Chinese Chemical Letters 34 (2023) 108028

Contents lists available at ScienceDirect

Chinese Chemical Letters

journal homepage: www.elsevier.com/locate/cclet

Photoregulated supramolecular hydrogels driven by polyradical interactions

Zehao Gong, Qiang Yan*

State Key Laboratory of Molecular Engineering of Polymers and Department of Macromolecular Science, Fudan University, Shanghai 200433, China

ARTICLE INFO

Article history:
Received 2 November 2022
Revised 24 November 2022
Accepted 28 November 2022
Available online 30 November 2022

Keywords:
Radical-radical interactions
Polyradical
Supramolecular hydrogel
Polymer network
Photoresponsiveness

ABSTRACT

Organic radical as a powerful tool has been extensively applied in synthetic chemistry. However, harnessing radical-mediated noncovalent interactions to fabricate soft materials remains elusive. Here we report a new category of supramolecular hydrogel system held by multiple radical-radical (polyradical) interactions, and its photosensitive cross-linking structure. A simple polyacrylamide with triarylamine (TAA) pendants is designed as the precursor. The TAA units in polymer can be converted into active $TAA^{\bullet+}$ radical cations with light and further associate each other *via* $TAA^{\bullet+}$–$TAA^{\bullet+}$ stacking interactions to form stable supramolecular network. Temporal control of the light irradiation dictates the degree of radical stacks, thus regulating the mechanical performance of the resulting hydrogel materials on-demand. Moreover, the reversible collapse of this hydrogels can be promoted by adding radical scavenger or exerting reduction voltage.

Supramolecular hydrogels, as a class of soft-matter materials that consist of physically cross-linked networks, have continued to receive attention owing to their functional uniqueness in self-adaptivity and stimuli-responsivity [1–6]. Unlike common covalent hydrogels with permanent chemical cross-linking, supramolecular hydrogels are held by noncovalent interactions, which endow them with tunable dynamic, reversible behaviors. To date, chemists have exploited a variety of noncovalent forces, such as H-bonding [7–10], electrostatic interactions [11–15], metal coordination [16–18], host-guest recognition [19–23], and charge-transfer interactions [24–26], to create supramolecular hydrogel systems. In addition to these extensively studied noncovalent interplays, we are curious whether there exist other new categories of weak bonds that could direct (or assist) the supramolecular hydrogelation and adjust their intrinsic properties.

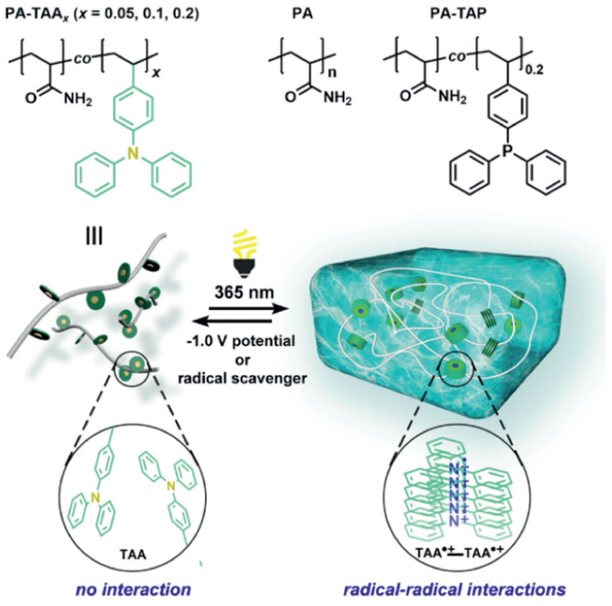
Organic radicals, spin compounds with unpaired electrons, were discovered as early as 1900s and have long been used in synthetic chemistry [27]. In spite of the fact that radical chemistry is well studied, it is not until recently that chemists have utilized radical-induced noncovalent interactions to design stable supramolecular systems [28]. For instance, the earlier work by Stoddart group has shown that intermolecular radical-radical interactions can be used to fabricate molecular motors [29,30]. Jiao *et al.* have developed a series of host-based radical complexes, which offers new horizons for supramolecular catalysis and photothermal therapeutics [31–33]. Recently, some nascent work have shown that radical dimerization and oligomerization enable hierarchically molecular self-assembly into highly ordered nanostructures [34–36]. However, the potential of radical-radical interactions has yet been explored in macroscopic supramolecular materials formation. To solve this unmet challenge, in this study, we present a novel supramolecular hydrogel system based on radical-radical interactions and show its photoregulated mechanical performance.

