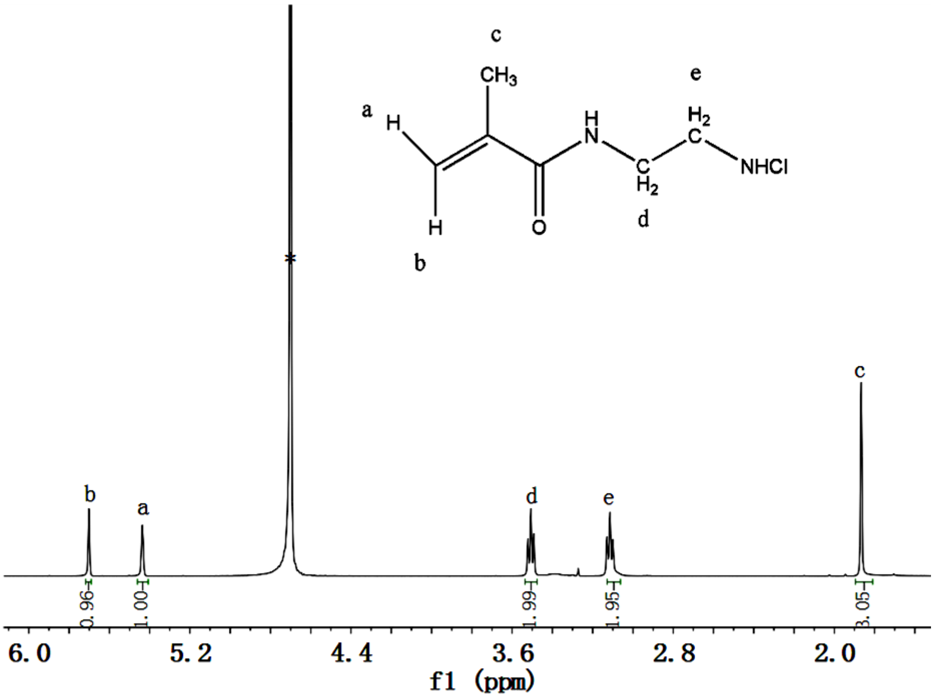


Figure S1. The ^{1}H NMR spectra of AEMA. "*" is the peak of DMSO-d^6.

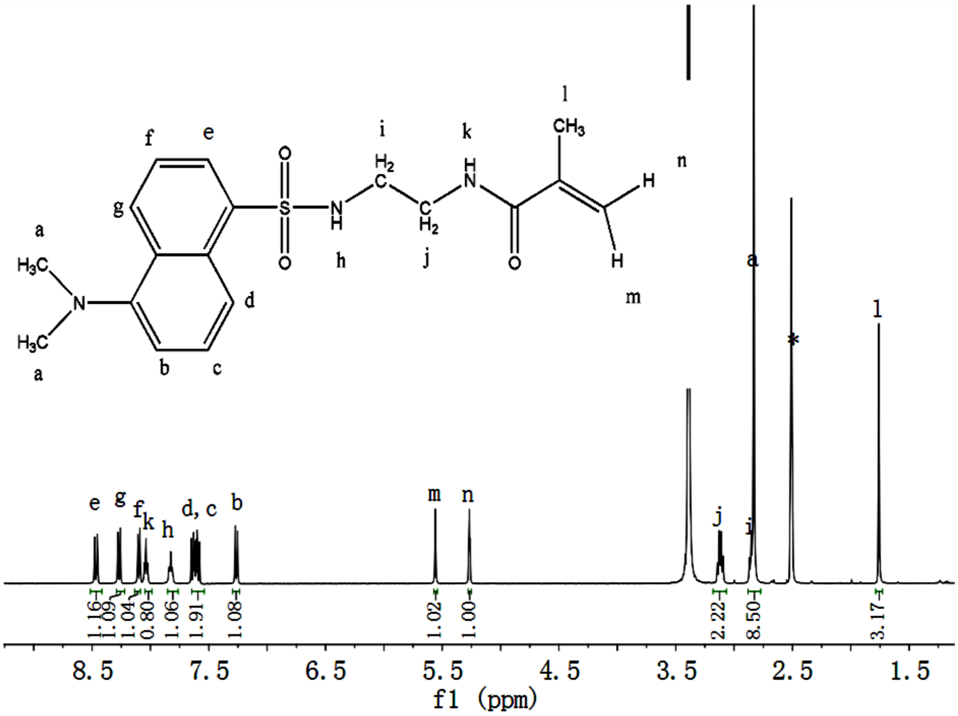


Figure S2. The ^{1}H NMR spectra of Dns-EMA. "*" is the peak of DMSO-d^6.

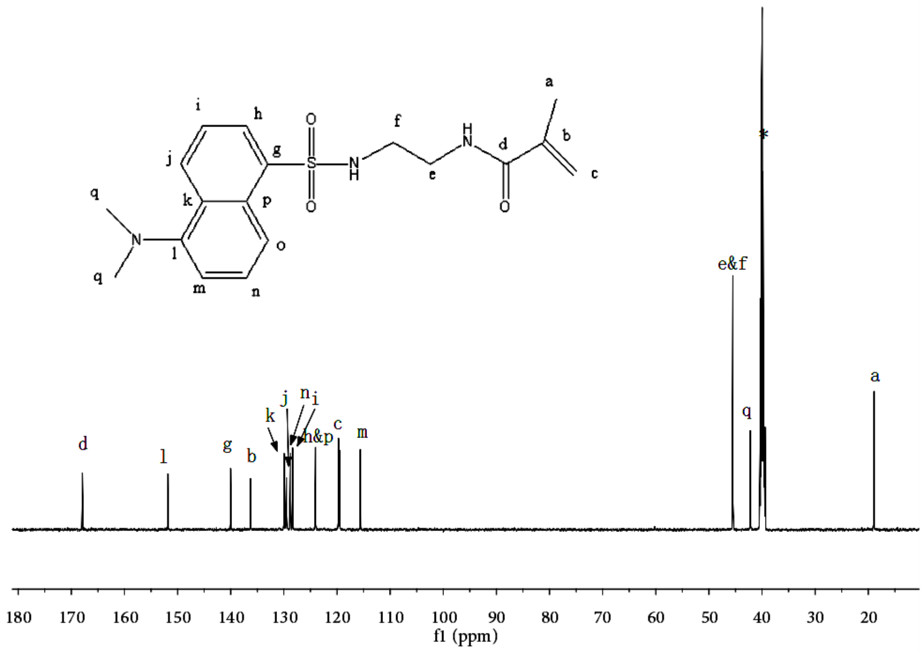


Figure S3. The ^{13}C NMR spectra of Dns-EMA. “*” is the peak of DMSO-d^6.

