Electronic Supplementary Material (ESI) for Soft Matter.

Supporting Information

Tuning the Dynamics of Metal Ion Crosslinked Hydrogels by Network Structures

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A. Figures

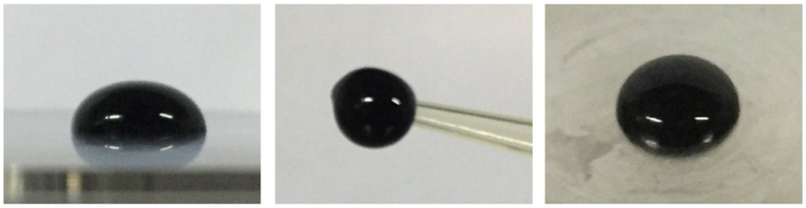

Fig. S1. Optical images of the dopa$_3$-Fe^{3+}-crosslinked hydrogels. The hydrogels were free-standing and adhesive.

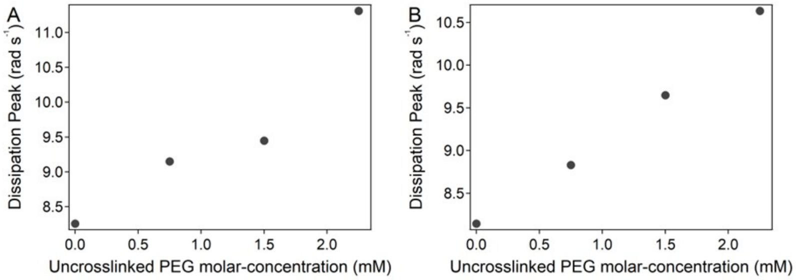

Fig. S2. Comparison of the experimentally obtained (A) and theoretically predicted (B) critical frequency (ω_c) of the dopa$_3$-Fe^{3+}-crosslinked hydrogels made of 112 mg mL^{-1} of 8-armed PEG-dopa (Mw: 15 kDa) and different concentrations of uncrosslinked PEG (Mw: 20 kDa).

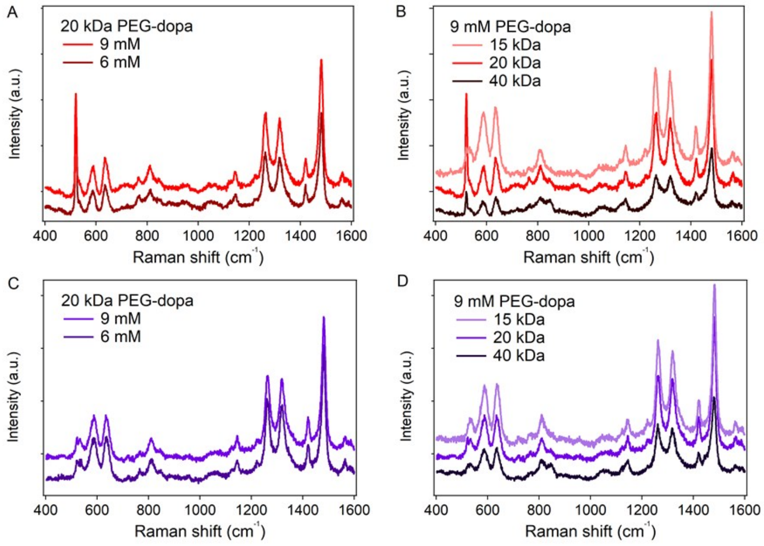

Fig. S3. Raman shift of dopa$_3$-Fe^{3+} hydrogels. (A) Spectra of the hydrogels at pH 11.2 with different polymer concentrations (A) and different polymer molecular weights (B). Spectra of the hydrogels at pH 9 of different polymer concentrations (C) and different polymer molecular weights (D).

