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Shape Memory Hydrogels Based on Noncovalent Interactions

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Abstract

Shape memory polymers (SMPs) are polymeric materials that are capable of fixing temporary shape and recovering the permanent shape in response to external stimuli. In particular, supramolecular interactions and dynamic covalent bond have recently been introduced as temporary switches to construct supramolecular shape memory hydrogels (SSMHs), arising as promising materials since they can exhibit excellent cycled shape memory behavior at room temperature. On the other hand, hydrogels, conventionally, are flexible but sometimes extremely soft, and they can be easily damaged under external force, which could limit their long-time application. Therefore, self-healing hydrogels that can be rapidly auto-repaired when the damage occurs have been recently developed to solve this problem. These materials present more than one triggering stimulus that can be used to induce the shape memory and self-healing effect. These driven forces can be originated from hydrogen bonds, hydrophobic interactions, and reversible covalent bonds, among others. Beyond all these, hybrid organic-inorganic interactions represent an interesting possibility due to their versatility and favorable properties that allow the fabrication of multiresponsive hydrogels. In this chapter, shape memory hydrogels based on noncovalent interactions are described.

Keywords: shape memory, hydrogels, supramolecular interactions, self-healing, smart materials

1. Introduction

Hydrogels are three-dimensional soft networks formed by physical and/or chemical cross-linking of hydrophilic polymers, which are able to swell absorbing and retaining a substantial

amount of water [1]. Hydrogels have been intensively studied due to their relevant properties, such as their similarity to body tissues, low surface friction, ability to encapsulate and release (molecules, ions, cells), appropriate morphology for cell proliferation and stimuli-responsive properties. This stimuli-responsiveness allows hydrogels to be programmed to vary spatially and/or temporally their properties as response against external changes. Different external triggers have been deeply studied along the last years to induce reversible hydrogel-solution or swollen-collapsed transitions, such as pH, temperature, radiation, redox reactions, or chemical triggers [2]. As a consequence of these switchable properties, these materials can behave as actuators or sensors, and therefore, they have been intensively investigated in the last decades in a great variety of fields, among which it is worth to highlight, biomedicine, agriculture and wastewater treatment [3]. Currently, hydrogels are being actively commercialized in all those application fields. However, hydrogels generally show poor mechanical properties, and consequently, mechanical damages and cracks limit their correct function over a long period of time, which is especially problematic for biomedical applications. For this reason, nowadays mechanically more stable materials, such as ceramics or metals, are preferred in this area. Thus, an interesting approach to exploit the full potential of hydrogels would be to promote their self-healing and shape memory properties, which are well known for conventional materials or even polymers but nowadays continues being a challenging issue for hydrogels [4].

Self-healing is one of the most fascinating functions encountered in nature, and it represents the ability of a material to regenerate and repair itself after damage. This property is based on reversible chemical or physical interactions that quickly and efficiently are reformed within the structure of the hydrogels, and they would allow to increasing the working lifespan and application frame of hydrogels [5]. A closely related but different property is that so-called shape memory effect (SME), which represents the nonisotropic response of the hydrogel network against changes in the medium. These materials constitute the growing family of shape memory hydrogels (SMH). This means that the polymeric network is able to switch spatially their shape without major volume alteration. This more complex effect requires more sophisticated structural and chemical approaches than self-healing. The SME implies an elastic deformation (programming) of the hydrogels that are temporarily fixed by means of reversible chemical or physical crosslinking. This temporary shape can reverse to the original shape when these molecular switches are turned off (**Figure 1**). So, shape memory effect lets to recover from the programmed temporary shape when the material is exposed to a given external stimulus; [6] typically temperature, but also light, magnetic or electric field response has been successfully developed [7]. Shape memory polymers (SMP) based on pure polymers, blends and composites have been intensively studied for actuators, sensors, microfluidic systems in aerospace technology, vascular grafts and cardiovascular stents in biomedicine, for textile industry applications and consumer care products [8]. However, SME on hydrophilic soft networks entails some additional difficulties that make impossible the direct transfer from the well-known molecular architecture of hydrophobic SMPs because temporary shape fixation requires crosslinks able to remain stable in an aqueous environment. For example, this fixation may not be carried out by crystalline domains from the hydrophilic polymer acting as main

