Electronic Supplementary Material (ESI) for Soft Matter.

Supporting Information

for

Dynamic Covalent Bond-based Hydrogels with Superior Compressive Strength, Exceptional Slice-resisting and Self-healing Properties

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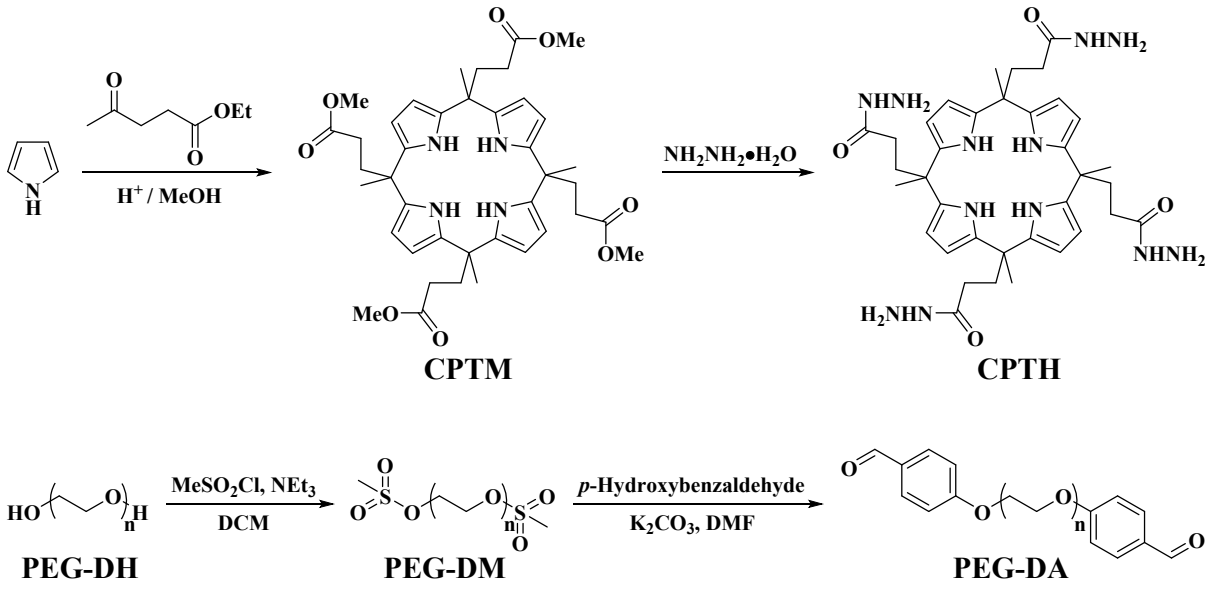
CONTENS

1. Experimental Section

1.1 Reagents and materials

Pyrrole (Aladdin, >99.0%), ethyl levulinate (J&K Technology Co., Ltd., >98.0%), hydrazine hydrate (Guangdong Guanghua Sci-Tech Co., Ltd., 80%), linear poly(ethylene glycol) (PEG-DH, Mn~4000, Shanghai Macklin Biochemical Co., Ltd.), methanesulfonyl chloride (Aladdin, >98.0%), *p*-hydroxybenzaldehyde (Shanghai Macklin Biochemical Co., Ltd.). These reagents were used without further purification. Other reagents were of analytical grade and used as received unless otherwise specified.

1.2 Synthetic routes



Scheme S1. The synthetic routes for CPTH and PEG-DA

1.3 Preparation of CPTM, CPTH and PEG-DA

CPTM was prepared from the acid-catalyzed condensation of pyrrole with ethyl levulinate with referring a literature method.[1] CPTH and PEG-DA were prepared in similar ways as reported earlier.[2] The details are described below.

Synthesis of CPTM: Pyrrole (6.0 mL, 86.8 mmol) and ethyl levulinate (12.5 mL, 86.8 mmol) were dissolved in MeOH (150 mL) at 0 ^{o}C and bubbled with Ar for ten minutes. Concentrated hydrochloric acid (1.5 mL) was dissolved in MeOH (50 mL) and added

dropwise over the course of twenty minutes by shielding from light and the mixture was stirred at 0 °C for 3 h and then stirred at room temperature for 3 days. The brown gray precipitate was filtered. Chromatographic purification (silica gel, petroleum ether/ethyl acetate: 3/1) yielded white solid (3.9 g, 25.1%). ^{1}H NMR (600 MHz; $CDCl_3$; Me_4Si): δ 1.41−1.42 (12H, m, -CH_3), 2.09−2.21 (16H, m, -CH_2CH_2-), 3.60−3.61 (12H, m, -OCH_3), 5.91−5.93 (8H, m, pyrrole -CH-), 7.05−7.06 (4H, m, -NH); ^{13}C NMR (150 MHz; $CDCl_3$; Me_4Si): δ 25.92−26.52 (-CH_3), 29.53 (-$COCH_2CH_2$-), 35.30 (-$COCH_2CH_2$-), 38.50 (pyrrole-*C*-pyrrole), 51.53 (-OCH_3), 104.30 (-NHC*C*H-), 136.74 (-NH*C*CH-), 174.09 (-*C*$OOCH_3$); HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{40}H_{53}N_4O_8^+$ 717.3858, found 717.3873.

Synthesis of CPTH: Under nitrogen, a suspension of CPTM (4.0 g, 5.6 mmol) in 150 mL of MeOH/CH_2Cl_2 (4/1) was prepared, then hydrazine hydrate (80%, 14.0 mL, 224.0 mmol) was added, and then the mixture system was refluxed at 66 °C for 4 days. The resulting solution was cooled to room temperature and concentrated under reduced pressure, then the obtained residue was added to pure water (20 mL), and then the suspension was treated with ultrasound for 3 min. Finally, white suspension was generated. The suspension was filtered to get the white solid. The crude product was washed several times with water to remove the un-reacted hydrazine hydrate, and thus pure CPTH was obtained (3.3 g, 82.4%).^{1}H NMR (600 MHz; DMSO; Me_4Si): δ 1.39−1.47 (12H, m, -CH_3), 1.70−2.20 (16H, m, -CH_2CH_2-), 4.12 (8H, br s, -NH_2), 5.65−5.78 (8H, m, pyrrole-CH-), 8.76−8.96 (4H, m, pyrrole-NH), 9.37−9.55 (4H, m, -CON*H*NH_2); ^{13}C NMR (150 MHz; DMSO; Me_4Si): δ 23.49−27.49 (-CH_3), 29.14−29.26 (-$COCH_2CH_2$-), 35.01−36.69 (-$COCH_2CH_2$-), 37.43−38.19 (pyrrole-*C*-pyrrole), 102.62−103.23 (-NHC*C*H-), 136.93−137.41 (-NH*C*CH-), 172.00 (-$CONHNH_2$); HRMS (ESI): *m*/*z* $[M + Na]^+$ calcd for $C_{36}H_{52}N_{12}O_4Na^+$ 739.4127, found 739.4133.

Synthesis of PEG-DA: Liner dibenzaldehyde-terminated poly(ethylene glycol) (PEG-DA) was prepared generally as follows.

(1) PEG-DH (50.0 g, 12.5 mmol, Mn~4000) was added in a 500 mL clean and dry flask and azeotropic distillation dried with 200 mL toluene. After most of the toluene was distilled from the flask, 60 mL dry CH_2Cl_2 was added. Under nitrogen, the trimethylamine (6.9 mL, 50.0 mmol) was added before the flask was immersed into ice bath, subsequently followed by adding 40 mL dry CH_2Cl_2 solution with methanesulfonyl chloride (4.3 mL, 55.0 mmol) into

the reaction system drop by drop with stirring. After addition, the mixture was allowed to stir for 40 h at room temperature. The resulting solution was diluted with 250 mL water and extracted with CH_2Cl_2 (5 × 50 mL). The organic phase was washed with 1 M HCl solution (4 × 50 mL) and saturated brine (4 × 50 mL), dried with anhydrous Na_2SO_4, and concentrated in vacuo before the crude product was precipitated in ethyl ether. The precipitate was filtered and washed with ethyl ether, then dried under vacuum at r.t. for 6 h to give white solid PEG-DM (51.8 g, 99.7%, Mn~4156). ^{1}H NMR, ^{13}C NMR and MALDI-TOF mass spectrum of PEG-DM was shown as **Fig. S10**, **Fig. S11** and **Fig. S12**.