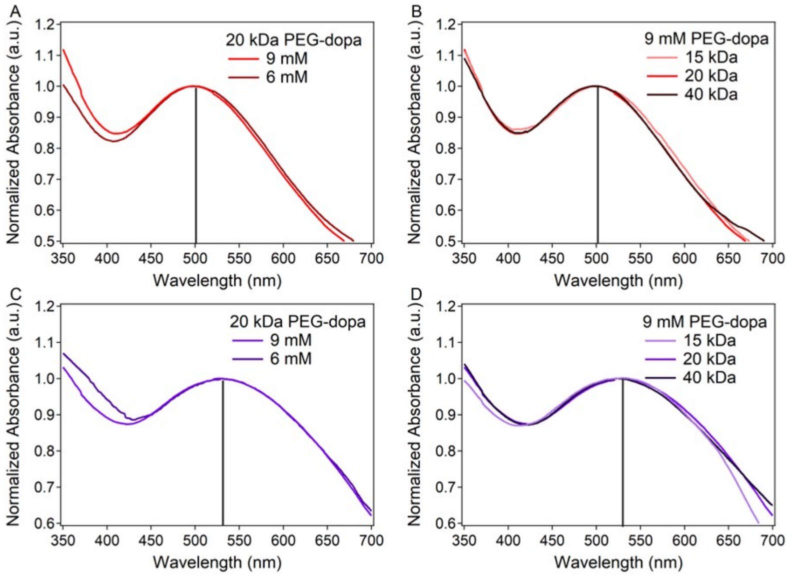

Fig. S4. UV absorbance of dopa$_3$-Fe^{3+} hydrogels. (A) Spectra of the hydrogels at pH 11.2 with different polymer concentrations (A) and different polymer molecular weights (B). Spectra of the hydrogels at pH 9 of different polymer concentrations (C) and different polymer molecular weights (D). The maxima were red-shifted when pH decreased from 11.2 to 9, indicating the change from tris-dopa-Fe^{3+} complexes to bis-dopa-Fe^{3+} complexes.

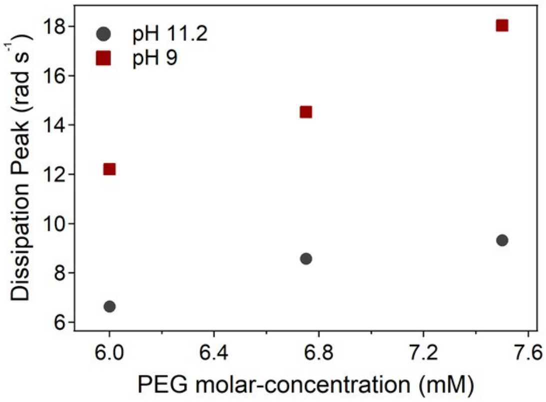

Fig. S5. The change of critical frequency (ω_c) of the dopa-Fe^{3+}-crosslinked hydrogels upon pH switch. The hydrogels were first prepared at pH 11.2 and corresponding ω_c were measured and shown as grey dots. After changing the pH from 11.2 to 9 using HCl. The ω_c of hydrogels were measured again and shown as red squares. The change of ω_c in the same hydrogel sample is consistent with that measured using two independent hydrogel samples.

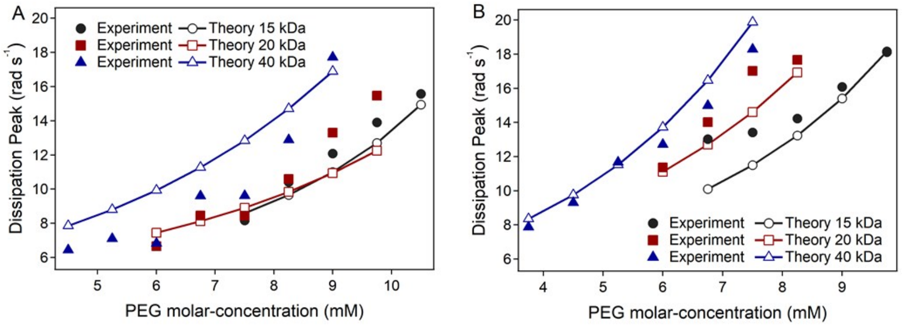

Fig. S6. The critical frequency (ω_c) of the dopa$_3$-Fe^{3+}-crosslinked hydrogels depends on the molecular weight of the PEG polymers. (A) experimental results (filled symbols) and theoretical results (open symbols) of pH 11.2 hydrogels; (B) experimental results (filled symbols) and theoretical results (open symbols) of pH 9 hydrogels.