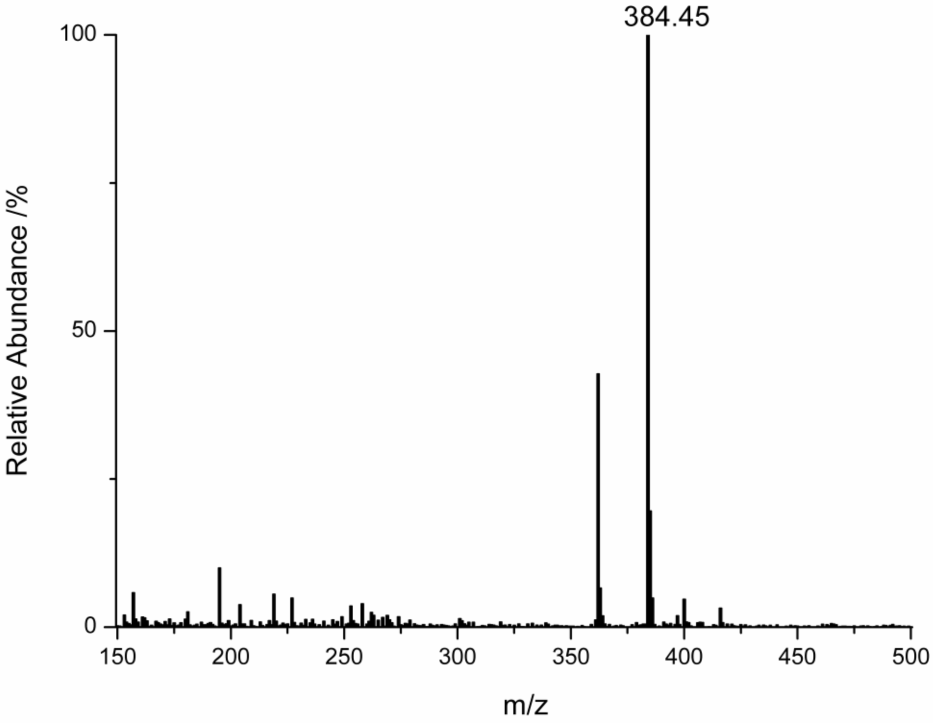


Figure S4. The MS spectra of Dns-EMA.

Synthesis and characterization of Azo-HEMA

4-(Phenylazo)benzoic acid (1.13 g, 0.005 mol), 2-hydroxyethyl methacrylate (HEMA) (2.6 g, 0.02 mol), N,N′-dicyclohexylcarbodiimide (DCC) (2.06 g, 0.01 mol), and 4-dimethylaminopyridine (0.61g, 0.005 mol) were dissolved in 50 mL of dried dichloromethane (DCM), and the solution was stirred for 24 h at room temperature. The precipitate was removed by the filtration, and the filtrate was dried under the reduced pressure to obtain the crude product, followed by purified by silica gel column chromatography with petroleum ether / ethyl acetate 15: 1 (v / v) mixed solvent as eluent. The yield of Azo-HEMA was 91.3%. Azo-HEMA: ^{1}H NMR (400 MHz, DMSO-d^6, ppm): δ=8.17 (m, 2H, phenyl), 8.0 (m, 2H, phenyl), 7.98(m, 2H, phenyl), 7.63 (m, 3H, phenyl), 6.06 (t, 1H, olefin), 5.71 (s, 1H, olefin), 4.6 (m, 2H, Azo-CO-O-CH2-), 4.5 (m, 2H, olefin-CO-O-CH2-), 1.88 (s, 3H, -CH3) (**Figure S5**). ^{13}C NMR (600 MHz, DMSO-d^6, ppm) δ=166.89, 165.43, 155.05, 152.48, 136.08, 132.77, 131.84, 131.03, 130.04, 126.61, 123.34, 123.17, 63.45, 62.81, 18.40 (**Figure S6**). MS: Calcd for $[C_{19}H_{18}N_2O_4 + Na]^+$ = 361.3502, found 361.35 (**Figure S7**).

