

Recent Advances in Supramolecular Polymer Networks: Hydrogels

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Supramolecular chemistry relies on non-covalent interactions to self-assemble molecules into molecular assemblies. Supramolecular polymer networks (SPNs) are three-dimensional structures composed of linear polymers crosslinked by non-covalent interactions such as hydrophobic interactions, hydrogen bonds, electrostatic interactions, metal coordination, π - π stacking, and host-guest interactions.^{1,2} A gel, as generally defined, is a chemically or physically crosslinked soft material which partly consists of liquid, either water (hydrogel) or solvent (organogel). Due to their dynamic nature, SPN hydrogels show very attractive properties, such as stimulus-responsiveness, self-healing, etc. As a result, they have promising applications in various fields such as healable materials, drug delivery, tissue engineering, and 3D printing.^{2,3}

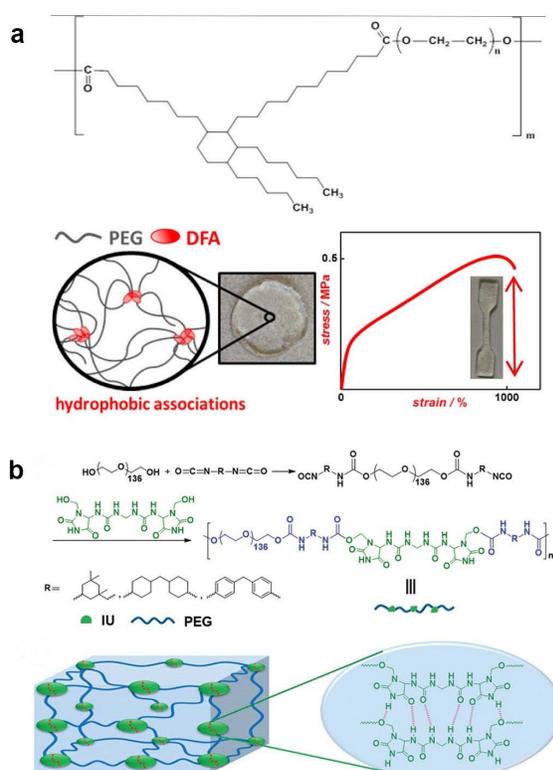


Figure 1. Schematic of a) SPNs based on hydrophobic interactions,⁴ b) SPNs based on hydrogen bonding.⁶

IU-based polyurethane hydrogels (**Figure 1b**).⁶ With increased IU concentration and hydrophobicity of diisocyanates, the gel-sol transition temperature increased and the hydrogel exhibited greater self-healing ability. Moreover, owing to the strong hydrophobicity and π - π stacking of 4,4'-methylene bis(phenylisocyanate) (MDI), the hydrogel film was mechanically quite strong: the break stress was as high as 1.6 MPa and the film could be elongated by 460% before it broke.

Host-guest interactions play a large role in both polymer science and supramolecular chemistry. The combination of covalent polymers with macrocyclic hosts can endow SPNs with

SPN hydrogels generally rely on hydrophobic interactions involving water-soluble polymers that have water-insoluble end groups or side chains that can form physical crosslinks. For example, Sijbesma and co-workers synthesized a linear multiblock, segmented copolymer of hydrophilic poly(ethylene glycol) (PEG) and hydrophobic dimer fatty acid (DFA) building blocks (**Figure 1a**).⁴ When this copolymer was swelled with water, a hydrogel network formed by self-assembly of the hydrophobic DFA units into micellar domains that act as stable physical crosslink points. This hydrogel showed excellent mechanical stability and toughness, with a tensile toughness of 4.12 MJ/m³. In addition, this hydrogel is easily recyclable and reprocessable.