(2) PEG-DM (50.0 g, 12.0 mmol, Mn~4156) was added to *p*-hydroxybenzaldehyde (5.3 g, 43.2 mmol) and K_2CO_3 (6.0 g, 43.2 mmol) in 120 mL of DMF and the mixture was heated at 80 °C for 4 d. The reaction mixture was then evaporated under reduced pressure at 50 °C. The residue was then dissolved in 200 mL CH_2Cl_2 and divided the black solution into four parts. Every 50 mL mother liquor extracted with saturated brine (2 × 50 mL) and ethyl acetate (1 × 150 mL). The organic layer was dried with anhydrous Na_2SO_4 and concentrated in vacuo before the crude product was precipitated in ethyl ether. The precipitate was filtered and washed with ethyl ether, then dried under vacuum at r.t. for 6 h to give yellowish solid PEG-DA (47.6 g, 94.0%, Mn~4208). ^{1}H NMR, ^{13}C NMR and MALDI-TOF mass spectrum of PEG-DA were shown as **Fig. S13**, **Fig. S14** and **Fig. S15**, respectively.

1.4 Preparation of H_2O/EtOH gels and hydrogels

Generally, the gels were prepared in a mixed solvent of H_2O/EtOH (1/9 − 9/1, *v*/*v*) at neutral pH, in which the total concentration of CPTH and PEG-DA is 30%, *w*/*v* (n_{CPTH}:$n_{PEG\text{-}DA}$ = 1:2). In a typical preparation, CPTH (0.012 g, 0.015 mmol) and PEG-DA (0.138 g, 0.03 mmol) were dissolved in 0.5 mL of H_2O/EtOH in a vial through careful heating, and then the mixture was stirred using a vortex mixer until the reactants were dissolved completely. Finally the resulting solution was cooled to room temperature, and the gels formed after a while. The hydrogels were prepared in a similar way.

1.5 Preparation of xerogels

A H_2O/EtOH gel or a pure hydrogel was transferred into liquid N_2, then frozen for 30 min,

and then frozen at −40 °C overnight. Finally, the frozen sample was freeze dried at vacuum (0.1 Pa) to yield dry xerogels.

1.6 Rheological measurements

Rheological measurements were carried out using a stress-controlled rheometer (TA instrument, AR-G2) equipped with a steel-coated parallel-plate geometry (20 mm in diameter). The gap between the two plates was fixed at ~1.0 mm. The following method was used to prepare the gel sample: CPTH (0.024 g, 0.03 mmol) and PEG-DA (0.276 g, 0.06 mmol) were dissolved in 1 mL of H_2O and then closed in a 20 mm diameter round container. The reaction mixtures were maintained at room temperature for 24 h to allow gel formation. The hydrogel as obtained was loaded onto the rheometer plate for measuring rheological properties. A solvent trapping device was placed above the plate to avoid solvent evaporation during the measurement. All measurements were conducted at 20 °C.

Stress sweep at a constant frequency (1 Hz) was performed, which provides information about linear viscoelastic region of the gel sample. Frequency sweep was performed from 0.01−100 Hz at a shear stress of 50 Pa, which is well within the linear viscoelastic region of gel samples that can bring small strains of the tested materials.

1.7 SEM observation

Scanning electron microscopy (SEM) images of the xerogels were taken on a Quanta 200 environmental scanning electron microscope (Philips-FEI). The accelerating voltage was 20 kV and the emission current was 10.0 mA. The xerogels to be examined were cut into slice first, then freeze dried, and were observed from the section.

1.8 FTIR measurements

FTIR measurements were performed on a Bruker VERTEX70 V infrared spectrometer. The testing scale was from 400 to 4000 cm^{-1} with 128 scans for each sample. The KBr pellet was obtained by mixing a small amount of the sample and anhydrous KBr powder. The FTIR measurements were carried out at room temperature.

1.9 Mechanical test

Mechanical properties of gels were measured by a Xie Qiang mechanical testing machine (CTM 2500 universal testing machine) at room temperature. All gels were prepared and aged for 24 hours in the test. All gel samples for compression test have a cylindrical shape with 9.2 mm in diameter and 7.5 mm in height. All samples were set on the lower plate and compressed by the upper plate at a strain rate of 2 mm/min.

The gel samples for tensile test were of a dumbbell-shape (the size of the heads: 50 mm in length, 8.5 mm in width, 1.5 mm in thickness; the size of the middle part: 30 mm in length, 3.5 mm in width, 1.5 mm in thickness). Besides, the uniaxially stretch tests were conducted at a constant stretching speed, which is 50 mm/min. The tensile strain was taken as the length change related to the initial length (*c.f.* **equation 1**), and the tensile stress was evaluated on the cross section of the initial sample.[3]

$$\varepsilon\ (\%) = (L\text{-}L_0)/L_0 \times 100\% \quad (1)$$

where L_0 is the initial length of the gel sample and L is the final length after stretching.

The modulus was calculated from the initial linear region of the stress-strain curves.[4]

The hydrogel sample for slicing test was of a cylindrical shape with 9 mm in diameter and 7.5 mm in height.

1.10 Self-healing study

The hydrogel samples used for self-healing testes were prepared in a vial with a diameter of 10 mm and height of 2.5 mm. One of the samples was doped with rhodamine B and another with methylene blue. After aged in the vial at room temperature for ~24 h, each of the specimens was cut into two pieces. Then, two selected pieces were spliced and placed in a container with moisture at room temperature without any other intervention for 24 h to accomplish the self-healing process.

2. Supplementary Tables and Figures

Table S1 Tension performance for G-3 and G-0 at room temperature.

Sample	G-3	G-0
σ_T (MPa)	0.13	0.23
ε_T (%)	44.4	282.3
E_T (kPa)	5.57	1.60

σ_T: failure tensile stress; ε_T: failure tensile strain, E_T: tensile modulus.

Table S2 Comparison of recently reported dynamic hydrogels and some other relevant gels.

No.	Hydrogel types	Bond types	Compressive stress (MPa) / Strain (%)	Tensile stress (MPa) / Strain (%)	Self-healing (Time, temperature)	Reference
Present work	SNDH	Acylhydrazone	27.3 / 98.4	0.23 / 282.3	24 h, 20 °C	This contribution
Recently work	SNDG[a)]	Acylhydrazone	6.4 / 88.2	0.18 / 185.5	96 h, 20 °C[b)]	*Macromol. Rapid Commun.* **2018**, *39*, 1700679
1	ICHG[c)]	Covalent; coordination	~3.5 / 85	0.25 / 2952	0.5 h, 20 °C	*Chem. Mater.* **2018**, *30*, 3110−3121
2	SNDH[d)]	Acylhydrazone; disulfide	~0.05 / ~65	NM	6 h, 25 °C	*Adv. Funct. Mater.* **2017**, *27*, 1703174
3	SNDH[e)]	Acylhydrazone	NM	0.29 / 11700	24 h, 20 °C	*ACS Macro Lett.* **2017**, *6*, 881−886
4	SNDH	Gold(I)-thiolate; disulfide	NM	NM	few seconds, NM	*Biomacromolecules* **2017**, *18*, 2360−2370
5	TPHG[f)]	Covalent	~20 / >90	NM	NM	*Biomaterials* **2017**, *120*, 11−21
6	SNDH	Boronic ester	30 / 98	5.3 / 250	NM	*Angew. Chem. Int. Ed.* **2016**, *55*, 9196−9201
7	DNHG[g)]	Covalent; hydrogen; hydrophobic	NM	~10 / ~600	1 h, 60 °C[h)]	*Adv. Mater.* **2016**, *28*, 4884−4890
8	SNDH[g)]	Acylhydrazone	NM	~25 / ~60	NM	*Nat. Commun.* **2015**, *6*, 6650
9	SNDH[i)]	Acylhydrazone; imine	~0.035 / ~60	NM	6 h, 25 °C[j)]	*Adv. Funct. Mater.* **2015**, *25*, 1352−1359
10	SNDH	Boronic ester	NM	NM	1 h, NM	*ACS Macro Lett.* **2015**, *4*, 220−224
11	SNDH[k)]	Disulfide	~0.135 / ~60	NM	1 h, 20 °C[l)]	*Polym. Chem.* **2015**, *6*, 7027−7035