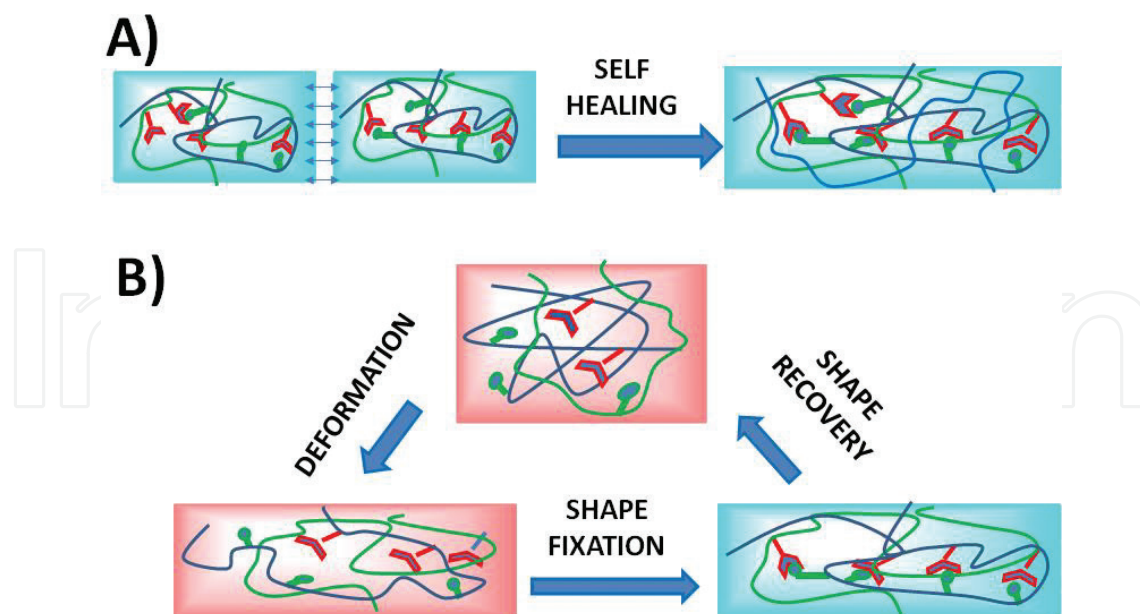


Figure 1. Schematic representation of (A) self-healing and (B) shape memory effects for hydrogels.

chain (which is one of the most used strategies for hydrophobic SMPs) because they may dissolve. Thus, more elaborated approaches have been developed, such as hydrogels in which hydrophobic crystallizable side chains have been grafted to hydrophilic polymer networks to act as temperature-sensitive temporary crosslinking [9]. However, due to the easy permeation by small molecules and light permeability of hydrogels on their swollen state, in contrast to hydrophobic shape memory polymers, stimuli different to temperature, such as light, [10] pH, [11] or ions [12] can be easily used. When molecular switches reply to more than one stimulus, multishape memory effect can be addressed inducing multiple actions on the hydrogels [13].

Therefore, self-healing and shape-memory are both originated from the same switchable interactions. In addition to the classical approach that involves the use of crystallizable side chains, these temporary linkers could be dynamic covalent bonds or supramolecular interactions, such as hydrogen bonding, host-guest recognition, or metal-ligand coordination. This chapter reviews the last advances in the strategies in which supramolecular interactions have been used to fix the temporary shape in the quest for obtaining SMH. The interactions can be properly employed in the efficient design of hydrogels for advanced applications and new functionalities that would display high impact in fields like biomedicine. In this sense, sensors for diagnosis, drug delivery systems for controlled and minimal invasive implantation, self-tightening degradable sutures, devices for easy in vitro growth and manipulation of cells, or materials for 3D printing of biomedical devices and soft tissue engineering, among others, are expected to be soon improved by the development of self-healing and shape memory hydrogels. Response time is a key factor in the design of new and effective self-healing and shape memory hydrogels. On the one hand, hydrogels with slow SME may be promising materials for medical implants, in order to

avoid post-implantation shocks originated by the sudden alterations. On the other hand, fast SME are of great importance for the development of sensors and actuators, such as robotic devices and artificial muscles. Recently, multiple supramolecular SMH combined with self-healing properties have been reported as an evidence of the promising future of this research field [14]. The obtaining of multiple programmed shapes triggered by diverse properties and tailored SME response speed are currently the main challenges in the development of SMH technology that would open opportunities for a wider range of potential applications and value-added properties.

2. Mechanism

Shape memory mechanism in polymers is based on a dual segment material. On the one hand, an elastic polymer network with netpoints is required to define the permanent shape. These netpoints usually are chemical cross-linkings or physical netpoints such as crystalline domains or complexes. In addition, a programming process consisting of the elastic deformation of the sample takes places and additional molecular switches provide temporary cross-links to reversibly fix the temporary shape of the material. As a result of the application of an external stimulus, usually temperature, molecular switches are disturbed and the polymer chains acquire their initial mobility that leads to a macroscopic movement resulting in the initial shape [15]. In case of thermoresponsive SME polymeric segments with specific thermal transitions like glass transition, melting, or liquid-crystalline phase transition, these transitions can act as molecular switches when temperature is varied.

