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Supramolecular Copolymer from Two-component gels: Metal Ion-Mediated Cross-Linking, Enhanced Viscoelasticity and Supramolecular Yarn

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Supramolecular polymers self-assembled from small molecules have been attracting great interest due to their reversible nature, which show potential applications in stimuli-responsive systems, luminescent materials, gene transfection and drug-delivery. However, in comparison with the covalently bonded polymers, supramolecular assemblies generally lack mechanical strength and viscoelasticity due to the relatively weak non-covalent interactions. Various efforts have been devoted to overcome such shortcomings of the supramolecular polymers, such as increasing the H-bond sites, combining them with covalently bonded polymers. One of the most distinguished viscoelastic supramolecular polymers systems can be from the assembly of small molecular building blocks containing 2-ureido-4-pyrimidone. The quadruple hydrogen bonding helped those small organic molecules reversibly self-assemble into linear supramolecular polymers with viscoelasticity in organic solvent. In addition, the cross-linking of supramolecular polymer is particularly noteworthy for increasing the mechanical properties.

However, most of the known viscoelastic supramolecular polymers were produced in organic solvent or ionic liquid with relatively high concentrations. It still remains a challenge to fabricate similar supramolecular polymers in aqueous solution, especially with diluted aqueous solutions. Definitely, constructing supramolecular polymers with good mechanical properties in water could be very important for biomedical applications. However, the cross-linking of supramolecular polymers in aqueous solution, which may gigantically change the nanostructures or macroscopic properties of those supramolecular polymers, is rarely reported. In this communication, by using the two-component hydrogels and the crosslinking by metal ions, we have successfully fabricated a supramolecular copolymer with good viscoelasticity, which can be further drawn into supramolecular yarn.

Figure 1. (A) Molecular structure of BolaHis and various dipyridine-dicarboxylic acids; (B) Changes on both nanostructures and macroscopic properties of supramolecular polymers, from hydrogels to viscoelastic solution until the macroscopic supramolecular yarn from direct drawing. a) Photograph and d)SEM images of supramolecular polymer hydrogels formed by BolaHis/B5D=1/1; b) Photograph and e)TEM images of viscoelastic solution formed by Cu²⁺/BolaHis/B5D=0.5/1/1; c) Photograph of drawing supramolecular yarn from viscoelastic solution, f)SEM and g)TEM images of macroscopic yarns.(The concentration of BolaHis=0.1 wt%)
binding sites for different metal ions, which could change the
for ordering molecular packing. Furthermore, the macroscopic yarns with the aqueous solution with enhanced viscoelasticity at very low concentration. While B3D and B6D cannot form hydrogels (Table S1), presumably due to the relative positions of two carboxylic acids are not favourable for ordering molecular packing. Interestingly, simple addition of Cu(II) ions to the B5D/BolaHis hydrogels could lead an aqueous solution with enhanced viscoelasticity at very low concentration. Furthermore, the macroscopic yarns with the length about several centimeters can be obtained from the viscoelastic solution by direct drawing (Figure 1c).

While comparing with the BolaHis/B4D system, the BolaHis/B5D hydrogels with different molar ratios always have better thermal stability; as confirmed by the sol-gel transition temperature \( (T_{\text{gel}}) \) (Figure S2) and the critical gelation concentration (CGC) of these hydrogels. For B5D/BolaHis=2/1, 0.034 wt% bolaamphiphile in the system can already produce stable hydrogels; while for B4D/BolaHis=2/1 system, the critical gelation concentration of BolaHis was determined as 0.067 wt%. Although B5D/BolaHis=1/1 already can form nice transparent hydrogels, addition of more dicarboxylic acid into the systems could increase the sol-gel transition temperature \( (T_{\text{gel}}) \) gradually (Figure S2). However, too much B5D in the systems cannot be dissolved well upon heating and also cannot form hydrogels.

For B5D/BolaHis and B4D/BolaHis systems, the interlaced helical nanofibers can be observed from the SEM images (Figure 1, S3). These fibers appear to be several micrometers long with the diameter about 40-50 nm. And the entanglement of these nanofibers could further gel water.