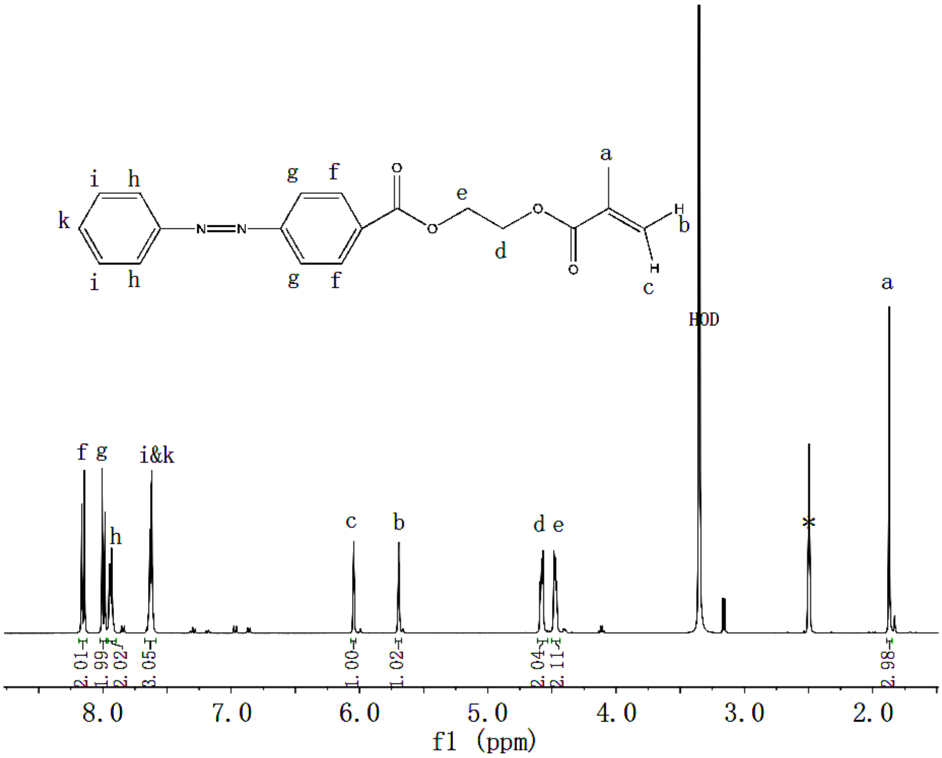


Figure S5. The ^{1}H NMR spectra of Azo-HEMA. “*” is the peak of DMSO-d^6.

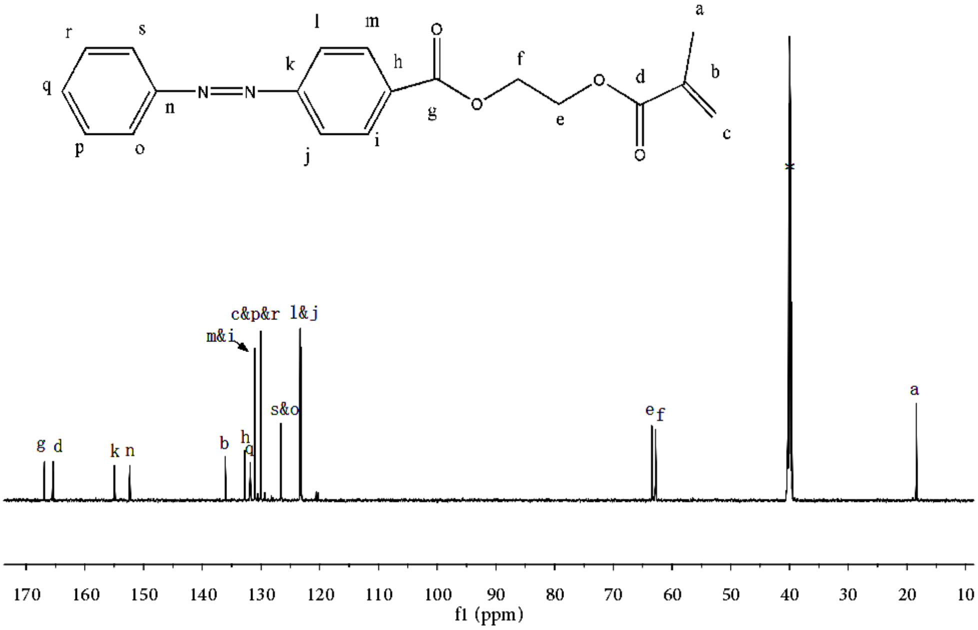


Figure S6. The ^{13}C NMR spectra of Azo-HEMA. "*" is the peak of DMSO-d^{6}.

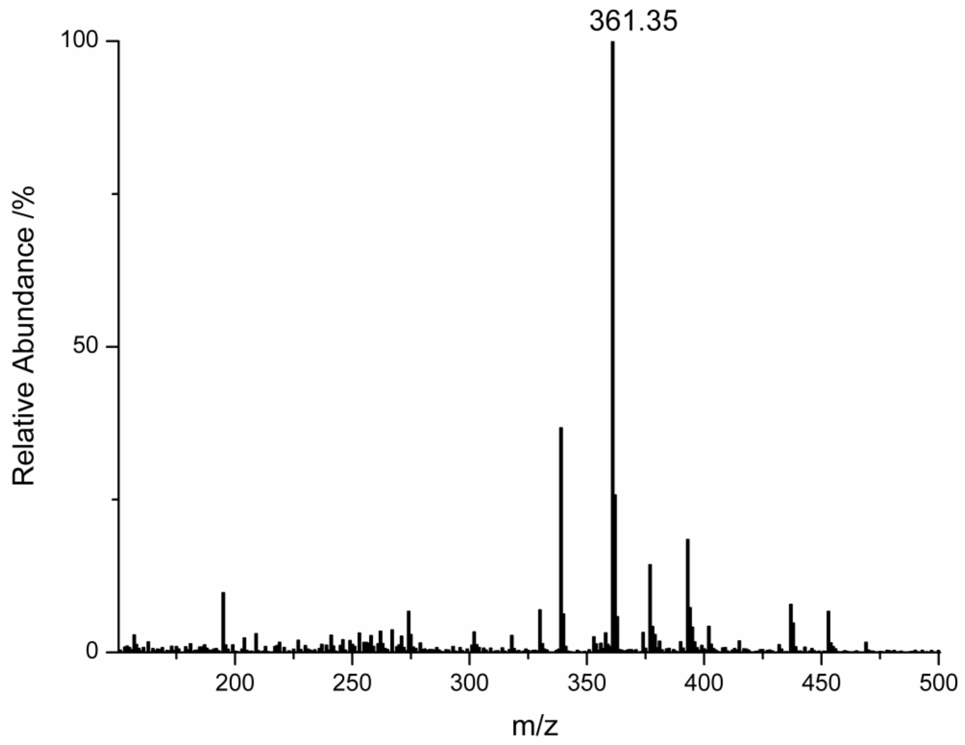


Figure S7. The MS spectra of Azo-HEMA.