In order to extend the potential of SMPs as biomaterials, crucial requirements such as biocompatibility, mechanical properties, and biodegradability have promoted the development of the hydrogels with SME. Similar to thermally induced SMPs, supramolecular shape memory hydrogels present cross-linkings that define the network, this is the permanent shape, and stimuli responsive switches, consisting of reversible interactions to fix the temporary shape (**Figure 1**). Thus, shape fixation and recovery demand interactions easy to be broken and formed, while adequate mechanical properties of the material are closely related to the concentration and strength of all the possible kinds of cross-linkings.

The temporary shape can be created by folding, elongation, or compression. The high water uptake in hydrogels gives rise to shape memory materials able of undergoing large deformation between the temporary and permanent states.

Molecular switches, in the case of hydrogels, usually are not part of the main chain forming the polymer network. Typically, are pending moieties such as short crystallizable side chains, [16] specific groups for host-guest interactions, [17] complex-forming groups [18] or groups able to form dynamic bonds [19]. Similar to self-healing process, polymeric segments reorganize and water flows through the polymer network via diffusion, and the kinetics of these process in different states of deformation of the network will govern the global rate of the SME.

The simplest SME is also referred as dual shape memory effect and corresponds to the case in which only one reversible interaction and thus one temporary shape is fixed in each shape memory cycle. Accordingly, triple shape memory effect corresponds to two reversible and independent interactions occurring in the same hydrogel network. Currently, despite the huge investigation effort made in the last years, still there is a reduced bibliography about triple and multishape memory hydrogels.

Although noncovalent interactions are weaker than covalent interactions, their importance in polymer science has been shown; in this context, supramolecular shape memory hydrogels based on noncovalent interactions present an arisen importance. The incorporation of noncovalent interactions into hydrogel network could modify the properties of the formed hydrogel. These variations increased the possible applications not only for shape memory effect or a closely related self-healable ability, but also for the development of high tough hydrogels. In **Figure 2**, the most common interactions used in shape memory hydrogels are described such as hydrogen bonds, metal-ligand interactions, and ion-ion interactions.

2.1. Hydrogen bonding

Hydrogen bond is an electrostatic attraction between donors and acceptors when a hydrogen atom is covalently bound to a highly electronegative atom. These interactions are considered as a key interaction in supramolecular chemistry due to their highly directionality and their relative high strength. In addition, their ability to form dynamic interactions, with a continuous formation/disruption of the bonds by external stimuli, has increased their use as a driving force in shape memory hydrogels.

The addition of moieties capable to form hydrogen bonds dimers in the hydrogel structure has been successfully used to improve the shape memory effect. For example, ureidopyrimidinone (UPy) presents strong self-complementary dimers by a quadruple hydrogen-bonding, [20] and

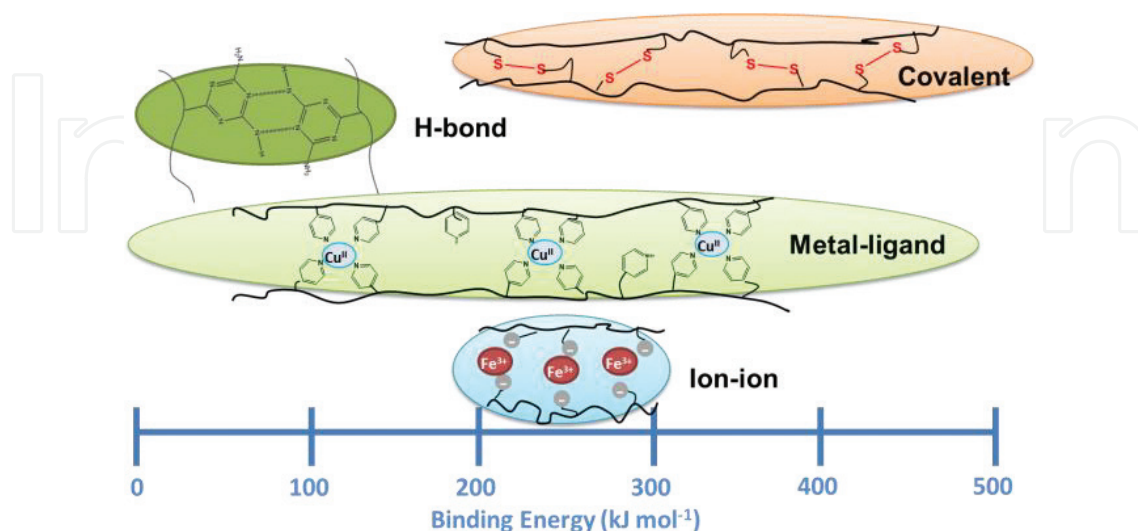


Figure 2. Reversible interactions for shape memory hydrogels construction.