The key to driving radical-induced hydrogelation is the pursuit of suitable radical precursors that are inactive, neutral species in normal, but can be translated into active, associable radicals under external stimuli for crosslinking. Previously, triarylamine (TAA) has been described as an effective radical generating species. It can convert to a radical cation ($TAA^{\bullet+}$) in response to light and pack into nanoscale assemblies *via* $TAA^{\bullet+}$–$TAA^{\bullet+}$ interactions [37,38]. Inspired by these, only using water-soluble polyacrylamides with different contents of TAA pendants ($PA\text{-}TAA_x$, $x = 0.05$, 0.1 and 0.2, the synthesis and characterization in Supporting information, Schemes S1 and S2, Figs. S10–S13), we pioneer the construction of a new family of supramolecular hydrogels held by photoinduced multiple radical-radical (polyradical) interactions (Scheme 1). Moreover, temporal control of light irradiation to vary the stacking degree of TAA radical species can realize tuning of the resulting hydrogel strength over a broad mechanical window (0.2–171 kPa), which would inspire an alternative mechanism for *in situ* photo-processing of soft materials.

---

* Corresponding author.
E-mail address: yanq@fudan.edu.cn (Q. Yan).

https://doi.org/10.1016/j.cclet.2022.108028



Scheme 1. Structure of triarylamine-containing polyacrylamide (PA-TAA) and its polymer controls (PA and PA-TAP), and schematic of photoregulated supramolecular hydrogelation of PA-TAA based on radical-radical interactions and its reversible hydrogel dissociation *via* chemical (radical scavenger) or electrical stimuli (voltage).

Preliminary studies used PA-TAA$_{0.2}$ as a model because of its highest content of TAA functional units. In aqueous solution, this polymer ($c = 0.2$ mmol/L) presented a colorless sol-state. Interestingly, upon exposure to UV light (365 nm), this sol can turn rapidly into a blue colored hydrogel within ~10 min (Fig. 1a). Quantitative zero-shear viscous measurement (Fig. 1b) showed that the light triggers an appreciable increase in viscosity (69 Pa s) while the initial sol had a negligible increase over that of native water ($\eta_0 = 10^{-3}$ Pa s), confirming this photosensitive sol-to-gel transition [39]. Since the inverted vial test hinted the free-standing behavior of the formed hydrogel, we deduced that it may possess favorable mechanical properties. To identify this point, rheological tests were carried out to detect the modulus change before and after light trigger (Fig. 1c). Prior to irradiation, the moduli were quite low (<10 Pa) and the loss modulus (G'') was greater than the storage modulus (G'), indicating the free-flowing sol-state of PA-TAA$_{0.2}$. However, an abrupt increase in modulus was observed as external light was exerted. The crossover of G' and G'' positioned at ~3 min, which is regarded as the critical irradiation time (t_c) for gelation. In the presence of light for 10 min, the sol transformed into a solid-like gel, as evidenced by the $G' > G''$ over the whole frequency range of 0.1–100 Hz, and its storage modulus can attain a high value of 9.6 kPa (Fig. 1d). As control, we also prepared two contrasts, a polyacrylamide lack of TAA groups (PA) and a triarylphosphine-bearing polyacrylamide (PA-TAP) in which the nitrogen atom is replaced by a phosphorus atom. However, neither PA nor PA-TAP could be gelated even with extended irradiation time (Figs. 1a and b, Figs. S1 and S2 in Supporting information). This points to that these TAA groups play decisive roles in driving the polymer hydrogelation.

Likewise, the other two kinds of TAA-bearing polyacrylamides are capable of forming hydrogels under the same treatment (Figs. S3 and S4 in Supporting information). By contrast, their moduli were determined to be 5.4 kPa for PA-TAA$_{0.1}$ and 1.9 kPa for PA-TAA$_{0.05}$. The values are weaker than that of PA-TAA$_{0.2}$, suggesting that the mechanical strength of the obtained gels exhibits a dependence on the TAA content.