B. Experimental Procedures

Synthesis of PEG-dopa$_8$. We used the EDC/NHS coupling reaction to conjugate dopamine and polyethylene glycol (PEG). First, 0.08 mmol 8arm-PEG-Succinimidyl Glutarate (PEG-SG$_8$; Mw: 15000, 20000, or 40000; JenKem, Inc) was dissolved in 50ml Milli-Q water. Next, 0.32mmol of EDC (Sigma-Aldrich) and 0.32mmol of NHS (Sigma-Aldrich) was added to PEG solution. 0.24mmol of dopamine and 0.24mmol L-Ascorbic acid were dissolved in PEG solution. pH of the solution is rising to 7.8 through adding NaHCO$_3$. After bubbling nitrogen for 10min to eliminate the dissolved oxygen, the reaction was conducted 24h at room temperature with mild magnetic stirring. The unreacted reactants were removed by dialysis against excess Milli-Q water using the dialysis tubing (Zhuyan Biotech, Nanjing, China) of a cutoff molecular weight of 3.5 kDa. The final product was lyophilized and stored at 4 ℃.

The Fe^{3+}-dopa Cross-Linked Gels. The above described PEG-dopa8 was used for all gel experiments. 100 μL dopa$_3$-Fe^{3+} gel under specific concentration was made as follows: first, polymer solution was prepared by dissolving polymer in 90 μL Tris-buffer. Second, FeCl$_3$ (Sigma Inc) solution was prepared by dissolving FeCl$_3$ in 10 μL Milli-Q water. The final molar ratio of dopa to FeCl$_3$ in pH = 11.2 gel is 3: 1, and it in pH = 9 gel is 2: 1. Third, the polymer solution was mixed with FeCl$_3$ solution, and the gel was physically mixed until gelation, a homogenous color and physical state were established (5 min). We establish samples at a final concentration range between 4.5 mM and 10.5 mM, and the quantity of polymer and FeCl$_3$ change proportionally.

Rheology of Gels. The dynamic properties of the hydrogels were tested using a rheometer (Haake RheoEtress 6000) with parallel plate geometry (C20/1° Ti L). All tests were done 10 min after transferring the gel sample onto the sample stage. Oscillatory shear testing of gels as a function of frequency was performed at constant 1 mrad strain (1% strain) while measuring storage modulus (G') and loss modulus (G"). Water loss during testing was negligible due to typical gap distances between parallel plates of 0.2 mm and the gel is liquid sealed by methylsilicone oil. All tests were performed at 20 ℃.

UV absorbance Spectrophotometry. The dopa$_3$-Fe^{3+} cross-linking stoichiometry was monitored on a UV/Vis spectrophotometer (Jasco V-550) using a quartz cuvette with a path length of 1 mm. Spectral of 9 mM PEG-dopa$_8$ gel was text after increasing pH to 11.2 (dopa: Fe molar ratio of 3: 1) or 9 (dopa: Fe molar ratio of 2: 1) with 1 M Tris-Buffer.

Resonance Raman Spectroscopy. The Raman spectra were acquired using a Renishaw in Via Raman microscope system with a laser excitation at wavelength of λ = 785 nm with 0.6 mW laser output power, and the Raman signals were collected during just 0.2 second of integration time via a 50 magnification objective. The spot size of exciting laser was about 2 μm^2.