Synthesis and characterization of β-CD-AAm

β-CD-AAm was synthesized according to the method of Harada et al.[2] The yields of mono-deoxy-6-(p-tosylsulfonyl)-β-CD and β-CD-AAm were 29.3% and 41%, respectively. Mono-deoxy-6-(p-tosylsulfonyl)-β-CD: ^{1}H NMR (400 MHz, DMSO-d^6, ppm): δ=7.74(s, 2H, phenyl), 7.42 (s, 2H, phenyl), 5.87-5.65 (d, 1H, olefin and m, 15H, O2,3H of CD), 4.84-4.76 (m, 7H, C1H of CD), 4.55-4.38 (m, 6H, O6H of CD), 3.84-3.21 (m, cyclodextrin, overlaps with HOD), 2.41 (s, 3H, phenyl-CH3) (**Figure S8**). β-CD-AAm: ^{1}H NMR (400 MHz, DMSO-d^6, ppm): δ =7.91(t, 1H, -NH-CO-), 6.24(dd, 1H, olefin), 6.04 (d, 1H, olefin), 5.77 (d, 1H, olefin) (**Figure S9**). ^{13}C NMR (600 MHz, DMSO-d^6, ppm): 165.29, 132.11, 125.34, 102.36, 82.05, 72.51, 60.25, 30.86 (**Figure S10**). MS: Calcd for $[C_{45}H_{73}NO_{35} +Na]^+$ = 1211.0327, found 1210.54 (**Figure S11**).

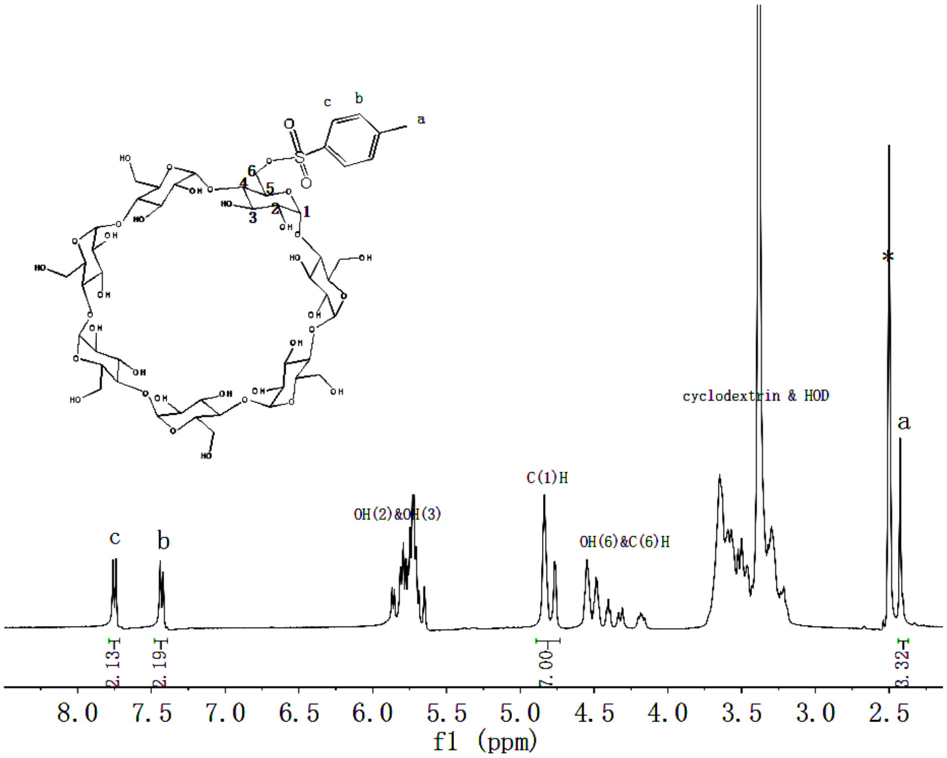


Figure S8. The ^{1}H NMR spectra of mono-deoxy-6-(p-tosylsulfonyl)-β-CD. “*” is the peak of DMSO-d^6.