No.	Hydrogel types	Bond types	Compressive stress (MPa) / Strain (%)	Tensile stress (MPa) / Strain (%)	Self-healing (Time, temperature)	Reference
Present work	SNDH	Acylhydrazone	27.3 / 98.4	0.23 / 282.3	24 h, 20 °C	This contribution
12	SNDH[m)]	Boronic ester	NM	NM	30 s, 25 °C	*Chem. Commun.* **2014**, *50*, 12277−12280
13	SRHG[n)]	Covalent; ionic	NM	0.03 / 1463	NM	*Nat. Commun.* **2014**, *5*, 5124
14	SNDH	Acylhydrazone; disulfide	NM	~0.08 / ~650	48 h, 20 °C[o)]	*ACS Macro Lett.* **2012**, *1*, 275−279
15	TPHG[p)]	Covalent	~27 / ~100	~0.13 / ~990	NM	*Macromol. Rapid Commun.* **2010**, *31*, 1954−1959
16	MMCH[q)]	Covalent	19.1 / 92.3	NM	NM	*Adv. Mater.* **2007**, *19*, 1622−1626
17	DNHG	Covalent	21 / 97	1.6 / 4.9	NM	*Adv. Mater.* **2003**, *15*, 1155−1158

[a)] mixture solvent (H_2O/EtOH) gel; [b)] catalyzed by aniline and recovered nearly the same to the original sample; [c)] combination of nanocomposite and coordination reinforcement; [d)] self-healing process needs 4-amino-DL-phenylalanine catalysis; [e)] combination of acylhydrazone bonds and micelle cross-linking and gelation in phosphate buffer saline (PBS) solution; [f)] gelation in PBS solution at 37 °C; [g)] hydrogel prepared by solvent exchange of organogel; [h)] the self-healing process needs the auxiliary of DMF; [i)] gelation in PBS solution; [j)] a representative result of self-healing tests at different temperatures; [k)] pre-gel solutions was degassed by nitrogen and hydrogel prepared by solvent exchange of organogel; [l)] a representative result of tests with different hydrogels along with different self-healing time at different temperatures; [m)] gelation with the assistance of 0.1 M NaOH aqueous solution; [n)] pre-gel solutions was degassed by nitrogen and the gelations were performed at 4 °C for 24 h; [o)] the self-healing process needs catalyst or under specific pH; [p)] gelation in PBS solution; [q)] γ-rays was used in creating process and the gelation process was degassed by nitrogen and performed in water bath at the required temperature. SNDH: single network dynamic covalent bonds (DCBs)-based hydrogel; SNDG: single network DCBs-based gel; ICHG: ionic crosslinked hydrogel; TPHG: tetrahedron-like poly(ethylene glycol) hydrogel; DNHG: double network hydrogel; SRHG: slide-ring hydrogel; MMCH: macromolecular microsphere composite hydrogel; NM: not mentioned.

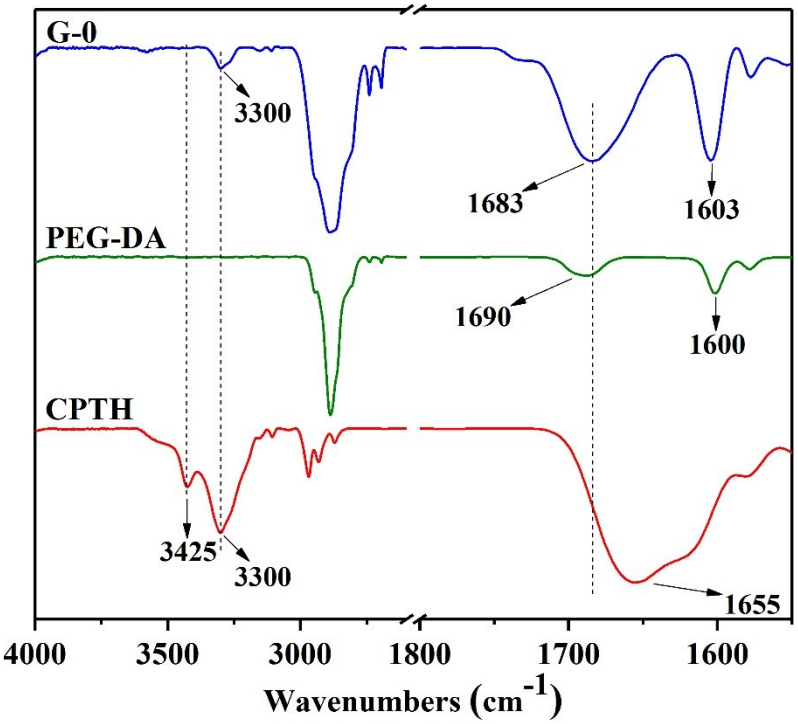


Fig. S1 FTIR spectra of CPTH, PEG-DA and xerogel of G-0.

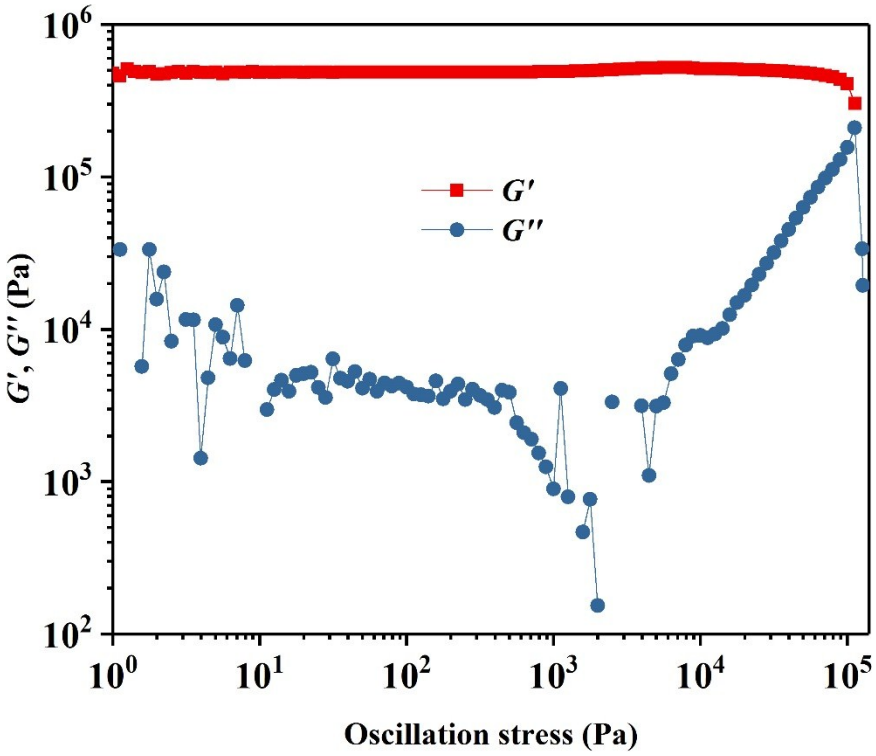


Fig. S2 Storage modulus (*G′*) and loss modulus (*G″*) recorded as functions of applied shear stress for G-0 at 1 Hz (30%, *w*/*v*).