To affirm the radical-radical interactions of TAA units is the major reason to govern this physical hydrogelation, we studied the optoelectronic properties of the polymer in dilute solution. By UV-vis spectroscopy, PA-TAA$_{0.2}$ ($c = 5 \times 10^{-3}$ mmol/L) showed a typical TAA absorption peak at 305 nm in the absence of light, while upon exposure to light two new absorbance bands in long-wavelength region appeared around 360 nm and 670 nm (Fig. 2a) and as a result the solution turned blue. Consistent with the previous studies on TAA small molecules [40,41], the peak at 670 nm accords with the characteristic absorption of the TAA$^{•+}$ radical cation generated by photoinduced electron transition, and the peak at 360 nm arises from their π-stacking complex [42]. As the irradiation proceeded, the absorption intensity ascribed to TAA$^{•+}$ was enhanced, whereas the free TAA absorption depressed (Fig. 2a, inset), indicating that

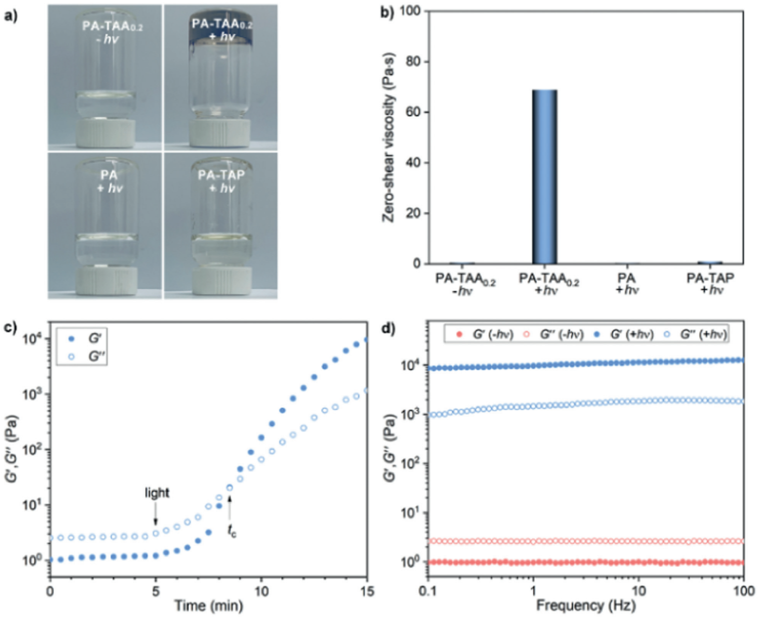


Fig. 1. (a) Inverted vial tests and (b) quantitative zero-shear viscosities of PA-TAA$_{0.2}$, PA and PA-TAP in the absence or presence of light irradiation. (c) Rheological variation of PA-TAA$_{0.2}$ plotted against irradiation time. At 0–5 min (blank), 5–15 min (light), and t_c is the critical irradiation time for gelation. (d) Modulus mutation of PA-TAA$_{0.2}$ before and after 10 min of light irradiation showing the photocontrolled hydrogelation.