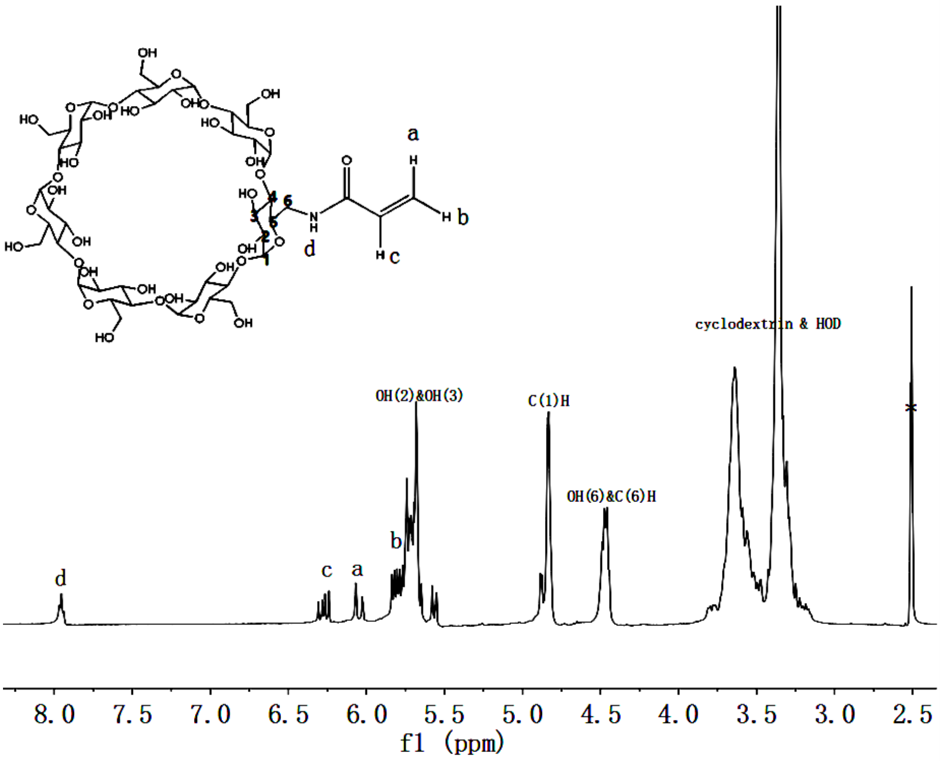


Figure S9. The ^{1}H NMR spectra of β-CD-AAm. "*" is the peak of DMSO-d^6

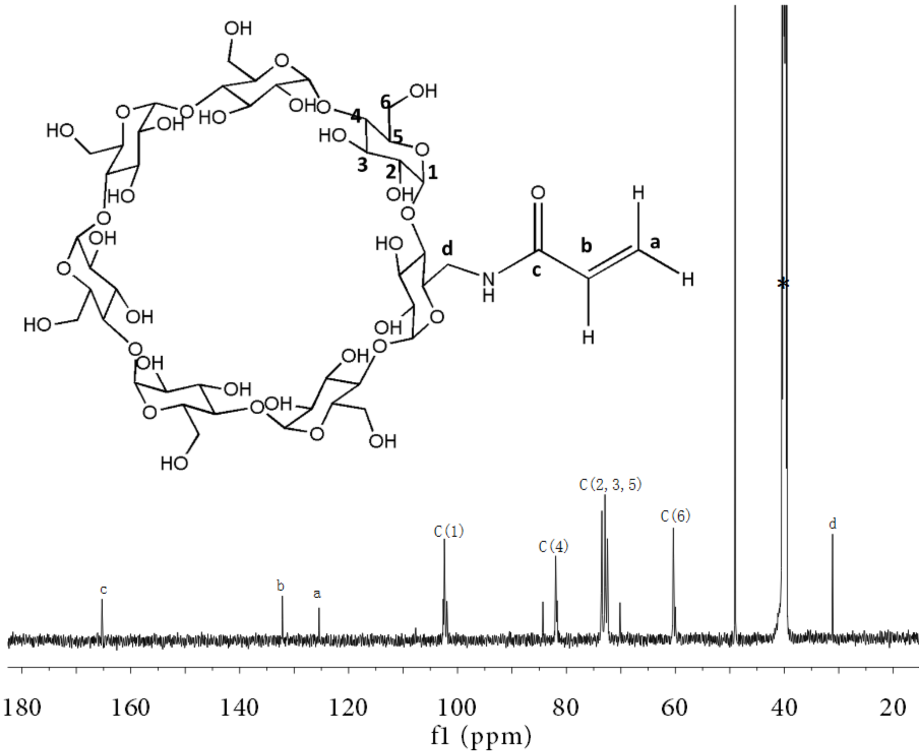


Figure S10. The ^{13}C NMR spectra of β-CD-AAm. "*" is the peak of DMSO-d^6

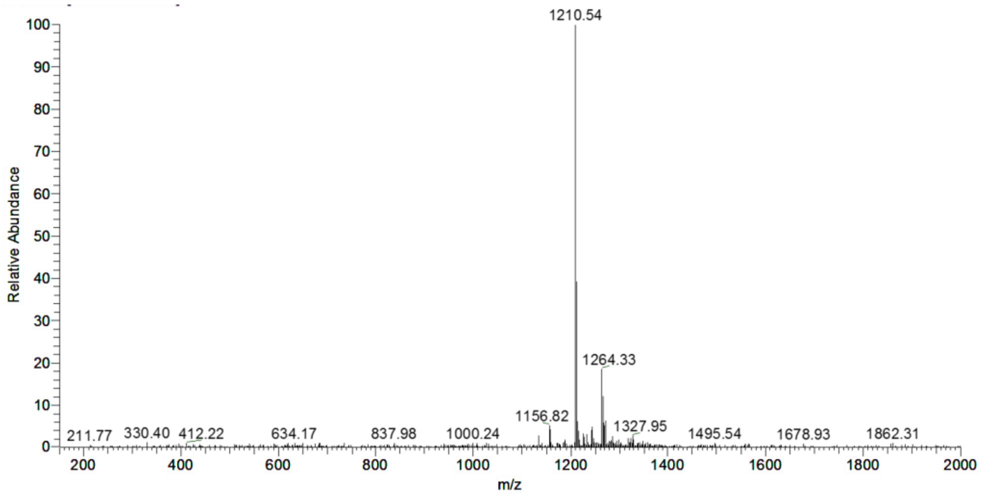
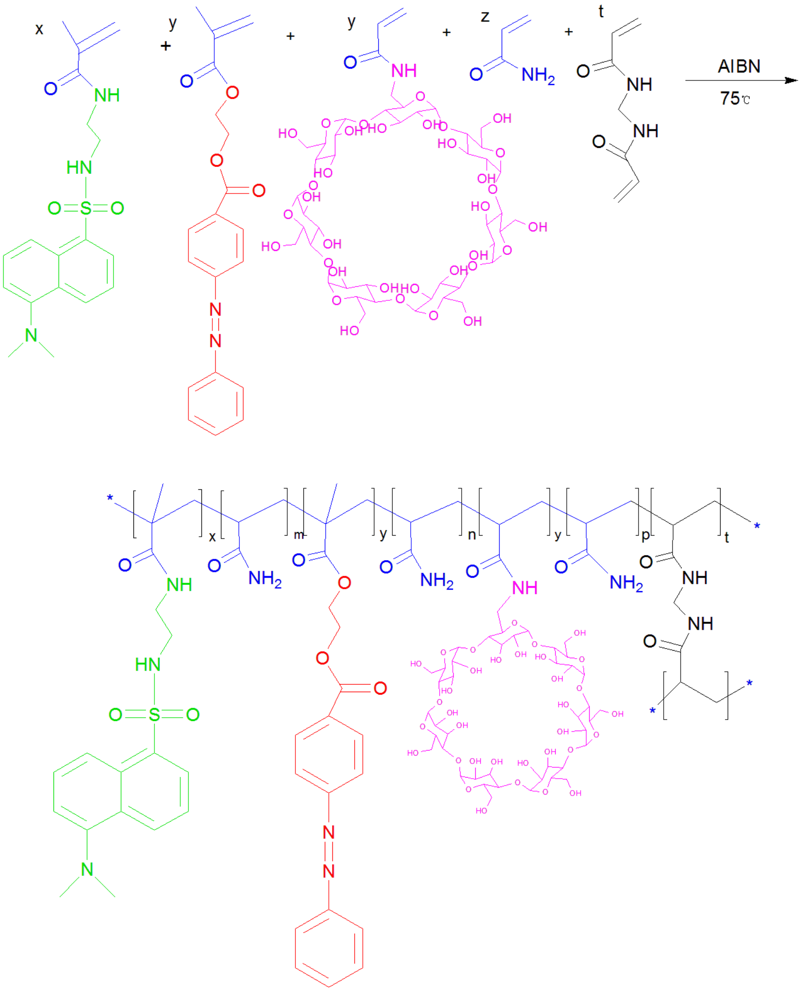


Figure S11. The MS spectra of β-CD-AAm.