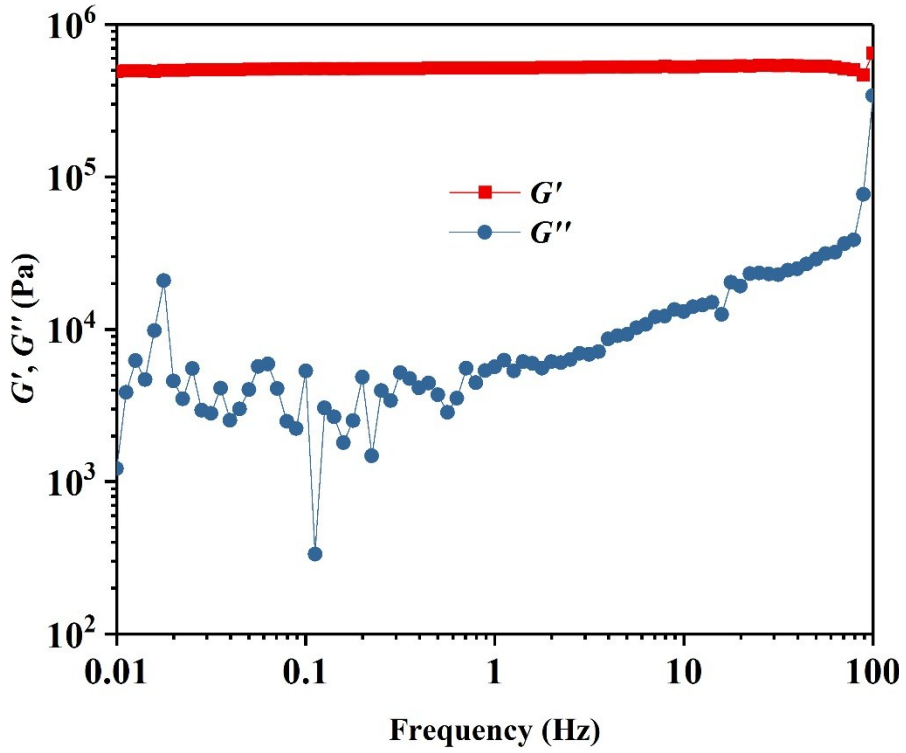


Fig. S3 Storage modulus (G') and loss modulus (G'') as functions of frequency for G-0 under 50 Pa (30%, *w*/*v*).

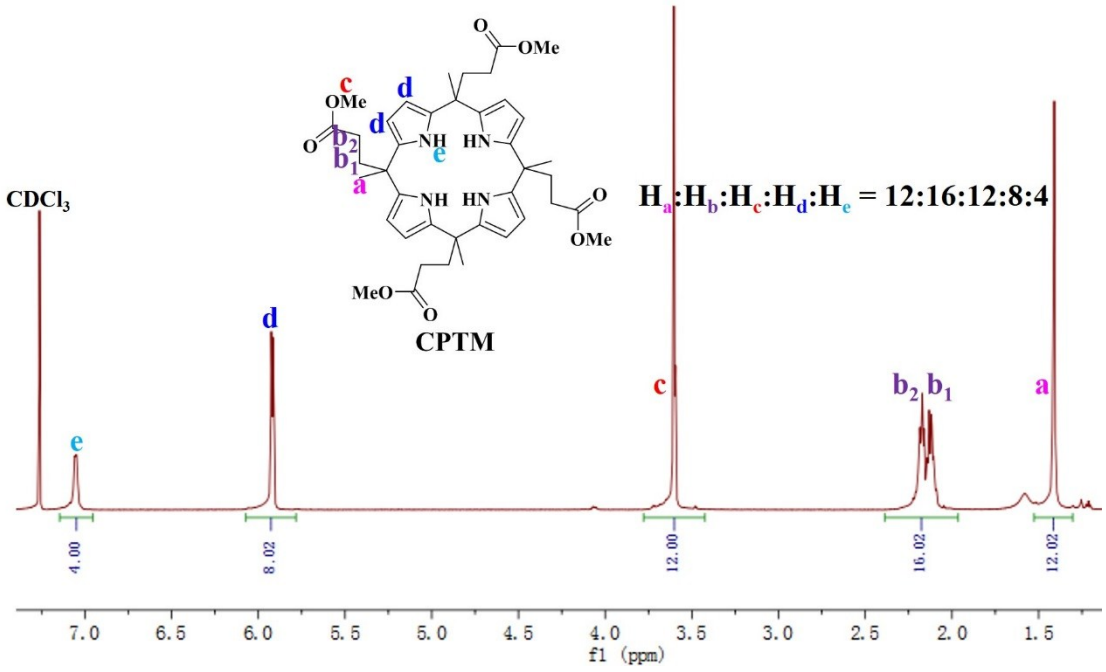


Fig. S4 ^{1}H NMR spectrum of CPTM.

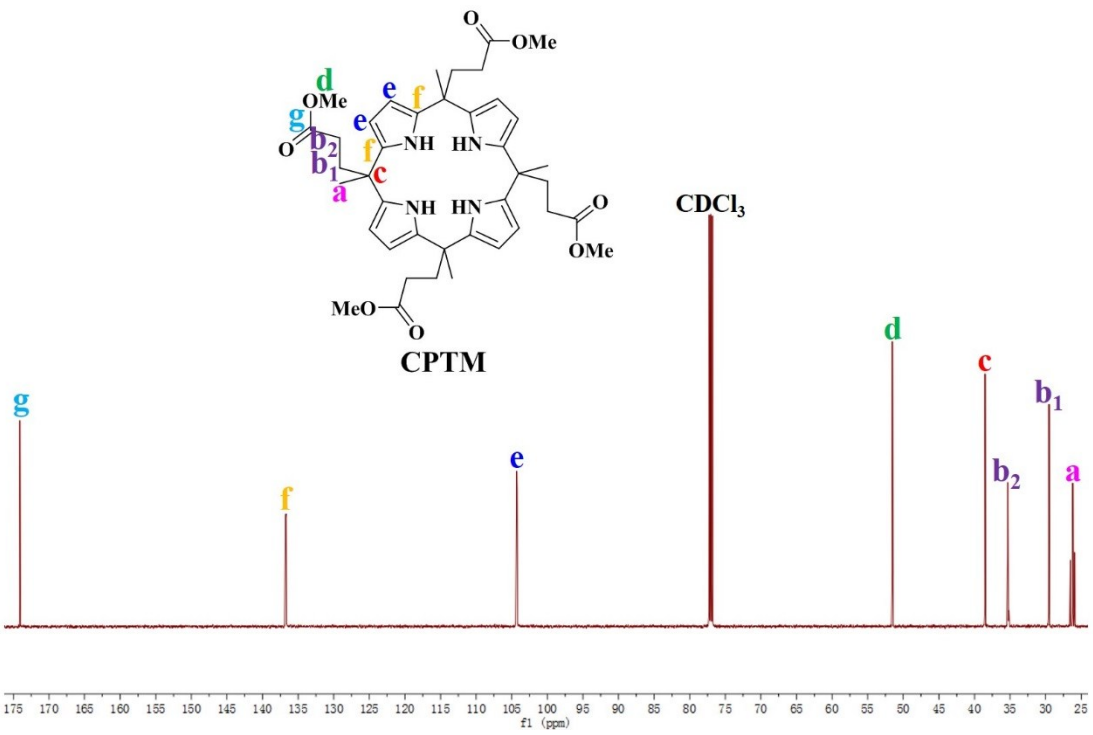


Fig. S5 ^{13}C NMR spectrum of CPTM.