Some SPN hydrogels are crosslinked by hydrogen bonds. One of the most widely used components in such materials is ureido-pyrimidinone (UPy), which can form four hydrogen bonds.⁵ UPy and its derivatives must be synthesized, but Cheng and co-workers found that they could avoid this disadvantage by employing commercially-available imidazolidinyl urea (IU), PEG, and diisocyanates to synthesize a series of

desirable properties, such as great mechanical strength, good structural stability, and various kinds of functionality. Among the commonly used macrocyclic hosts are crown ethers, cyclodextrins, pillar[n]arenes, calix[n]arenes, and cucurbit[n]urils.²

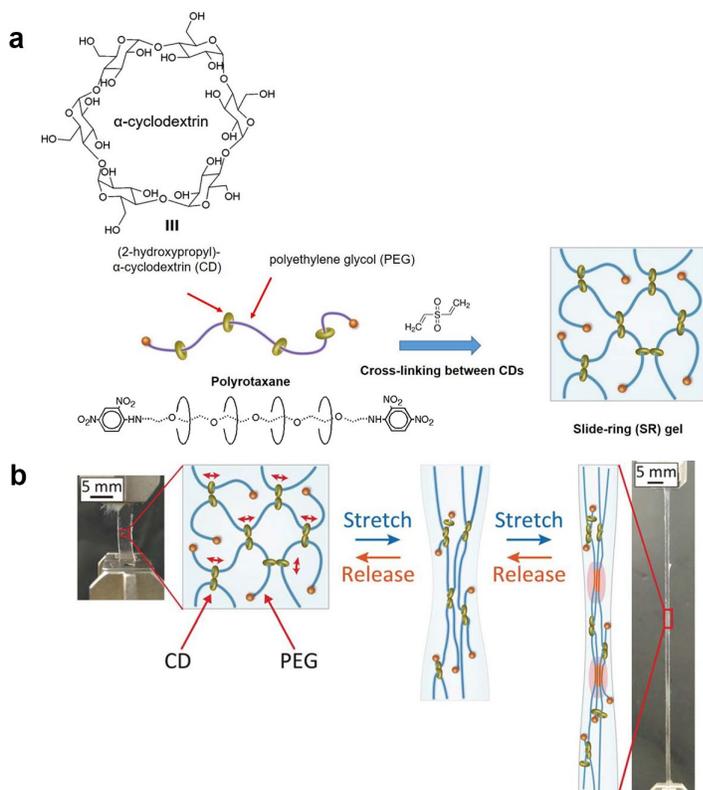


Figure 2. Schematic of a) synthesis of slide-ring (SR) gels, b) SR gel reinforcement strategy.⁷

increasing the PEG concentration up to 38% can enhance the PEG-PEG interactions, giving rise to enhanced strain-induced crystallization and a higher modulus. The crystallization reverses with release of the strain, resulting in almost 100% rapid recovery, even after 100 cycles. The films show excellent toughness of 22MJ/m³, which is one order of magnitude larger than covalently crosslinked PEG hydrogels.

Although most current systems focus on the fabrication of rubber-like SPNs, Scherman and co-workers synthesized highly compressible glass-like SPNs using the cucurbit[n]uril complex CB[8], which relies on phenyl-perfluorophenyl polar- π interactions⁸ as the non-covalent crosslink (**Figure 3a**).⁹ The authors formed CB[8]-mediated heteroternary SPNs by incorporating perfluorobenzyl vinylimidazolium bromide (5FBVI) as the first guest, and a variety of substituted vinylimidazolium bromides (RBVI) as the second guest (5FBVI-CB[8]-RBVI). The viscoelastic properties of these hydrogels are tunable by changing the dissociation rate (k_d) of the second guest. Unlike previously reported rubber-like, fast-dissociative SPNs whose k_d is generally larger than 10 s⁻¹, the glass-like slow-dissociative SPNs possess a k_d as low as 0.01 s⁻¹ that enables high compressibility, showing a transition from the typical rubber-like state to an uncommonly observed glass-like regime (**Figure 3b**).⁹ The resultant glass-like SPNs have compressive strengths up to 100 MPa with no fracture, even when compressed at 93% strain over 12 cycles of compression and relaxation. Furthermore, the materials can recover their original strength within