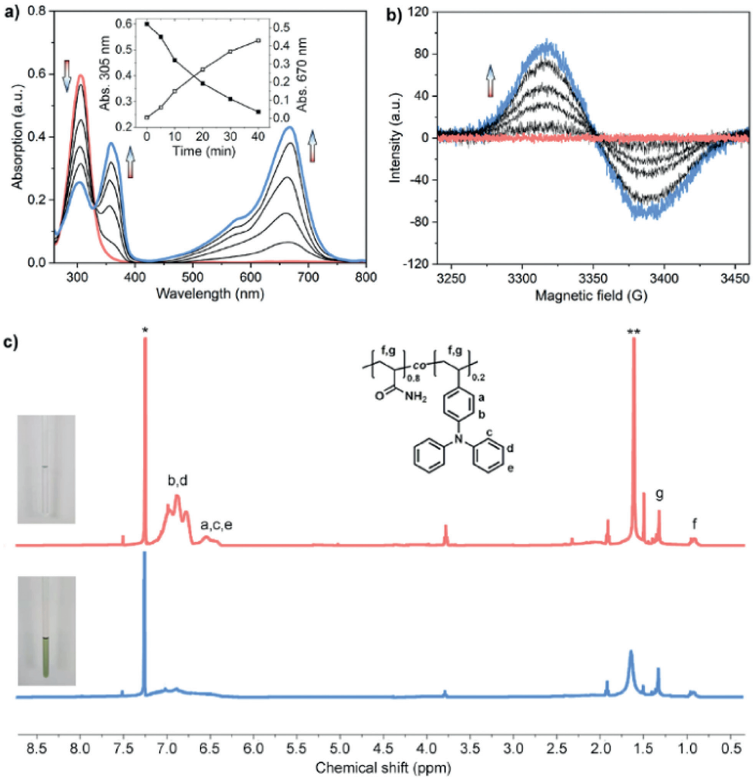


Fig. 2. (a) UV-vis spectra for PA-TAA$_{0.2}$ solution as a function of irradiation time (0–40 min, red to blue). Inset: absorption variation of 305 nm (solid squares) and 670 nm (open squares) plotted *versus* irradiation time. (b) EPR spectra of PA-TAA$_{0.2}$ as a function of irradiation time (0–40 min, red to blue). (c) NMR spectra showing PA-TAA$_{0.2}$ in CDCl$_3$ before and after light treatment (*: CDCl$_3$; **: H$_2$O; photographs indicate the color change of polymer solution, colorless to blue).

the extension of light stimulation is benefit to enlarge the stacking number of TAA$^{\bullet+}$ species. In addition, the fluorescent change of the polymer solution was recorded. Its emission intensity at 472 nm gave a considerable increase in the first 30 min, accompanied by a red-shift to 493 nm (Fig. S5 in Supporting information). This is due to the yielding of TAA$^{\bullet+}$ radical cations, which have unpaired electrons both in their ground and excited states that can act as radical luminophores for doublet emission and thus result in a fluorescent enhancement [43]. Similar phenomenon has also been found in other organic radical chromophores [44,45]. The emission showed a subsequent declining process, which could be attributed to the exciton quenching caused by the aggregation of generated radicals through radical-radical interactions.

Electron paramagnetic resonance spectroscopy (EPR) directly probed the formation of TAA$^{\bullet+}$. As shown in Fig. 2b, no EPR effect was observed without light, but after photoreaction a typical EPR signal at 3320 G emerged and enhanced over time, and its g-factor was calculated to be 2.019. This result is close to the data of TAA derivatives in other literatures [46], corroborating the fact that most of TAA groups in the polymer are gradually converted from the neutral form to their radical ones. NMR experiments further revealed that the proton signals assigned to TAA species ($\delta = 6.2$–7.1 ppm) were strongly suppressed after UV illumination (Fig. 2c). This means that the formed radical cations bind each other *via* TAA$^{\bullet+}$–TAA$^{\bullet+}$ interactions, which noncovalently cross-link the polymer into a supramolecular network. A possible mechanism is on the basis of charge hopping effect [37], that is, upon irradiation the triarylamine species can transform into a triarylammonium cationic radical while the excited charge can hop onto another species, thus allowing the association of adjacent radical cations through the delocalized charge. This attractive interaction should be higher than that of the repulsive forces among the radical cations, by which the pendant TAA species can assemble each other. In the same way, we also surveyed PA-TAP, a polymeric analogue of PA-TAA. In contrast, it had no EPR pattern in the presence of light, indicating that TAP species is not a photogenerated radical precursor, unlike TAA (Fig. S6 in Supporting information).

After knowing that the photosensitive polyradical interactions are the primary driving force to induce supramolecular cross-linking, we wondered whether the mechanical strength of these hydrogels could be tuned by control of this kind of interactions. To this end, their modulus change was monitored versus irradiation time. Clearly, as prolonged the exposure from 5 min to 50 min, the gel modulus (G') displayed a continuous increase ranging from 0.2 kPa to 171 kPa (Fig. 3a and Fig. S7 in Supporting information). This suggests that the density of radical-radical crosslinks inside the hydrogel is growing with irradiation and thus results in a light-dependent mechanical reinforcement. On the other hand, tensile tests also supported this point of view. From the stress-strain curve, the fracture stress gave a gradual elevation as a function of irradiation time and the upper limit attained 124 kPa, whereas the elongation at break decreased with the irradiation (480% → 260%, Fig. 3b), in agreement with the tensile feature of conventional supramolecular hydrogels [6,14]. Notably, the hydrogel mechanics no longer altered over 50 min light irradiation. This is because the increment of supramolecular junctions impedes the chain movement, which in turn prevents the further radical stacks.