On the other hand, the 2, 2'-bipyridine units are good binding sites for different metal ions, which could change the structural and functional properties of the assemblies. Different metals ions, such as Cu\(^{2+}\), Ag\(^{+}\), Co\(^{2+}\), Ni\(^{2+}\), Zn\(^{2+}\), Fe\(^{3+}\) and Fe\(^{2+}\) were studied. The results show that only the interactions between B5D/BolaHis hydrogel and Cu\(^{2+}\) or Zn\(^{2+}\) can form viscous solution. Adding Ag\(^{+}\) cannot change the properties of B5D/BolaHis hydrogels. While when Ni\(^{2+}\), Co\(^{2+}\), Fe\(^{3+}\) and Fe\(^{2+}\) were added into the B5D/BolaHis hydrogels, the solution without viscosity were formed(Figure S4). Thus, only the metal ions with preferred geometries and appropriate binding strengths for forming complex can change B5D/BolaHis hydrogel to viscous solution. Notably, the quantity of Cu\(^{2+}\) or Zn\(^{2+}\) should be carefully controlled; too much metal ions in the systems would lead precipitation. The Cu(II)-coordinated supramolecular polymers have viscoelastic properties; and macroscopic supramolecular yarns can be obtained by direct drawing from the aqueous solution of Cu\(^{2+}\)/B5D/BolaHis supramolecular polymers. Thus, when a needle was put into the solution with gentle stirring and then carefully lifted out of the water surface, a visible thin fiber with the length about centimeters can be obtained (Figure 1c).

For the Cu(II)-coordinated supramolecular polymers (CuCl\(_2\)/B5D/BolaHis), interlaced thin nanoribbons were detected from TEM measurement (Figure 1b, S5). For the macroscopic supramolecular yarns, the SEM images show that the diameters of these centimeter length fibers are about 1.5-5 \( \mu \)m (Figure 1c), and aligned nanofibers can be detected from the end of yarns. Moreover, the TEM images of the divergent end on macroscopic fibers clearly show thin nanoribbons, which are similar like the morphologies observed from the original Cu(II)-coordinated supramolecular polymers. These results indicate that the macroscopic supramolecular yarns are constructed by ordering arranged nanoribbons, which can be further demonstrated by cross-polarized microscope measurements. Thus, the anisotropic entities can be detected throughout the supramolecular yarns, with length in the scale of several centimeters (Figure S6).

The viscoelasticity of these supramolecular polymers was characterized by rheological measurements, which were performed at 298 K with BolaHis at a concentration of 0.1 wt%. First, to detect the tolerance performance of B5D/BolaHis hydrogel, a strain sweep was conducted (Figure S7). Both moduli G' (storage modulus) and G'' (loss modulus) remained roughly constant below a critical strain value of 0.3 %, known as the upper limit of the linear viscoelastic regime. Above this strain value, a sharp decrease of G' and G'' was observed and the value of G'' became larger than that of G', representing a partial broken of the hydrogels. We choose the strain value of 0.1% in the frequency sweeps, by recording the evolution of storage and loss moduli.

![Figure 2](image)

For two-component supramolecular hydrogels with BolaHis/B5D=1/1 or 1/2, the G' and G'' versus frequency plot are nearly linear and invariant with angular frequency (\( \omega \)). And G' is always higher than G'' over the entire range of frequency (from 1 to 100 rad s\(^{-1}\)), showing the stability of the hydrogels (Figure 2A, C). For CuCl\(_2\)/B5D/BolaHis equal to 0.5/1/1 (A, B) or 1/2/1 (C, D).

![Figure 3](image)

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are closer to liquid. Interestingly, when \(\omega\) was further increased, the G’ again became higher than G”. In contrast, although the rheological measurements on CuCl\(_2\)/B5D/BolaHis=1/2/1 systems also showed the viscoelasticity at lower frequency, the assemblies quickly changed into liquid upon increasing \(\omega\) values (Figure 2C).

The shear rate dependent viscosity of these supramolecular polymers were also studied (Figure 2B, D). At low shear rates, the viscosity of B5D/BolaHis hydrogels is larger. Interestingly, when the shear rate was increased, the viscosity of Cu(II)-coordinated supramolecular polymer became larger than that of two component supramolecular hydrogels. Moreover, the viscosity of hydrogels decreased exponentially upon increasing the shear rate from 0.1 S\(^{-1}\) to 100 S\(^{-1}\), indicating the disassembly of the gels. In contrast, although the viscosity of Cu(II)-coordinated supramolecular polymers can also decrease along with the increasing of shear rates, the changes of \(\eta\) values are relatively small within the shear rate range from 0.01 S\(^{-1}\) to 100 S\(^{-1}\).

Although B5D/BolaHis hydrogel can also form viscous aqueous solution with Zn\(^{2+}\), the rheological measurements on ZnCl\(_2\)/B5D/BolaHis systems cannot show any viscoelastic properties (Figure S8). Thus, G’ is always lower than G”, and the viscosity of ZnCl\(_2\)/B5D/BolaHis systems also decrease rapidly upon increasing the shear rate. Therefore, no macroscopic supramolecular yarn can be drawn from ZnCl\(_2\)/B5D/BolaHis solution.

