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stimuli and the good mechanical property of shear thinning.

A luminescent and injectable supramolecular hydrogel was successfully constructed through the non-

covalent cross-linking of polymers mediated by tetraphenylethylene-bridged cyclodextrin oligomers,

presenting the strong blue fluorescence, the reversible gelation behavior responsive to various external

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Communication

A polysaccharide/tetraphenylethylene-mediated blue-light emissive and injectable supramolecular hydrogel



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ABSTRACT

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Supramolecular hydrogels are a class of soft materials using water as the dispersion medium and molecules taking advantage of noncovalent interactions as the gelation factor [1,2]. Owing to the dynamic and reversible interactions that hold the gel network, supramolecular hydrogels possess the advantages of convenient and reproducible preparation, good sensitivity to the environmental condition, as well as the potential self-healing ability [3–5]. Recently, water-soluble macrocyclic hosts were widely exploited to build supramolecular hydrogels due to their good water solubility and excellent binding ability. Among these macrocyclic hosts, cyclodextrin (CD), a torus-shaped cyclic oligosaccharide, was widely regarded as one of the most noticeable candidate because of its good binding capabilities towards inorganic/organic/biological substrates in both aqueous solution and the solid state [6-10]. For example, Harada et al. successfully achieved the redox-responsive expansion and contraction of a hydrogel using inclusion complexes between β -CD and ferrocene [9]. Li *et al.* reported a thermo-, photo- and chemo-responsive shape-memory hydrogel by introducing α -CD and azobenzene into a poly(acrylate acid)/alginate network [11]. Kato and Ito reported a slide-ring supramolecular hydrogel through the intermolecularly crosslink of γ -CD-threaded polyrotaxane in solution [12]. On the other hand, since Tang et al. firstly reported the phenomenon of "aggregation-induced emission (AIE)" in 2001 [13], tetraphenylethylene (TPE) and its

* Corresponding author at: College of Chemistry, State Key Laboratory of Elemento-Organic Chemistry, Nankai University, Tianjin, 300071, China. *E-mail address:* yuliu@nankai.edu.cn (Y. Liu). choosing TPE-bridged CD oligomer as a mediate: (1) the selective binding ability of CD cavities towards various neutral and ionic polymers may enable the non-covalent cross-linking of polymers mediated by TPE-bridged CD as a unified protocol of constructing polymer-based hydrogel [21–25]; (2) the possible sliding of CD cavities along the polymer chain may enable the good mechanical property of hydrogel; (3) owing to the RIR effect, the supramolecular hydrogel shows the good luminescence property [26]. As a result, the resultant supramolecular hydrogel exhibits not only the good blue-light emissive property but also the ability of shear thinning, which enables it as an injectable probe in labelling, sensors, biomedicine, *etc.* and is expected to be adaptable for further practical applications.

derivatives attracted more and more interest due to their facile

synthesis and most importantly the restriction of intramolecular

rotation (RIR) fluorescent characteristics [14–17]. For example, Han

et al. reported a TPE-based glycoconjugate showing significant AIE

characteristics along with the increase of solvent fraction [18]. In a

preliminary study, we also reported the association of TPE with

macrocyclic cycles, such as sulfonatocalixarenes or cyclodextrins,

led to the greatly enhanced fluorescence of TPE via the AIE or RIR

effect [19,20]. In the present work, four α -CD units were linked to a

TPE core to give a CD-grafted TPE derivative (TPE-tetra- α -CD).

Subsequently, TPE-tetra- α -CD was employed as a non-covalent

cross-linker to interconnect numerous polymer chains to construct

supramolecular hydrogel. There are several inherent advantages of

TPE-tetra- α -CD was synthesized through copper(I)-catalyzed click reactions between tetra-p-propynyloxy-TPE and azido-

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Scheme 1. Construction route of TPE-tetra- α -CD/PEG supramolecular hydrogel.

functionalized α -CD (Scheme 1). The formation of triazole rings was confirmed by a chemical shift at 7.78 ppm (single peak, 4 H) in the ¹H NMR spectrum (Fig. S1 in Supporting information). In addition, the NMR signals aggregation of TPE-tetra- α -CD (Fig. S4 in Supporting information). This self-aggregation assigned to the protons of triazole rings and phenyl units broadened dramatically in D₂O, indicating the possible self-phenomenon was also confirmed by the clear Tyndall effect of TPE-tetra- α -CD solution (Fig. S4). The critical aggregation concentration (CAC) of TPE-tetra- α -CD was measured by means of UV-vis spectroscopy. In Fig. S5 in Supporting information, the absorbance of TPE-tetra- α -CD at 318 nm increased linearly with the increasing concentrations from 0.001 mmol/L to 0.1 mmol/L, and no absorption band was observed at a wavelength longer than 425 nm, indicating no self-aggregation of TPE-tetra- α -CD below 0.1 mmol/L. However, the optical transmittance at 425 nm gradually decreased with further increasing the concentration, indicating the formation of aggregates in solution. An inflection point at 0.15 mmol/L was observed on the plot of optical transmittance at 425 nm versus the concentration of TPE-tetra- α -CD, referring to a CAC value as 0.15 mmol/L (Fig. 1a). The similar result was also obtained by monitoring the fluorescence emission intensity as a function of concentration (Figs. S6 and S7 in Supporting information). Furthermore, the TEM image of TPE-tetra- α -CD self-aggregate showed a number of discrete spherical nanoparticles with a uniform diameter of 50 nm (Fig. 1b), which was basically consistent with the value (50.8 nm) measured by DLS (Fig. S8 in Supporting information).