Scanning electron microscope (SEM) visualized a considerable change in the hydrogel microstructure with the cross-linking density. Upon 10 min of light treatment, a 3D interconnected, porous network formed could be observed, and their average porosity was larger at 26.4 µm, typical for the internal architecture of a slight cross-linked gel (Fig. 3c). Extending the trigger to 50 min the network became dense and compact, forming smaller pores of ~8.5 µm (Fig. 3d). This significant reduction in pore size arises from the increase of the degree of crosslinkings [39,47], which

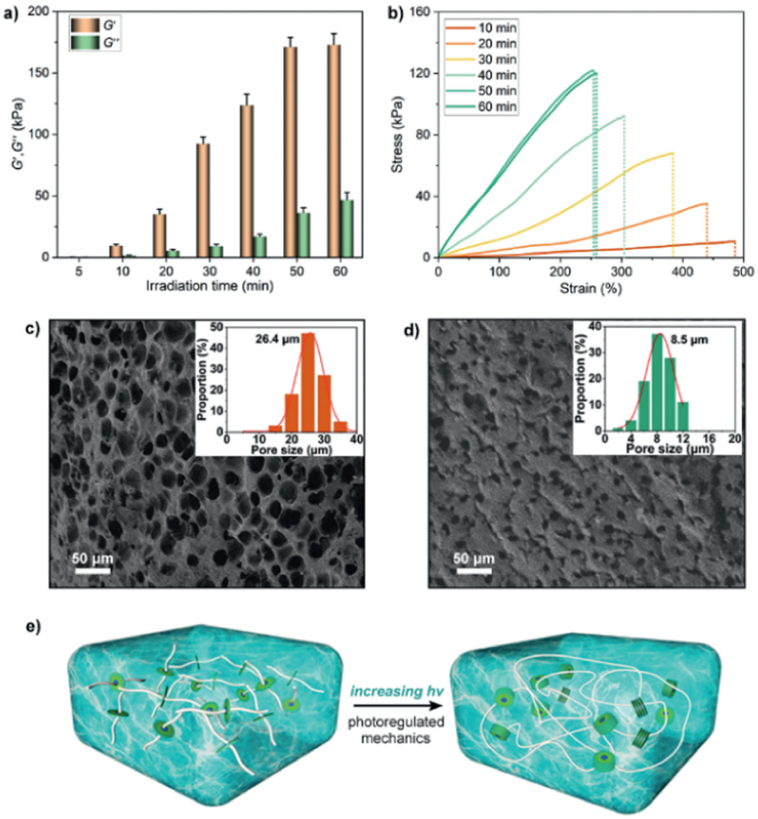


Fig. 3. (a) Photoregulated modulus strengthening of PA-TAA$_{0.2}$ hydrogel monitored by rheology. (b) Stress-strain curves of the PA-TAA$_{0.2}$ hydrogel under various irradiation time. SEM images showing the internal network structures of PA-TAA$_{0.2}$ hydrogel at (c) 10 min and (d) 50 min irradiation. (e) Schematic of the proposed mechanism on light-dependent regulation of radical stacking number and degree.

evidences that light can facilitate the accumulation of radical stacking domains (Fig. 3e), matching the said spectrometric and rheological results.

As well, the other two PA-TAA samples manifested similar light-strengthened mechanical feature. But in comparison, their modulus rise was lower than that of PA-TAA$_{0.2}$ (Fig. S8 in Supporting information, 0.1 kPa → 16.5 kPa for PA-TAA$_{0.1}$ and 0.1 kPa → 3.1 kPa for PA-TAA$_{0.05}$) even though applying more than 2 h irradiation, due to their less contents of TAA functionalities interior.