Hydrogels are generally mechanically weak materials. Ito and co-workers proposed a new hydrogel reinforcement strategy involving slide-ring hydrogels, in which polyethylene glycol (PEG) chains are connected by slidable crosslinks composed of cyclodextrin (CD) rings (**Figure 2a**).⁷ After PEG chains are threaded through CD rings to form polyrotaxanes, the CD rings are crosslinked by divinyl sulfone to form SPN hydrogels. The ability of the CD rings to slide on the PEG chains releases stress upon stretching, so that the SR hydrogels are much tougher than other hydrogels. At high strains, the PEG chains orient in parallel, leading to rapid and reversible strain-induced crystallization, which is confirmed by wide-angle and small-angle X-ray scattering (**Figure 2b**).⁷ The authors found that, with longer PEG chains and fewer CD rings on each chain, the slide-ring gels possess better stretchability owing to the longer slidable range. Also,

2 minutes at room temperature, thus making them promising materials for applications in soft robotics, tissue engineering and wearable bioelectronics.

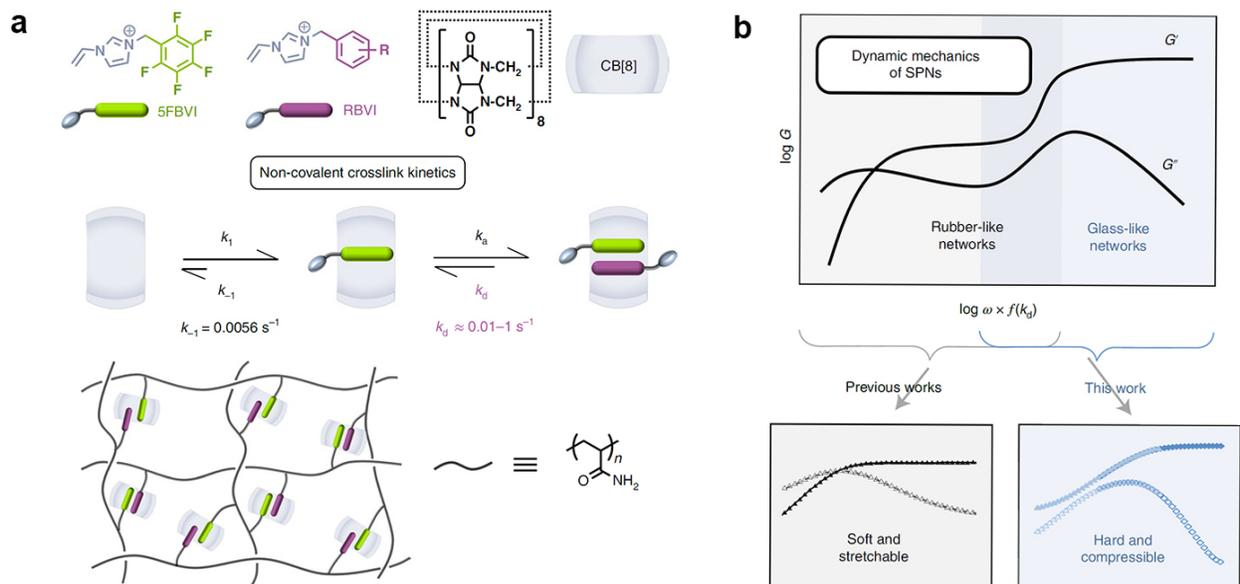


Figure 3. Schematic of a) synthesis of glass-like SPNs, b) differences of rubber-like and glass-like networks.⁹

SPN hydrogels are excellent components of dynamic and responsive materials. However, there will always be a subtle trade-off between the dynamics and responsive properties on the one hand and the strength of the materials on the other. One remaining challenges remaining is to create SPN hydrogels that are both dynamic and strong.

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