.

Preparation of hydrogels

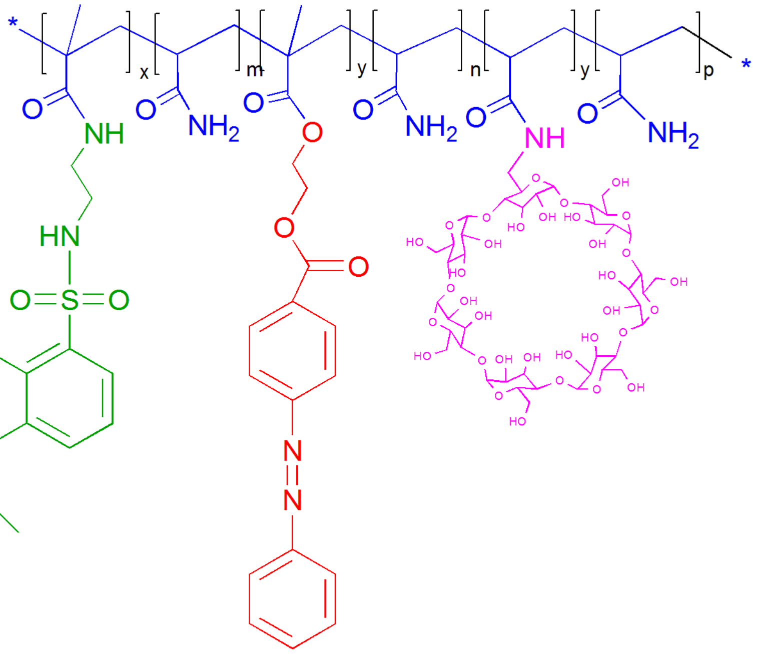
The hydrogels were prepared by copolymerization of a mixture of Azo-HEMA, Dns-EMA, β-CD-AAm and acrylamide (AAm) with N,N′-methylenediacrylamide (MDA) as cross-linker and 2,2'-azobis(2-methylpropionitrile) (AIBN) as initiator in DMSO (**Scheme S1**). General procedure: Azo-HEMA (73.1 mg, 0.216 mmol), Dns-EMA (130.1 mg, 0.36 mmol), β-CD-AAm (256.6 mg, 0.216 mmol), MDA (55.5 mg, 0.36 mmol), and AAm (174.0 mg, 2.448 mmol) were dissolved in DMSO (4 mL), and the monomer solution was added into a Polytetrafluoroethylene mold and sealed. After purging with nitrogen for 15 min, AIBN (29.6 mg, 0.18 mmol) dissolved in 0.4ml DMSO was added to the mixing solution. The mold was set into an oven thermostated at 80 °C for 10 h. The gel formed was purified by exposing to DMSO 24 h to remove the unreacted monomer, and then repeated washing with water to remove DMSO.



Scheme S1. The copolymerization of the crosslinked PAAm-TSMP hydrogel.(the x, y, z and t are 10%, 6%, 68% and 10%). Noting that m+n+p=z.

Structure Characterization of PAAm-TSMP hydrogels

The PAAm-TSMP hydrogels were characterized by Fourier transform infrared (FTIR) spectroscopy. Further structure characterization of the cross-linked copolymer network was manipulated by characterizing corresponding linear copolymer (**Scheme S2**) by FTIR, ^{1}H NMR, and ^{13}C NMR (**Figure S12, S13 and S14)**.



Scheme S2. The chemical structure of the linear copolymer. In this test, the x and y are 10% and 6%, respectively. Noting that m+n+p=68%.

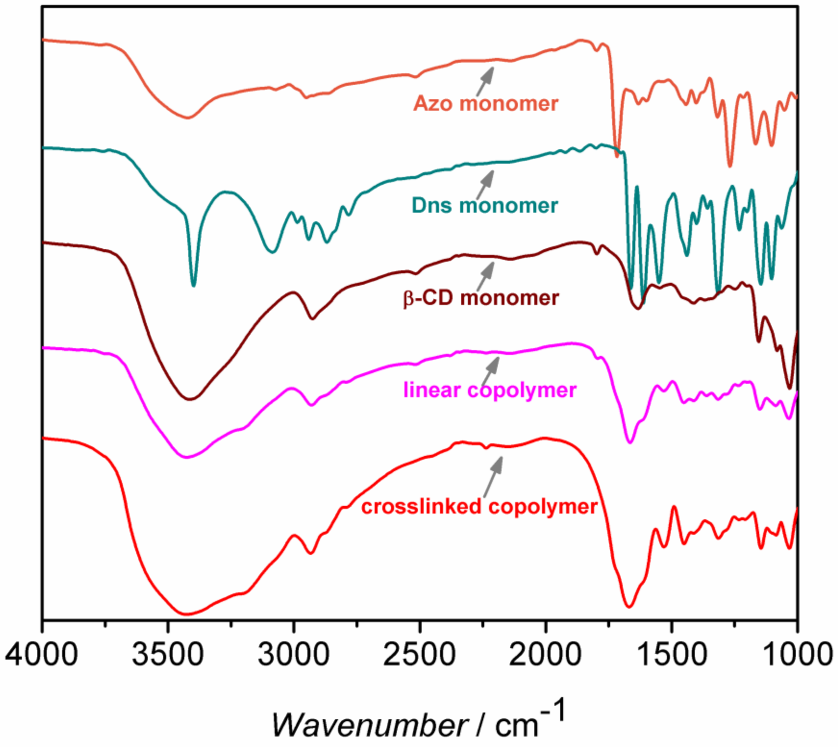


Figure S12. The FT-IR spectra of Azo-monomer, Dns monomer, β-CD monomer, linear copolymer and crosslinked copolymer：1150 - 1180 cm^{-1} comes from the β-CD groups, the peak at 2783 cm^{-1} (v $N\text{-}CH_3$) and 1313 cm^{-1} (vas SO_2) comes from the Dns groups, the peak at 1440 cm^{-1} comes from the Azo groups.