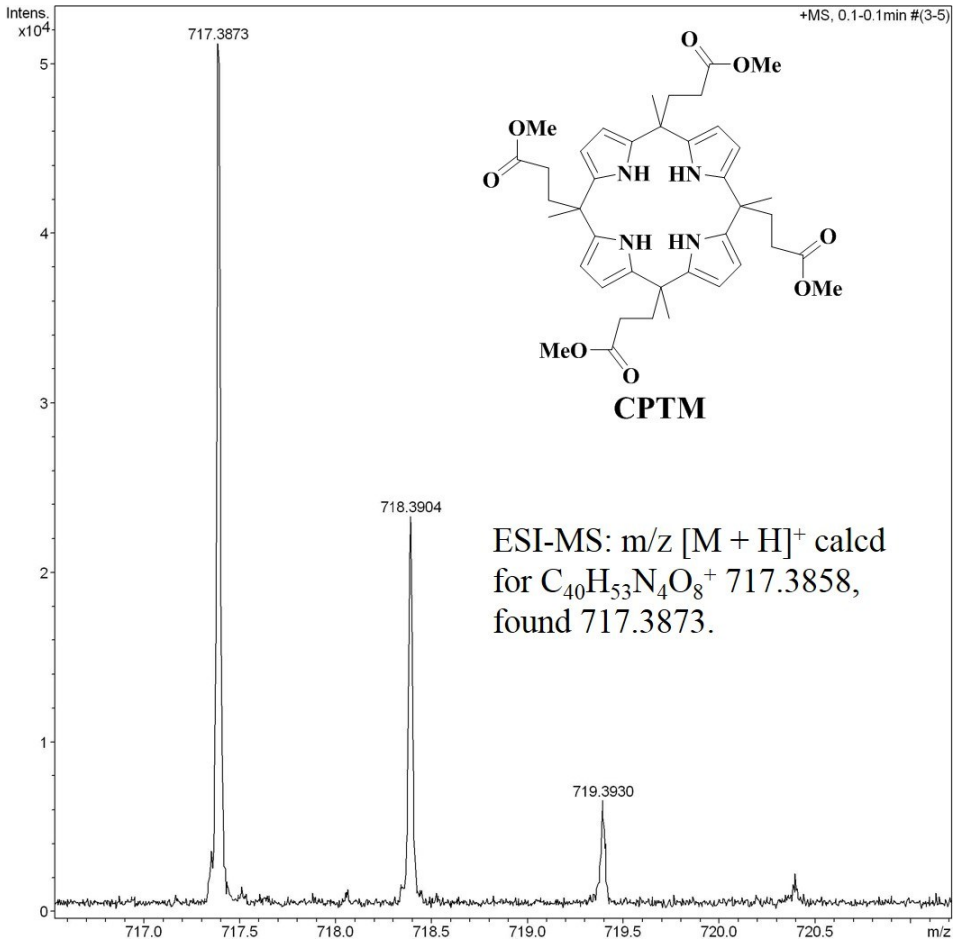


Fig. S6 ESI mass spectrum of CPTM.

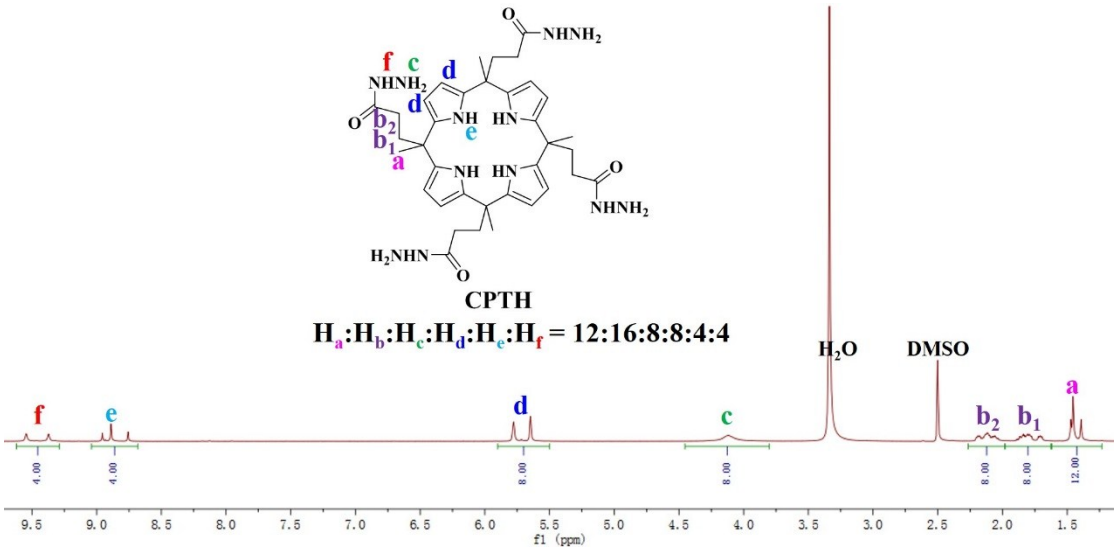


Fig. S7 ^{1}H NMR spectrum of CPTH.

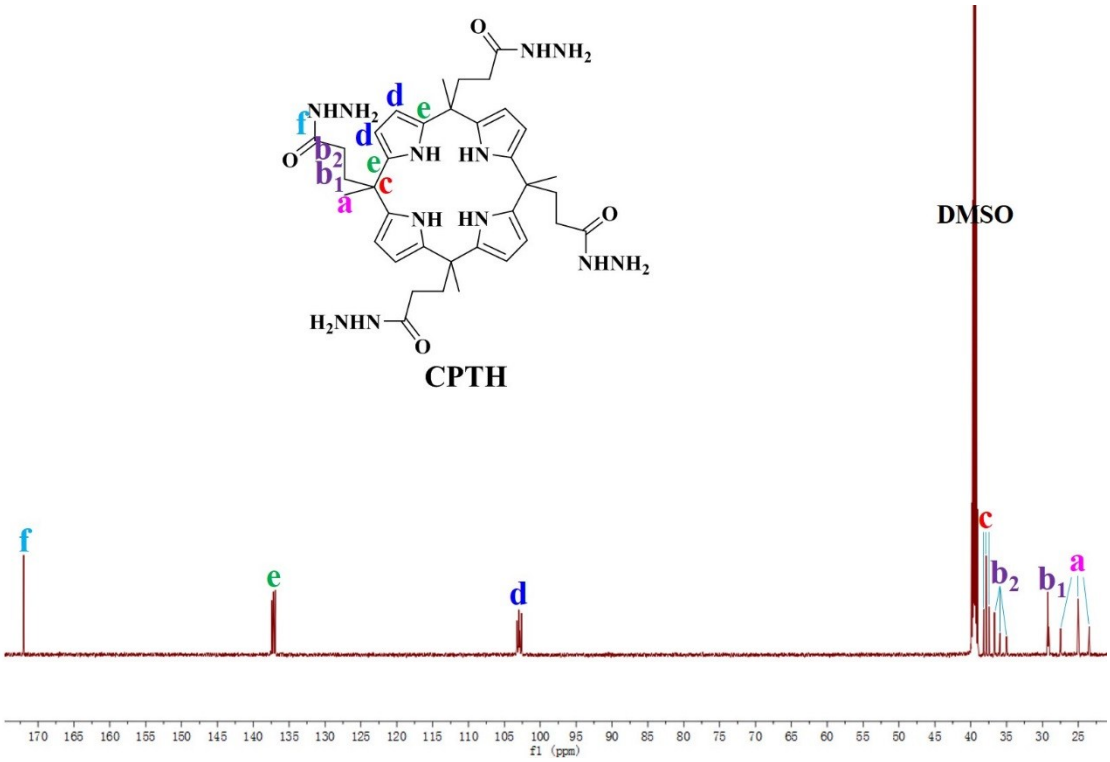


Fig. S8 ^{13}C NMR spectrum of CPTH.