The B5D/BolaHis hydrogels do not show optical activity upon CD measurements, even though BolaHis is chiral molecule. However, for the Cu(II)-coordinated supramolecular polymers, the strong negative Cotton effect can be observed (Figure 3A) at about 303 nm, which corresponds to the UV-Vis absorption of B5D (Figure S9), indicating ordered packing of bipyridine rings upon binding with Cu(II) ions. Interestingly, even though very small amount of Cu\(^{2+}\) in the systems already can give strong CD signals, larger amount of Cu(II) ions only produce weak CD signal (Figure S10A), presumably due to the disturbing of the molecular packing. It is worth mentioning that, the CD spectra of ZnCl\(_2\)/B5D/BolaHis supramolecular polymers with different molar ratios do not show any clear Cotton effect (Figure S11), suggest that bipyridine molecules cannot form ordering aggregation after binding with Zn\(^{2+}\), presumably due to the weak binding capability between Zn\(^{2+}\) and pyridine ligands\(^{16}\) as well as the larger diameter of zinc cations.

The XRD patterns of two-component hydrogels (Figure 3C) clearly show periodical diffraction peaks, suggest the monolayer lipid membranes (MLM) formed from the self-assembly of BolaHis.\(^{66}\) While the XRD patterns (Figure 3C) of CuCl\(_2\)/B5D/BolaHis cross-linked supramolecular polymer show a new diffraction peak at 20\(\theta\) value of 14.9. The corresponding long spacing (d=0.59nm) of the assemblies can be assigned to ordered packing of bipyridines upon forming complex with Cu(II) ions.

For the FT-IR spectra of B5D/BolaHis hydrogels, the asymmetric (2919 cm\(^{-1}\)) and symmetric (2850 cm\(^{-1}\)) stretching vibrations of CH\(_2\) indicate the ordering packing of long alkyl spacers. And the amide I (1645 cm\(^{-1}\)) and II (1542 cm\(^{-1}\)) peaks clearly show the amide hydrogen bonding between the bolaamphiphiles.\(^{17}\) While interactions between imidazole and carboxylic acid groups can be probed by the broad band around 1940–1960 cm\(^{-1}\), which illustrates the formation of imidazolium carboxylate salts (Figure 3B, S12).\(^{13}\) On the other hand, the FT-IR spectra of CuCl\(_2\)/B5D/BolaHis supramolecular polymers are very similar like that of the B5D/BolaHis hydrogels, indicating the linear supramolecular polymer chains as well as the layered nanostructures preserved upon adding Cu(II) ions. However, the only exception is that the amide I band changed from 1645 to 1650cm\(^{-1}\) upon adding Cu\(^{2+}\), indicate the amide hydrogen bonding between different parallel packed BolaHis molecules changed after the cross-linking from the Cu(II) ions (Figure 3B, S10C, D).

These results suggest that COOH on B5D could interact with the histidine head-groups of BolaHis to form linear assemblies.\(^{66}\) When Cu\(^{2+}\) was introduced, the metal ions would interact with the nitrogen atom on pyridine (Figure 4). Because two nitrogen atoms in 2, 2’-bipyridine are close to each other, there are strong cooperative effects for binding Cu(II) ions. On the other hand, the XRD pattern and FT-IR spectra also suggest that the bolaamphiphiles always self-assemble into monolayer lipid membranes (MLM),\(^{66}\) even though bipyridine-dicarboxylic acids and metal ions were introduced into the systems. For CuCl\(_2\)/B5D/BolaHis supramolecular polymers, the BolaHis MLM would render linear supramolecular polymers chains align parallel with each other. Moreover, binding with identical Cu(II) ions from different 2, 2’-bipyridine molecules would produce cross-linked supramolecular polymers, which would produce further hierarchically organized nanostructures. Therefore, the assemblies would become much more aligned manner in the presence of copper ions, and show viscoelasticity for drawing macroscopic yarns.

In summary, the co-assembly of bolaamphiphilic L-histidine and 2, 2’-bipyridine-dicarboxylic acids form supramolecular hydrogels, while simply adding Cu(II) ions changed the hydrogels into viscoelastic supramolecular polymers, which produce macroscopic supramolecular yarn via direct drawing. These viscoelastic supramolecular polymers are based on the hierarchical self-assembly of simple organic molecules in water with very low concentration. The hydrogen bonding, hydrophobic interactions between organic molecules played an important role in forming the linear supramolecular polymer, while the Cu(II) ion-mediated cross-linking between linear polymer contribute to the viscoelasticity of the polymer.
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Notes and references