In general, the dynamics of noncovalent connections confers the supramolecular hydrogels of self-healing behavior [3,5]. Our radical-induced hydrogels also possess this function. We selected an optimal hydrogel (PA-TAA$_{0.2}$ with 50 min light irradiation) to monitor its self-recovery process by rheology analysis using the shear amplitude sweeping mode (Fig. 4a). At a low shear strain (1%), the polymer can maintain stiff state ($G' > G''$), but after the shear strain improved to 300% it collapsed rapidly ($G' < G''$), indicating a gel-to-sol dissociation. Subsequently, if returning to the low strain mode, the gel state and its mechanical strength can recover, and this cycle can be reproduced (Fig. S9 in Supporting information). To quantitatively assess the self-recovery ability, we compared the stress-strain properties between the original and mended samples at different repairing cycles. It was found that the hydrogel could retain >90% healable efficiency even though experiencing 10 rounds of test (Fig. 4b). It can be drawn that such supramolecular hydrogel constituted by polyradical interactions owns satisfactory self-healing ability.

The reversibility and responsiveness of such radical-induced noncovalent hydrogelation is highly desired. To fulfil this purpose, we introduced radical scavenger into the hydrogel system and checked whether it could be dissociated. Selecting sodium thiosulfate ($S_2O_3^{2-}$) or L-ascorbic acid (VC) as the irritant because both are commonly used for the radical trapping [48], monitoring the moduli change against incubation time can reflect the hydrogel transition process. In the absence of stimuli, the gel strength remained invariable (Fig. 4c, black line). However, remarkable mechanical loss occurred when $S_2O_3^{2-}$ or VC solution (10 mmol/L) that is capable of converting TAA$^{\bullet+}$ to its neutral TAA form was added, indicating a complete gel collapse (Fig. 4c, blue and red lines). In comparison, VC exhibited better radical scavenging ability than that of $S_2O_3^{2-}$ since its gel-to-sol transition became faster. On the other hand, exerting negative potentials (−1.0 or −2.0 V) to reduce the radicals can achieve the same effect, and that the higher the voltage is the faster the dissociation rate is (Fig. 4d).

In conclusion, harnessing new forms of noncovalent bonds to build up supramolecular materials offers continuous impetus to engineer novel functional materials. This work describes the first dynamic hydrogel system formed by polyradical interactions. In this system, only requiring a simple water-soluble polymer with TAA units, the supramolecular hydrogelation can be access by photocontrolled TAA$^{\bullet+}$–TAA$^{\bullet+}$ radical association. This radical-induced hydrogel system has potential to use in the field of conducting hydrogels since radical-type conducting polymers are considered as a new family of conducting materials. On the other hand, spin compounds usually own ferroelectric or electromagnetic function, especially the organic radicals can align orientationally. The TAA$^{\bullet+}$–TAA$^{\bullet+}$ interactions can assist the radicals to stack in an axial direction, which might facilitate new ferroelectric or electromagnetic hydrogels. Moreover, such a polyradical binding effect can be *in situ* adjusted by light irradiation time, which suggests a distinct strategy for optical manipulation of the mechanical performance and dynamic functions towards soft matters apart from the commonly used light control methods, such as photoisomerization and photoreaction [49]. The relationship between radical-radical