C. Theoretical Section

Following the 8-chain model[1], the hydrogel is represented with a volume element of a cube (RVE), within which each 8 polymer chains, corresponding to arms of PEG chains, extend from the cubic center[2]. In the dry state, the cube of RVE is of dimension, l_d. Due to solvent absorption, the cube of the RVE is of dimension l at the current state. The volume of the RVE at the current state is assumed to be the sum of the volume of a dry polymer network and that of the absorbed solvent[3], i.e.,

$$l^3 = (1-\alpha)l_d^3 + \Omega M \quad \text{(S1)}$$

where α = 0 is the fraction of free volume within a dry polymer network, the volume of a single water molecule, and M the number of water molecules. At the current state, the principal stretch of the cube is λ. The stretch of a chain is denoted as λ^{ch}. The geometric constraint that enforces $\lambda^{ch}\,\lambda^{ch}_0 = \sqrt{3}\,\lambda l_d/2$, and Lch0 is the reference length of a polymer chain at the dry state. Dividing both sides of Eq. (S1) by l_d^3, we have

$$1 + \Omega C = \lambda^3 \quad \text{(S2)}$$

where $C=M/l_d^3$ is the nominal concentration of the solvent.

The force-stretch curve of a polymer chain is described by the worm-like chain theory[4], given by

$$F = \frac{k_B T}{\xi}\left[\frac{1}{4}\left(1-\frac{x}{L_c}\right)^{-2} - \frac{1}{4} + \frac{x}{L_c}\right] \quad \text{(S3)}$$

where k_B is the Boltzmann constant, T is the absolute temperature, ξ is the persistence length of the polymer chain, and Lc is the contour length of the polymer, and $x = (\lambda^{ch} - 1)L^{ch}_0$.

Let the RVE at the current state change its dimensions by infinitesimal small amounts, δl. The resulting virtual work done by external forces, denoted as P, will be $3P\delta l$. Meanwhile, the number of iron ions in the block would increase by $X_{iron}\delta M$, with X_{iron} being the molar fraction of free Fe^{3+} in the gel. The virtual work done by the chemical potential of Fe^{3+} should then be $X_{iron}\mu_{iron}\delta M$, where μ_{iron} is the difference between the chemical potential of a free Fe^{3+} ion in the solvent and that in the gel. The virtual work done by the chemical potential of other matter, such as free dopa, is neglected. Based on the principle of virtual work, the change in the internal energy within the RVE[3], denoted as $\delta\mu$, should satisfy $\delta\mu=3P\delta l+\mu\delta M$, with $\mu=X_{iron}\mu_{iron}$. With Eq. (S1), we have $\delta M=3l^2\delta l/\Omega$. Therefore,

$$\delta u = 3\left(P + \mu\frac{l^2}{\Omega}\right)\delta l \quad \text{(S4)}$$

Considering that $\sigma = P/l^2$, where σ is the principal true stress, we have $\delta u = 3(\sigma + \mu/\Omega)ld^3\lambda^2\delta\lambda$. At the current state, we also have $\delta u=\partial u\delta\lambda/\partial\lambda$. Thus,

$$\left[\frac{\partial u}{\partial\lambda} - 3\left(\sigma + \frac{\mu}{\Omega}\right)l_d^3\lambda^2\right]\delta\lambda = 0 \quad \text{(S5)}$$

Let $\delta U=\delta u/ld^3$. With Eq. (S5), we have

$$\left[\frac{\partial U}{\partial\lambda} - 3\left(\sigma + \frac{\mu}{\Omega}\right)\lambda^2\right]\delta\lambda = 0 \quad \text{(S6)}$$

Since $\delta\lambda$ in Eq. (S6) is an arbitrary variable, we have

$$\sigma = \frac{1}{3\lambda^2}\frac{\partial U}{\partial\lambda} - \frac{\mu}{\Omega} \quad \text{(S7)}$$