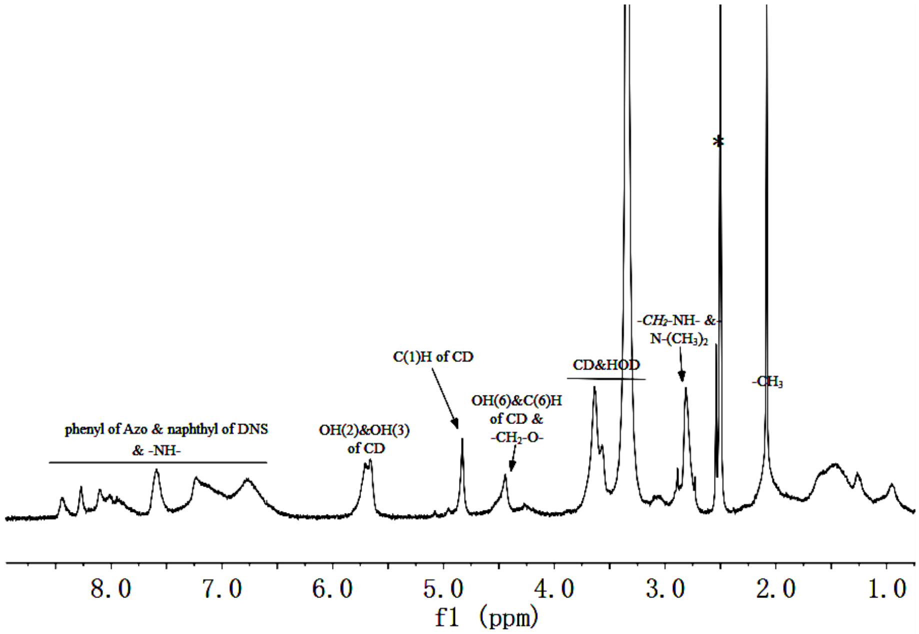


Figure S13. The ^{1}H NMR spectra of linear copolymer. "*" is the peak of DMSO-d^{6}.

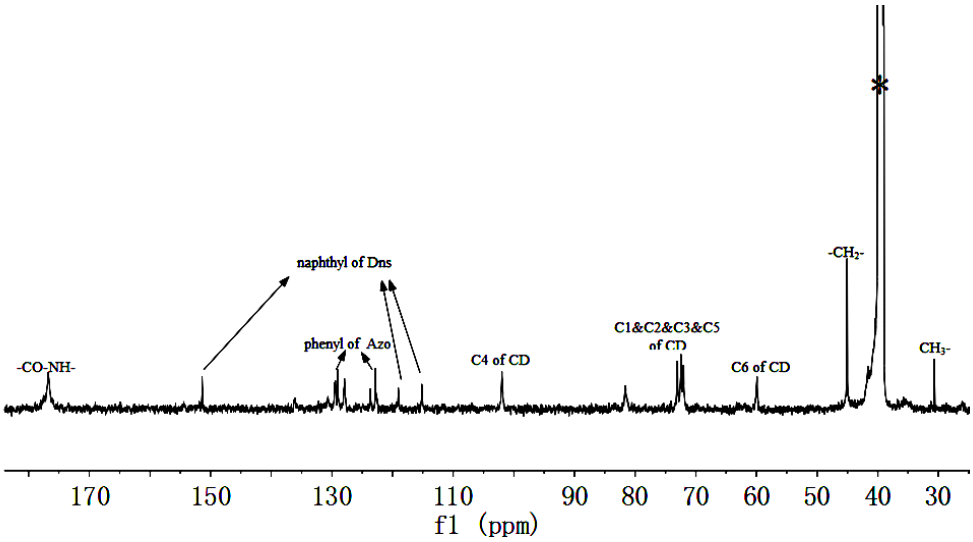
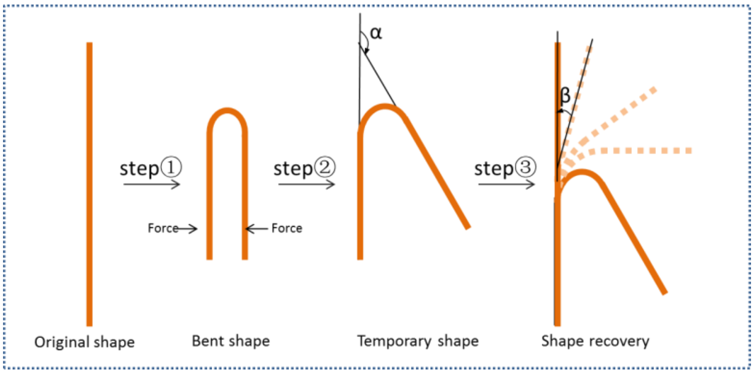


Figure S14. The ^{13}C NMR spectra of linear copolymer. "*" is the peak of DMSO-d^{6}.

Shape-Memory Experiments

Dual shape-memory test

The procedure used to measure the dual shape-memory effect (SME) based on a single variable (light, pH or heat) was according to the literatures.[3-5] For each test, a straight strip of the hydrogel film was used. The method to determine the dual shape-memory property is illustrated in the **Scheme S3**.



Scheme S3. The schematic representation of the dual shape-memory test.

pH responsive shape-memory test:

Step①: The straight strip film of PAAm-TSMP was deformed to an angle 180° after immersing in pH 2 overnight. This deformation was kept for 30 min in pH 5 before the external force was removed.