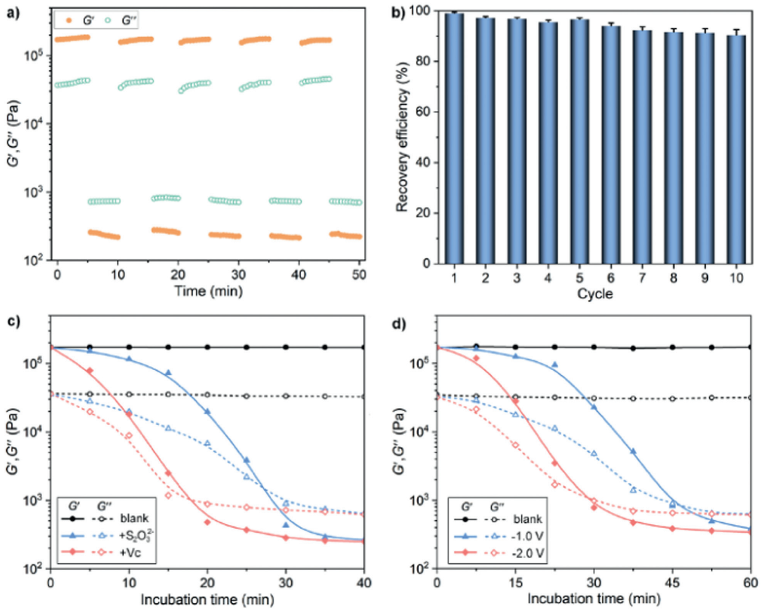


Fig. 4. Studies on the self-healing behavior of PA-TAA$_{0.2}$ hydrogel. (a) Changes of storage and loss moduli tested by oscillatory rheology: The hydrogel was exposed to a 300% strain for complete collapse and applied 1% strain during the recovery process. (b) Column plot of the hydrogel self-recovery efficiency versus tensile cycles. Error bars in (b) denote the deviations from three parallel tests. Studies on the reversible dissociation of PA-TAA$_{0.2}$ hydrogel. (c) Changes of storage and loss moduli upon addition of various radical scavengers: blank (black), 10 mmol/L of $S_2O_3^{2-}$ (blue), and 10 mmol/L of VC (red). (d) Changes of storage and loss moduli upon exerting various reducing potentials: blank (black), −1.0 V (blue), and −2.0 V (red).

interactions and intrinsic properties of hydrogels requires to be uncovered in future studies; however, this study would open a promising direction of radical-mediated supramolecular functional materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the fund support of the National Natural Science Foundation of China (Nos. 21674022 and 51703034), the National Defense Science and Technology Innovation Zone (No. 163 Program), and the Shanghai Rising-Star Program (No. 19QA1400700). We thank the Prof. Guo Li in Shaanxi Normal University for the help of hydrogel mechanical characterization.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cclet.2022.108028.