δU is the sum of the change in the elastic energy of polymer chains, denoted as $U1$ and that in the energy of mixing water with polymers, denoted as $U2$, i.e.,

$$\delta U = \delta U_1 + \delta U_2 \quad \text{(S8)}$$

Among them,

$$\delta U_1 = \nu N \delta\varepsilon^{ch} \quad \text{(S9)}$$

where N is the number of chains per unit reference volume, given by $N = 8/ld^3$, υ is the percentage of chains that take part in forming the 8-chain complex within the RVE, and ε^{ch} is the elastic energy of a single polymer chain at the current state, given by

$$\varepsilon_{ch} = \int_0^{(\lambda^{ch}-1)L_0^{ch}} F dx \quad \text{(S10)}$$

In the theory, we regard that the energy of mixing solvent with polymers is given by[5,6]

$$U_2 = k_B T\left(C\log\frac{\Omega C}{1+\Omega C} + \frac{\chi\Omega C}{1+\Omega C}\right) \quad \text{(S11)}$$

where χ is a measure of the interaction between the polymer and the solvent, given by[7]

$$\chi = \chi_0 + \chi_1\frac{\Omega C}{1+\Omega C} \quad \text{(S12)}$$

where χ_0 and χ_1 are two constants. With Eqs. (S7-S12), we have

$$\sigma = vN\frac{\sqrt{3}}{6\lambda^2}l_d F + \frac{k_B T}{\Omega}\left[\log\left(1-\frac{1}{\lambda^3}\right) + \frac{1}{\lambda^3} + \frac{\chi}{\left(\lambda^3\right)^2} + \frac{\chi_1}{\left(\lambda^3\right)^2}\left(1-\frac{1}{\lambda^3}\right)\right] - \frac{X_{iron}\mu_{iron}}{\Omega} \quad \text{(S13)}$$

It is realistic that a certain amount of PEG chains does not crosslink to the main chain network and may form a second phase and exist as, for example, nanoparticles within gels. These nanoparticles will take up or compete for solvents to occupy significantly large volumes within the RVE, which should affect the interaction energy between polymer chains and the solvent within gels. To account for such effects, we consider that, in the vicinity of the free swelling state of gels,

$$l^3 = (1+\beta)l_d^3 + \Omega M \quad \text{(S14)}$$

where βld^3 is assumed to be a fixed volume occupied by nanoparticles within the RVE. Following the same derivation procedure given above, we obtain

$$\sigma = vN\frac{\sqrt{3}}{6\lambda^2}l_d F + \frac{k_B T}{\Omega}\left[\log\left(1-\frac{1}{\lambda^3 - \beta}\right) + \frac{1}{\lambda^3 - \beta} + \frac{\chi}{\left(\lambda^3 - \beta\right)^2} + \frac{\chi_1}{\left(\lambda^3 - \beta\right)^2}\left(1-\frac{1}{\lambda^3 - \beta}\right)\right] - \frac{X_{iron}\mu_{iron}}{\Omega} \quad \text{(S15)}$$

In the theory, the free swelling state is considered to be at a steady state. At this state, σ=0. Lch0 is given by $L^{ch}_0 = bN_0^{3/5}$, where b is the Kuhn length, which is approximately 1.1nm, N0 is the number of Kuhn segments in one arm of the PEG chain, which is 73 for 10 KDa PEG[8]. The persistence length, ξ is set to be half of the Kuhn length, *b*. The difference between the chemical potential of a free Fe^{3+} in the solvent and that in the gel is given by

$$\mu_{iron} = k_B T\ln\left(X_0 / X_{iron}\right) \quad \text{(S16)}$$

where X_0 is the molar fraction of free Fe^{3+} in the solvent. As suggested in the experiments, the PEG concentration in the solution, denoted as c_p, can have a strong effect on β. For simplification, a linear relation is adopted between them in our analysis, which is given by