Step②: After releasing the force, an angle α was obtained. The shape fixity ratio Rf was calculated as follows:

$$Rf=\alpha/180 \tag{1}$$

Step③: The film was transferred into pH 2 to recover to the original shape, the ultimate angle was recorded as β. The shape recovery ratio Rr was calculated as follows:

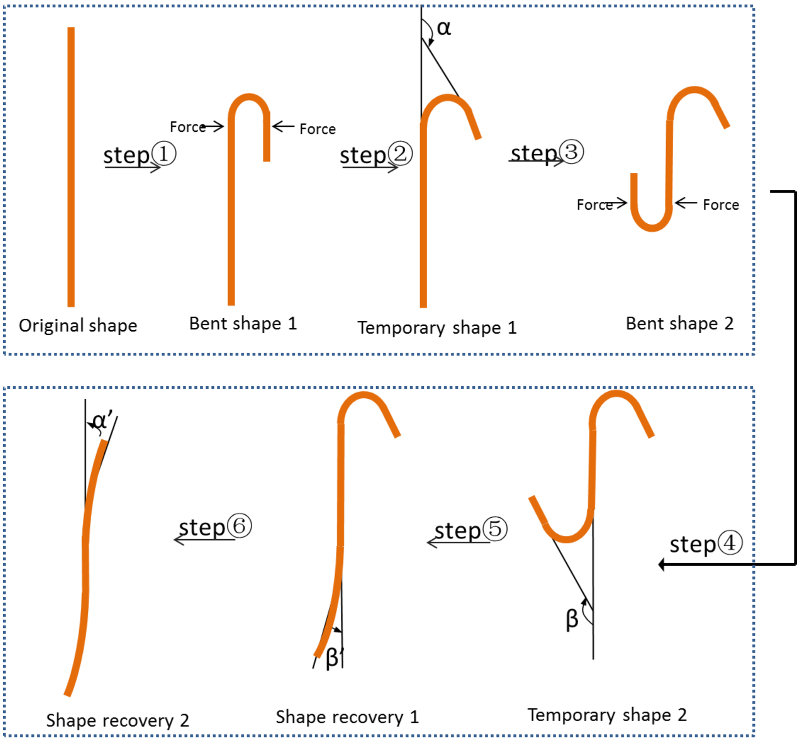
$$Rr=(\alpha-\beta)/\alpha \tag{2}$$

Light responsive shape-memory test: Similarly, the hydrogel film at pH 2 was first deformed with an angle 180° after 1 hour UV irradiation. The external force was maintained for 20 min under visible light to fix the deformation. After releasing the force, an angle α was obtained. Then, the film was irradiated by UV light for 1 hour to recover to the original shape, the ultimate angle was recorded as β. The shape fixity ratio Rf and the shape recovery ratio Rr were calculated as follows: Rf=α/180; Rr=(α-β)/α.

Thermal responsive shape-memory test: The film at pH 5 was first deformed with an angle 180° after heating at 80℃ for 5 min. This deformation was kept for 1 min at room temperature before the external force was removed. After releasing the force, an angle α was obtained (in this case, the α was 180°. Then, the film was heating at 80 ℃ to recover to the original shape, the ultimate angle was recorded as β. The shape fixity ratio Rf and the shape recovery ratio Rr were calculated as follows: Rf=α/180; Rr=(α-β)/α.

Triple shape-memory test

As shown in the **Scheme S4**, in triple-shape shifting cycle, first, the hydrogel film (at pH 2) were irradiated by UV light for 1h, and the hydrogel film was deformed with an angle 180° by external force at one end (step①). After that, the hydrogel was irradiated by Vis light while maintaining the external force for 20 min to fix the deformation. Temporary shape 1 with an angle α was obtained upon removing the external force (step②). The fixity ratio (Rf_1) was defined as α/180. Then, the other end of the hydrogel was deformed with an angle 180° and fixed by keeping the deformation in pH 5 for 30 min (step③), temporary shape 2 with an angle β was obtained when external force was removed (step④). The fixity ratio (Rf_2) was defined as β/180. The recovery from temporary shape 2 to temporary shape 1 was carried out by transferring the hydrogel from pH 5 to pH 2, and the fixed angle β changed to an angle β′ (step⑤). The shape recovery ratio (Rr_2) was defined as β-β′/β. The recovery from temporary shape 1 to original shape was carried out under UV irradiation for 1 h (step⑥), and finally an angle α′ of the hydrogel that was recovered from the fixed angle α was obtained. The shape recovery ratio (Rr_1) was defined as α-α′/α.



Scheme S4. The schematic representation of the triple shape-memory test.

It should be noted that the temperature was controlled no higher than room temperature throughout the UV irradiation (cold solution (0℃) ice packs were used during irradiation), therefore, the photothermal effect was ruled out. The rest procedures of triple shape memory test were carried out at room temperature (25℃). In particular, the hydrogel was heated to 50℃ for 10min after the shape fixation under Vis light, no shape relaxation was observed, thus further excluding the influence of photothermal effects during the light-induced shape memory process.

Shape memory property in manifold shape change cycles:

Table S1: the Rf and Rr values in eight pH-induced shape memory cycle times.

Cycle times	1	2	3	4
Rf	77.8%	79.8%	71.6%	66.5%
Rr	92.8%	88.6%	92.3%	91.7%

Table S2: the Rf and Rr values in eight light-induced shape memory cycle times.

Cycle times	1	2	3	4
Rf	73.4%	77.2%	65.1%	63.2%
Rr	88.5%	86.3%	81.3%	72.5%

Table S3: the Rf and Rr values in eight thermal-induced shape memory cycle times.

Cycle times	1	2	3	4
Rf	100%	100%	100%	100%
Rr	100%	100%	100%	100%

References

1. Z. Deng, H. Bouchékif, K. Babooram, K. Babooram, A. Housni, N. Choytun and R.Narain, *J Polym. Sci. A*, 2008, **46**, 4984-4996.

2. Y. Takashima, S. Hatanaka, M. Otsubo, M. Nakahata, T. Kakuta, A. Hashidzume, H. Yamaguchiand A. Harada, *Nat. Comm.*, 2012, **3**, 1270.

3. U. N. Kumar, K. Kratz, W. Wagermaier, M. Behl and A. Lendlein, *J. Mater. Chem.*, 2010, **20**, 3404–3415.

4. H. Lu and J. Gou, *Polym. Adv. Technol.*, 2012, **23** 1529–1535.

5. Y. Liu, C. Han, H. Tan and X. Du, *Mat. Sci. Eng. A*, 2010, **527**, 2510–2514.