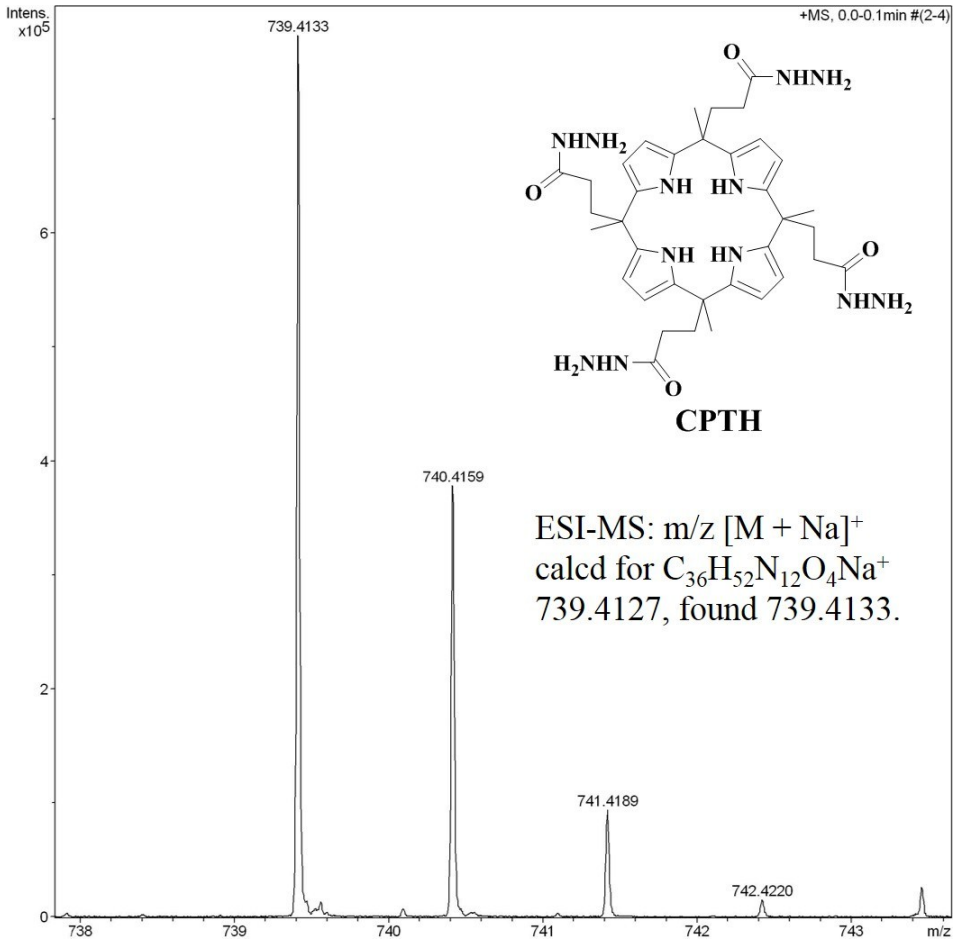


Fig. S9 ESI mass spectrum of CPTH.

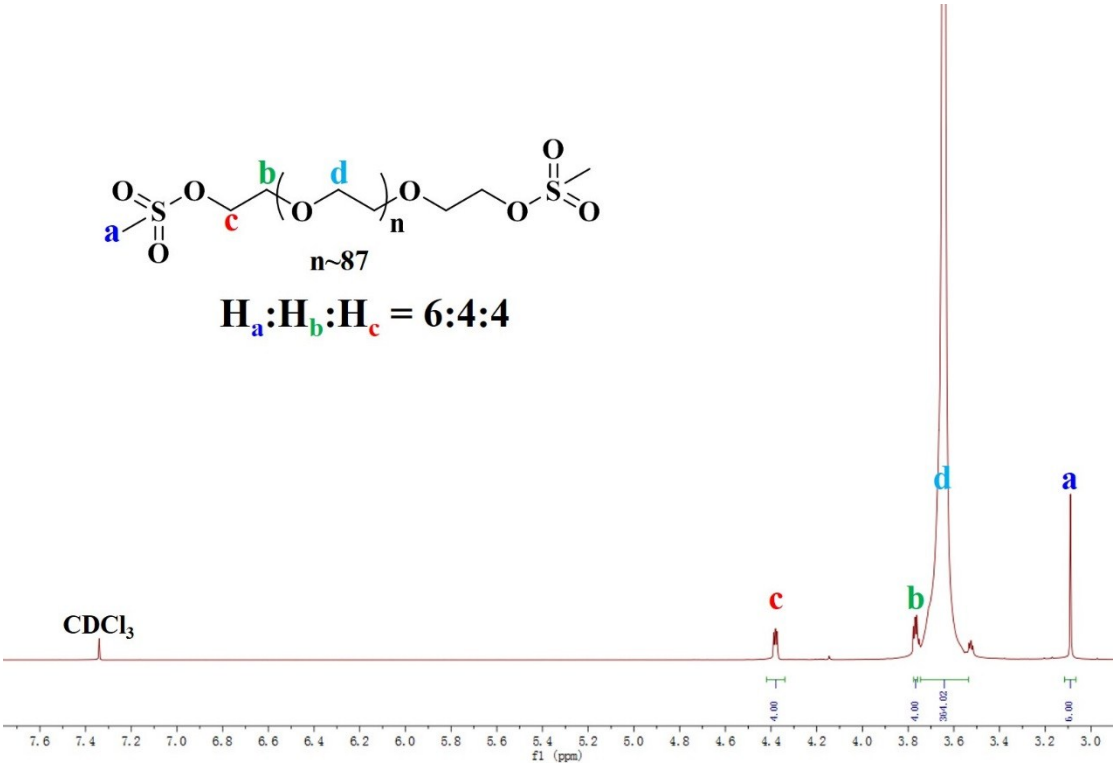


Fig. S10 ^{1}H NMR spectrum of PEG-DM.

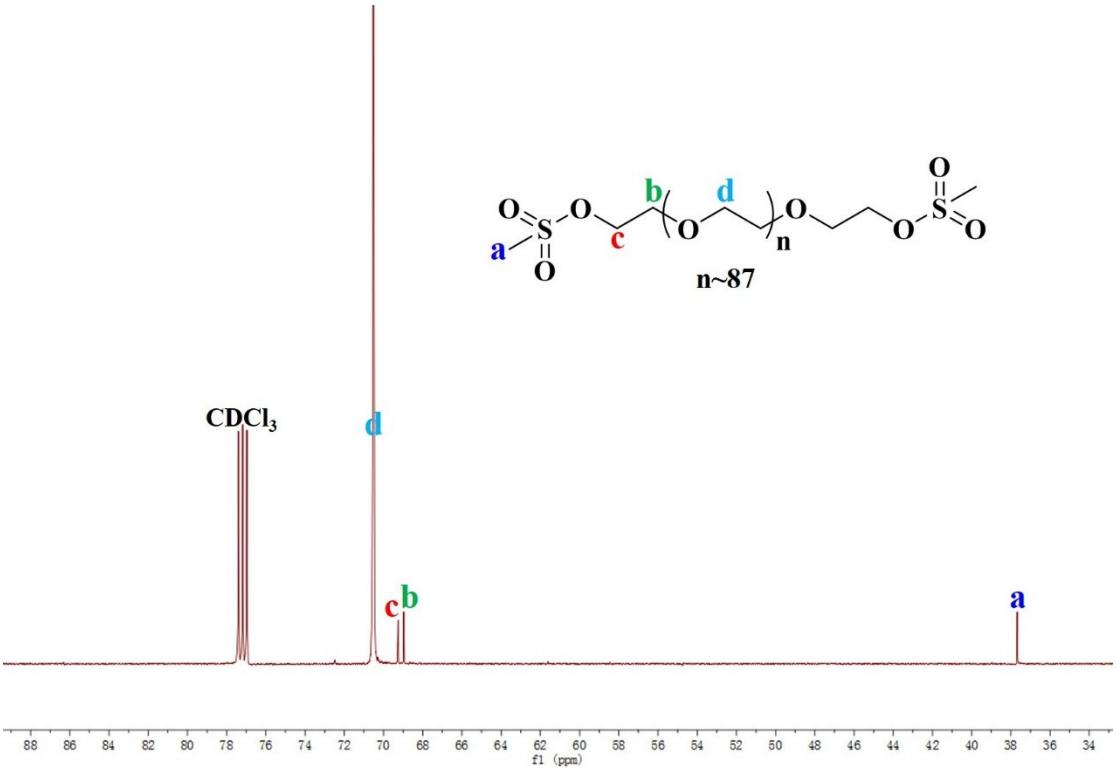
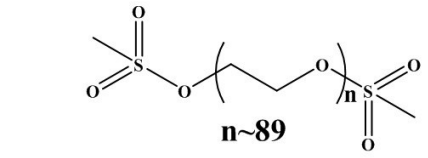
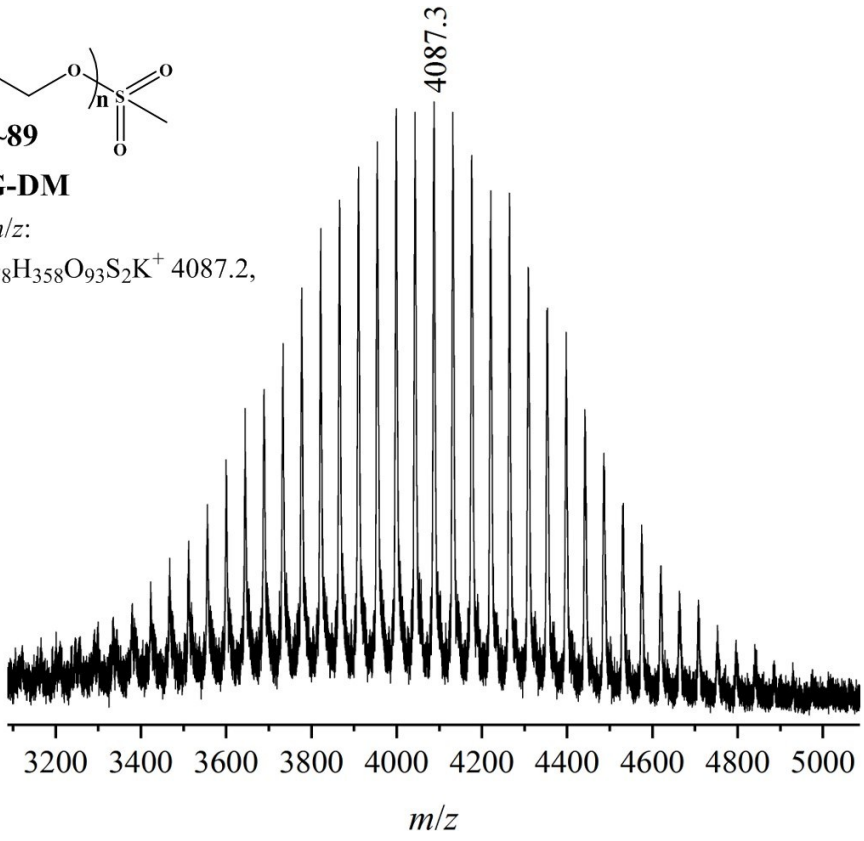