$$\beta = \beta_0 + \beta_1 c_p \quad \text{(S17)}$$

where β_0 and β_1 are two constants in the analysis. With Eqs. (S3, S15-S17), the chain force, Fchain, at the steady state can be determined. The breaking rate of bonds formed between PEG and dopa depends on the chain force and is described by Bell's law[9], given by

$$\omega_c = \omega_{c0}\exp\left(\frac{F_{chain}}{F_b}\right) \quad \text{(S18)}$$

where ω_{c0} is the breaking rate at F_{chain}=0, and F_b is a force scale with a unit of pN. Fitting the experimental data[10] yields ω_{c0}=2.6 s-1 and F_b=23.5 pN. The breaking rate of bonds formed between PEG and dopa, ω_c, at the steady state of gels is then taken as the dissipation peak. As suggested in our analysis, PEG chain molecular weight, free Fe^{3+} concentration, and PEG concentration would affect the dissipation peak of the gels. In Fig. 4 (B), υ=0.67 for 40 kDa PEG gels; In Fig. 4 (C), υ=0.38 and for both 15 kDa PEG and 20 kDa PEG gels, and υ = 0.7 and for 40 kDa PEG gels.

References：

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Table S1. Default parameters in the analysis

Item	Parameter	Item	Parameter
N_0	0.6×1025 /m^3[8]	v	0.36 [8]
a	0	ξ	0.55 nm [8]
χ_0	0.2	χ_1	0
Ω	$3\times10\text{-}29$ m^3	T	298 K
k_B	$1.38\times10\text{-}23$ J/K	L_0^{ch}	9.52 nm [8]
β_0	-12	β_1	1.3×105

Table S2. Concentration of PEG or free Fe^{3+} for 15k PEG with pH=11.2

PEG (mmol/L)	In the solvent (mmol/L)	Within the gel (mmol/L)
7.5	20	7.5002
8.25	22	8.2502
9	24	9.0002
9.75	26	9.7502
10.5	28	10.5002

Table S3. Concentration of PEG or free Fe^{3+} for 20k PEG with pH=11.2

PEG (mmol/L)	In the solvent (mmol/L)	Within the gel (mmol/L)
6	16	6.0002
6.75	18	6.7502
7.5	20	7.5002
8.25	22	8.2502
9	24	9.0002
9.75	26	9.7502

Table S4. Concentration of PEG or free Fe^{3+} for 40k PEG with pH=11.2

PEG (mmol/L)	In the solvent (mmol/L)	Within the gel (mmol/L)
4.5	12	4.5002
5.25	14	5.2502
6	16	6.0002
6.75	18	6.7502
7.5	20	7.5002
8.25	22	8.2502
9	24	9.0002

Table S5. Concentration of PEG or free Fe^{3+} for 15k PEG with pH=9

PEG (mmol/L)	In the solvent (mmol/L)	Within the gel (mmol/L)
6.75	27	10.12502
7.5	30	11.25002
8.25	33	12.37502
9	36	13.50002
9.75	39	14.62502

Table S6. Concentration of PEG or free Fe^{3+} for 20k PEG with pH=9

PEG (mmol/L)	In the solvent (mmol/L)	Within the gel (mmol/L)
6	24	9.00002
6.75	27	10.12502
7.5	30	11.25002
8.25	33	12.37502

Table S7. Concentration of PEG or free Fe^{3+} for 40k PEG with pH=9

PEG (mmol/L)	In the solvent (mmol/L)	Within the gel (mmol/L)
3.75	15	5.62502
4.5	18	6.75002
5.25	21	7.87002
6	24	9.00002
6.75	27	10.12502
7.5	30	11.25002

Table S8. Concentration of PEG or free Fe^{3+} for 15k PEG with unconnected PEG

PEG (mmol/L)	In the solvent (mmol/L)	Within the gel (mmol/L)
7.5	20	7.5002
8.25	20	7.5002
9	20	7.5002
9.75	20	7.5002