References

[1] E.A. Appel, J.del. Barrio, X.J. Loh, O.A. Scherman, Chem. Soc. Rev. 41 (2012) 6195–6214.
[2] L. Voorhaar, R. Hoogenboom, Chem. Soc. Rev. 45 (2016) 4013–4031.
[3] Y. Yang, M.W. Urban, Adv. Mater. 5 (2018) 1800384.
[4] J. Hoque, N. Sangaj, S. Varghese, Macromol. Biosci. 19 (2019) 1800259.
[5] J. Xie, P. Yu, Z.H. Wang, J.S. Li, Biomacromolecules 23 (2022) 641–660.
[6] Q. Wen, Q.Q. Cai, P. Fu, et al., Chin. Chem. Lett. 33 (2022) 1650–1658.
[7] M.Y. Guo, L.M. Pitet, H.M. Wyss, et al., J. Am. Chem. Soc. 136 (2014) 6969–6977.
[8] D.E. Clarke, E.T. Pashuck, S. Bertazzo, J.V.M. Weaver, M.M. Stevens, J. Am. Chem. Soc. 139 (2017) 7250–7255.
[9] B. Qin, S. Zhang, P. Sun, et al., Adv. Mater. 32 (2020) 2000096.
[10] X. Li, Z.L. Wang, W. Li, J.Q. Sun, ACS Mater. Lett. 3 (2021) 857–882.
[11] F. Luo, L.T. Sun, T. Nakajima, et al., Adv. Mater. 27 (2015) 2722–2727.
[12] Y.T. Sun, A.L. Wollenberg, T.M. O'Shea, et al., J. Am. Chem. Soc. 139 (2017) 15114–15121.
[13] M.X. Wang, P.Y. Zhang, M. Shamsi, et al., Nat. Mater. 21 (2022) 359–365.
[14] P. Shi, Y.F. Wang, W.W. Tjiu, C. Zhang, T.X. Liu, ACS Appl. Mater. Interfaces 13 (2021) 49358–49368.
[15] Y.M. Zhang, Y.H. Ding, X.X. Li, et al., Chin. Chem. Lett. 32 (2021) 3636–3640.
[16] K.C. Bentz, S.M. Cohen, Angew. Chem. Int. Ed. 57 (2018) 14992–15001.
[17] S.Y. Zheng, H.Y. Ding, J. Qian, et al., Macromolecules 49 (2016) 9637–9646.
[18] S.C. Grindy, R. Learsch, D. Mozhdehi, et al., Nat. Mater. 14 (2015) 1210–1216.
[19] S.M. Mantooth, B.G. Munoz-Robles, M.J. Webber, Macromol. Biosci. 19 (2019) 1800281.
[20] D.Y. Xia, P. Wang, X.F. Ji, et al., Chem. Rev. 120 (2020) 6070–6123.
[21] H. Ke, L.P. Yang, M. Xie, et al., Nat. Chem. 11 (2019) 470–477.
[22] C. Liu, N. Morimoto, L. Jiang, et al., Science 372 (2021) 1078–1081.
[23] Z.H. Huang, X.Y. Chen, S.J.K. O'Neill, et al., Nat. Mater. 21 (2022) 103–109.
[24] M. Pandeeswar, S.P. Senanayak, K. Narayan, T. Govindaraju, J. Am. Chem. Soc. 138 (2016) 8259–8268.
[25] K.V. Rao, K. Jayaramulu, T.K. Maji, S.J. George, Angew. Chem. Int. Ed. 49 (2010) 4218–4222.
[26] L. Gao, Y.X. Gao, Y. Lin, et al., Chem. Asian J. 11 (2016) 3430–3435.
[27] I. Ratera, J. Veciana, Chem. Soc. Rev. 41 (2012) 303–349.
[28] M. Lucarini, Supramolecular radical chemistry, basic concepts and methodologies, Encyclopedia of Radicals in Chemistry, Biology and Materials In, Wiley, Weinheim, 2012, p. 229.
[29] Y.P. Wang, M. Frasconi, W.G. Liu, et al., J. Am. Chem. Soc. 137 (2015) 876–885.
[30] K. Cai, B.B. Cui, B. Song, et al., Chem 7 (2021) 174–189.
[31] Y. Jiao, W.L. Li, J.F. Xu, et al., Angew. Chem. Int. Ed. 55 (2016) 8933–8937.
[32] Y. Yang, P. He, Y. Wang, et al., Angew. Chem. Int. Ed. 56 (2017) 16239–16242.
[33] H. Wang, K.F. Xue, Y.C. Yang, et al., J. Am. Chem. Soc. 144 (2022) 2360–2367.
[34] W.L. Jiang, Z.Y. Peng, B. Huang, et al., J. Am. Chem. Soc. 143 (2021) 433–441.
[35] Z.H. Yin, G.B. Song, Y. Jiao, et al., CCS Chem. 1 (2019) 335–342.
[36] L. Zhang, T.Y. Zhou, J. Tian, et al., Polym. Chem. 5 (2014) 4715–4721.
[37] E. Moulin, F. Niess, M. Maaloum, et al., Angew. Chem. Int. Ed. 49 (2010) 6974–6978.
[38] G.F. Huo, X.L. Shi, Q. Tu, et al., J. Am. Chem. Soc. 141 (2019) 16014–16023.
[39] E.A. Appel, F. Biedermann, U. Rauwald, et al., J. Am. Chem. Soc. 132 (2010) 14251–14260.
[40] S. Amthor, B. Noller, C. Lambert, Chem. Phys. 316 (2005) 141–152.
[41] K. Sreenath, C.V. Suneesh, V.K.R. Kumar, K.R. Gopidas, J. Org. Chem. 73 (2008) 3245–3251.
[42] S. Sumalekshmy, K.R. Gopidas, Chem. Phys. Lett. 413 (2005) 294–299.
[43] Z.Y. Cui, A. Abdurahman, X. An, F. Li, CCS Chem. 2 (2020) 1129–1145.
[44] X. Zhao, J. Gong, P. Alam, et al., CCS Chem. 3 (2021) 2518–2526.
[45] X. Ai, E.W. Evans, S. Dong, et al., Nature 563 (2018) 536–540.
[46] A.J. Sindt, B.A. DeHaven, D.F. McEachern, et al., Chem. Sci. 10 (2019) 2670–2677.
[47] W.Y. Zhao, X. Zhang, R. Zhang, et al., ACS Appl. Mater. Interfaces 12 (2020) 56898–56907.
[48] A. Bendich, L.J. Machlin, O. Scandurra, G.W. Burton, D.D.M. Wayner, Adv. Free Radic. Biol. Med. 2 (1986) 419–444.
[49] L. Li, J.M. Scheiger, P.A. Levkin, Adv. Mater. 31 (2019) 1807333.