Significantly, TPE-tetra- α -CD gave a fairly high fluorescence quantum yield (ϕ F) as 58% in water. With increasing the temperature from 25 °C to 75 °C, the fluorescence emission intensity of TPE-tetra- α -CD decreased by 90% (Fig. 1c calculated



Fig. 2. a) TEM images of TPE-tetra- α -CD/PEG assembly. b) SEM images of cryo-dried and lyophilized hydrogel. c) Solid-state fluorescence emission spectrum of hydrogel (ex: 330 nm). d) Confocal laser scanning microscopy of hydrogel. e) Gel-sol transition under natural light and under 365 nm light. f) Photographs taken under 365 nm light at different time interval after gelation.

on the emission data at 470 nm). In contrast, the quenched fluorescence would recover to the original level when the temperature continuously decreased from 75 °C to 25 °C, and this temperature-dependent fluorescent change was reversible. A possible reason may be that the steric hindrance of four bulk α -CD cavities grafted to the TPE core disfavored the rotation of phenyl units in a great degree, leading to the restriction of energy relaxation through the phenyl rotation. On the other hand, increasing the temperature would promote the rotation of phenyl units, and thus resulted in the fluorescence quenching (Fig. 1d).

It was well documented that PEG chain could thread through cavities of α -CDs to form polypseuorotaxane. At a low concentration, the TPE-tetra- α -CD/PEG assembly existed as a clear solution. TEM image showed that the TPE-tetra- α -CD/PEG assembly formed the short rod-like structure (Fig. 2a). Upon increasing the concentration, the aqueous solution turned into a soft hydrogel that could not flow down in the inverted vial, and the critical gelation concentration was measured to be 7.5 wt%. A possible reason may be that the interconnection of TPE-tetra- α -CD resulted in the cross-linking and intertwining of polymer chains, which subsequently sealed in moisture and led to the formation of hydrogel. Furthermore, SEM images (Fig. 2b) of the cryodried and lyophilized hydrogel gave the morphological information as



Fig. 1. a) Transmittance of TPE-tetra- α -CD at different concentrations in water (insert: transmittance at 425 nm as a function of concentrations). b) TEM image of TPE-tetra- α -CD. Fluorescence emission of TPE-tetra- α -CD (0.01 mmol/L) upon temperature increasing c) and decreasing d) (ex = 330 nm).



Fig. 3. Rheological characterization of hydrogel. a) Dynamic strain sweep curves at fixed angular frequency of 0.1 rad/s. b) Dynamic frequency sweep curves at fixed strain of 1%. c) Viscosity and shear stress of hydrogel as a function of shear rate. d) Illustration of injectable ability of hydrogel.

porous lamellar nanosheets, which were expected to be able to act as the scaffolds for 3D encapsulation. Significantly, because the threading of PEG chain and the gelation process strictly restricted the rotation of phenyl parts in TPE, the supramolecular hydrogel also exhibited the strong blue fluorescence emission with the maximum wavelength at 470 nm as observed in the solid-state fluorescence spectrum (Fig. 2c). Meanwhile, the confocal laser scanning microscopy (Fig. 2d) also revealed the morphology of supramolecular hydrogel in a micrometer scale and its blue emissive optical property.

The stability, responsibility and mechanical property of supramolecular hydrogel were also investigated. As shown in Fig. 2f, the supramolecular hydrogel was found very stable at room temperature, giving no appreciable changes on either the gelation state or the fluorescence emission even after two months. In addition, the supramolecular hydrogel also presented the good responsibility to temperature. In an inverted vial test (Fig. 2e), the gel-sol transition was triggered upon heating to 58 °C, and a clear solution was obtained by continuing increasing the temperature to 62 °C. Furthermore, when PEG was added to the sol, a new hydrogel formed again. On the other hand, the addition of 1,6-hexanediol as a competitive guest could also trigger the gel-sol transition, the gel could recovered when further adding α -CD to the sol.

Fig. 3a showed the plots of storage moduli (G') and loss moduli (G'') versus the applied range of external strain at a fixed angular frequency of 0.1 rad/s. Under the strain from 0.1% to 20%, G' and G" remained nearly constant. In addition, G' was larger than G", indicating that the supramolecular hydrogel network was stable and the physical cross-linkage remained undamaged [27]. When the strain kept increasing, G' and G" began to decrease and G' dropped more dramatically, leading to the cross of G' and G" curves at the strain of 50%, indicating that a gel-sol transition would occur. After analyzing the viscoelastic region, 1% strain was chosen to investigate the colloidal sensitivity to the oscillation frequency. As shown in Fig. 3b, both G' and G" did not show any obvious changes within the range of angular frequency (0.1-100 rad/s), and G' kept larger than G", indicating a good stability of hydrogel towards the oscillation. Moreover, the steady shear rheological experiments (Fig. 3c) revealed the shear-thinning behavior of supramolecular hydrogel. When the shear force was applied, the viscosity of supramolecular hydrogel reached the maximum at a shear rate of 0.015 s⁻¹ but then decreased significantly with further increasing the shear rate. Moreover, the supramolecular hydrogel could be pressed and injected through a syringe with a narrow needle by applying a gentle force and regain its gel structure after escaping the needle (Fig. 3d), which would be important for its future application as the injectable material with in situ recovery ability. In summary, a supramolecular hydrogel was successfully constructed at a low concentration through the non-covalent cross-linking of polymer mediated by TPE-bridged α -CD oligomers. Significantly, the obtained supramolecular hydrogel was blue-light emissive and injectable. These advantages, along with the easy preparation, reversible gelation behaviors responsive to various external stimuli, as well as good stability and mechanical property, would enable the supramolecular hydrogel a vast application prospect in many fields of soft materials.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cclet.2017.07.024.

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