Fig. S11 ^{13}C NMR spectrum of PEG-DM.



PEG-DM

MS (MALDI-TOF) *m/z*:
$[M+K]^+$ calcd for $C_{178}H_{358}O_{93}S_2K^+$ 4087.2,
found 4087.3.



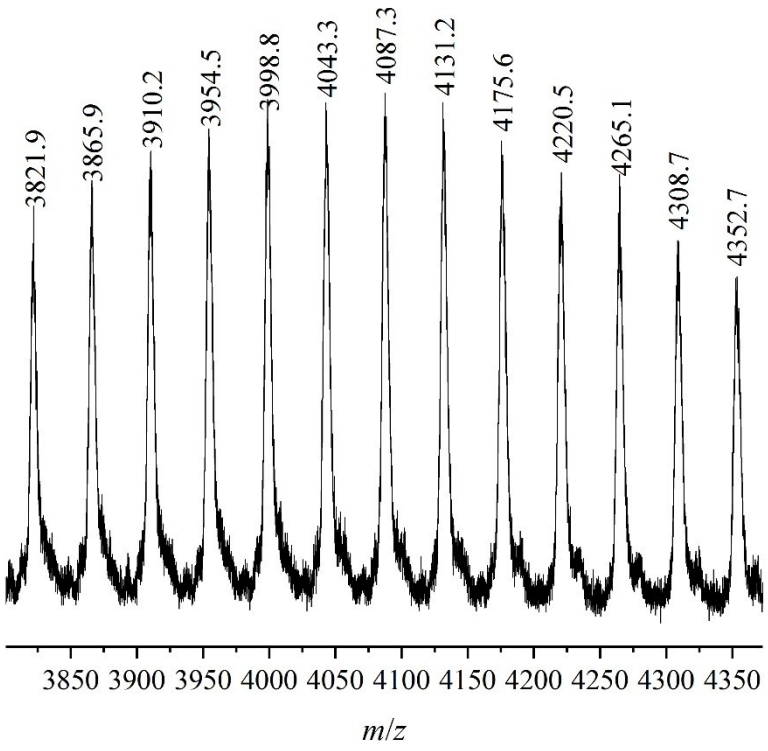


Fig. S12 MALDI-TOF mass spectrum of PEG-DM. Peaks with number labels ascribed to the formula of PEG-DM binding with K^+.

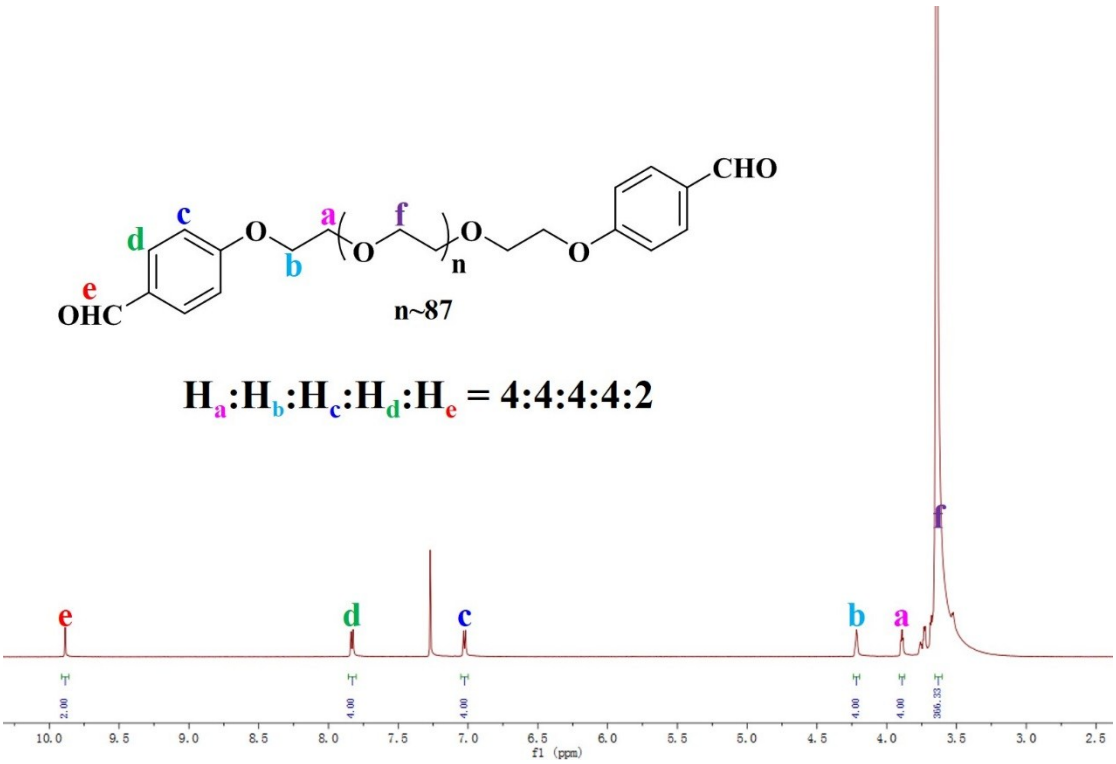


Fig. S13 ^{1}H NMR spectrum of PEG-DA.

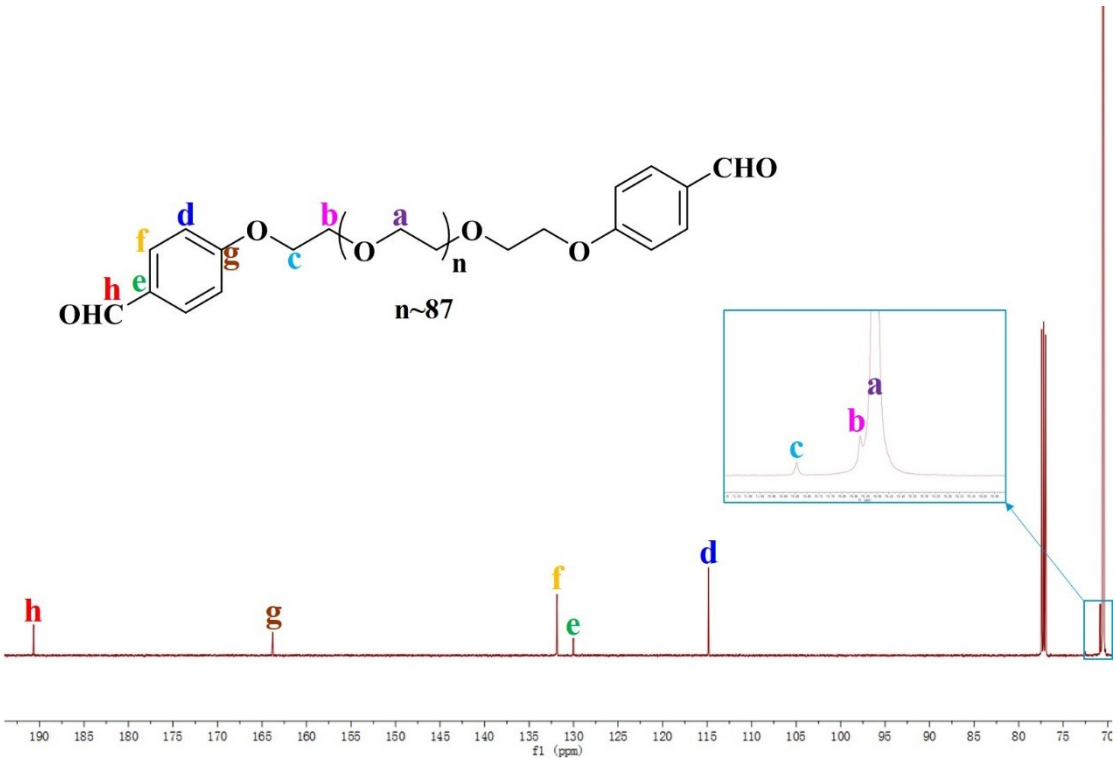


Fig. S14 ^{13}C NMR spectrum of PEG-DA.

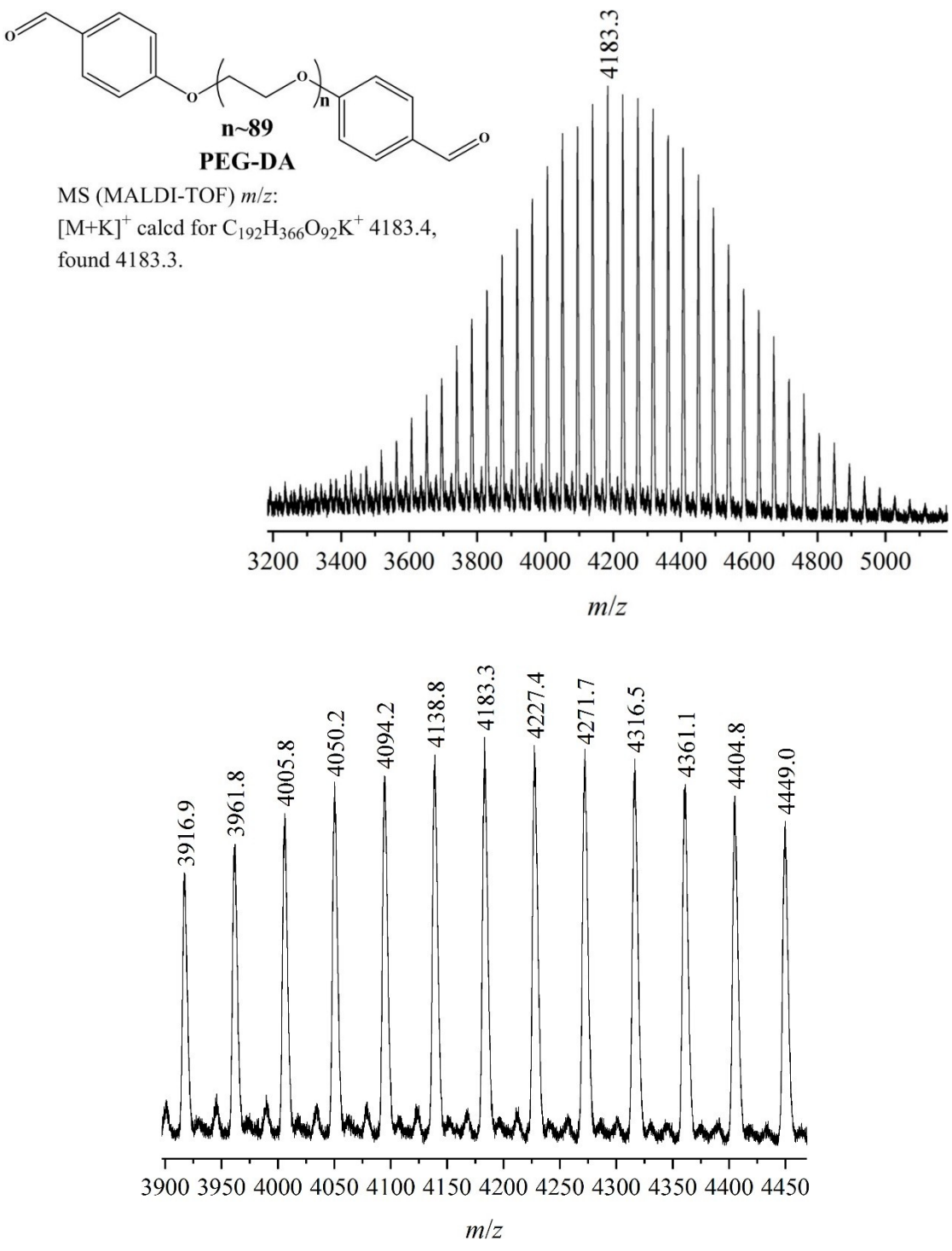


Fig. S15 MALDI-TOF mass spectrum of PEG-DA. Peaks with number labels ascribed to the formula of PEG-DA binding with K^+.

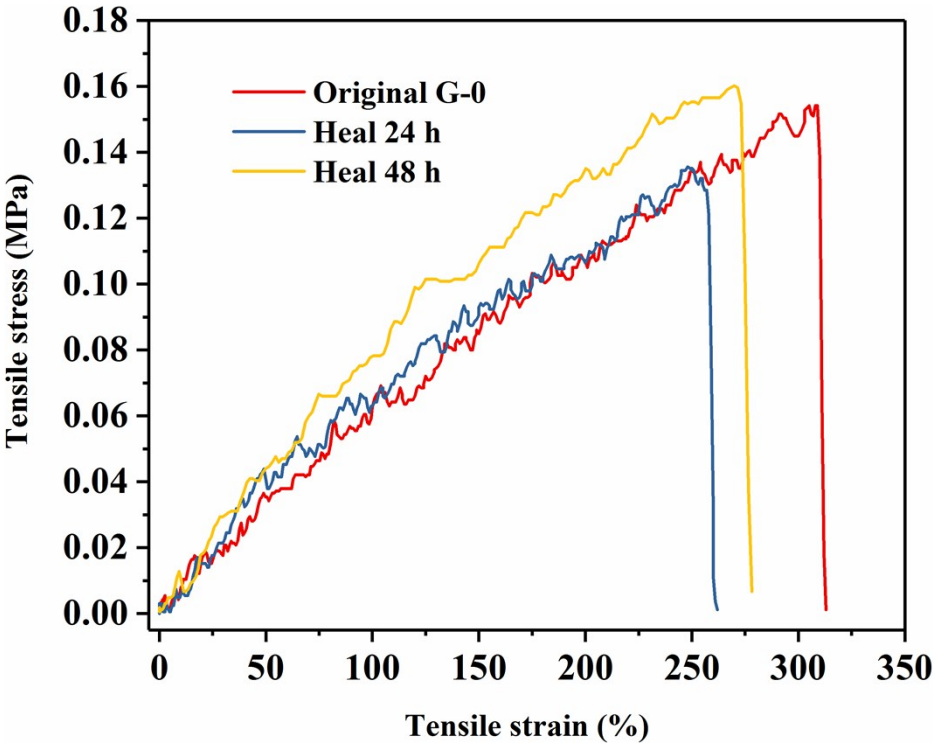


Fig. S16 The tensile stress–strain curves of the original, self-healed hydrogels of G-0.

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