this strong and unidirectional dimerization could induce the shape recovery effect in the hydrogels. These moieties could be added to the hydrogel by a direct substitution on the main chain of the hydrogel, for example poly(vinylalcohol) (PVA) chain [21] or by modifying one of the monomers such as in a triblock copolymer of poly(*N*-isopropylacrylamide-*b*-ethylene oxide-*N*-isopropylacrylamide) with UPy motifs on some of *N*-isopropylacrylamide monomers and polymerize by reversible addition-fragmentation chain-transfer (RAFT) [22]. Similarly, some authors have used the strong H-bond dimer of diaminotriazine (DAT) present in 2-vinyl-4,6-diamino-1,3,5-triazine groups to construct SMHs that present strong hydrogen bond dimer (**Figure 3**). Liu et al. have copolymerized DAT units with *N,N*-dimethylacrylamide and PEG diacrylate. These hydrogels possessed robust mechanical properties because of the strong double hydrogen bonds (DAT-DAT hydrogen bonds) that could be broken by the protonation of the two amino groups of DAT, being the shape memory of this hydrogels triggered by pH changes in the medium [23].

A slightly different approach has been described by Chen et al. [24] in which tannic acid (TA), a polyphenol derived from plants which easily forms H-bonds, develops strong multiple hydrogen bonds with poly(vinyl alcohol) (PVA), and they coagulate when they are physically mixed around 60°C and easily obtained hydrogel at room temperature. The strong hydrogen bonds between PVA and TA fix the permanent crosslink, whereas the H-bonds formed between poly(vinyl alcohol) chains, weaker than the PVA-TA H-bonds, are the temporary crosslinks.

Often the described hydrogen bond interactions not only provide a shape memory effect in the hydrogels but also give a self-healing capability to the formed networks.

2.2. Self-assembly processes in biomimetic systems

The self-assembly process of biomacromolecules can be considered as a specific way to get the hydrogen bonding-based shape memory performance. Formation of triple-helix structures is

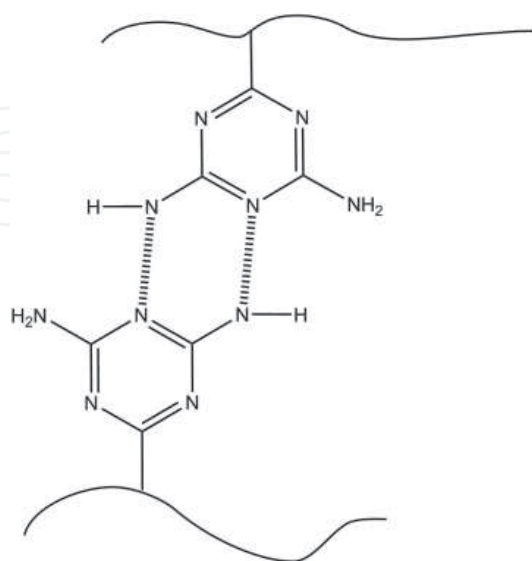


Figure 3. Hydrogen bond dimer associated to diaminotriazine.

in the origin of (1) thermally triggered shape memory behavior of collagen-containing hydrogels [25] and (2) near-infrared light induced rapid shape recovery in a (gelatin/graphene oxide)-based hybrid system, among others [26]. This concept has been extensively studied by Willner and collaborators for the fabrication of DNA-acrylamide SMHs. A pH-responsive material containing polymeric chains with self-complementary DNA strands fixed its temporary triangular shape *via* self-assembly at pH = 5, whereas it transformed back to the original quasi-liquid state when pH was increased to 8 [27]. This rational approach was later extended to more complicated systems exhibiting more than one pair of self-complementary DNA strands and exhibiting two pH-dependent temporary states, [28, 29] and as much as three different triggering stimuli [30].

2.3. Host-guest interactions

Host-guest interactions are in the basis of another interesting method to construct SMHs. The supramolecular interactions established between molecular hosts with large cavities and complementary guests that usually exhibit molecular recognition are able to induce a temporary crosslink. Hydrogels can be synthesized by (1) mixing polymers bearing host entities with those containing guest species or (2) copolymerizing monomers functionalized host and guest units. Although different macrocyclic hosts such as cucurbit[n]urils, crown ethers and cyclodextrins have been used to fabricate self-healing hydrogels based on host-guest interactions according to a recent review [31], only the latter have been exploited to date for the preparation of SSMHs.

Cyclodextrins (CD) are a family of cyclic oligosaccharides which have been traditionally used in supramolecular chemistry due to their capability to generate host-guest complexes. Typical cyclodextrins contain six (α -CDs), seven (β -CDs), or eight (γ -CDs) glucose units disposed in a ring, and thus, the size of the inner cavity varies accordingly. CDs have been widely used as drug-delivery systems in pharmaceutical applications because they can form inclusion compounds with hydrophobic drugs and become them water-soluble [32]. Analogously, their shape and chemical properties make CDs ideal candidates for the preparation of rotaxanes [33]. Inspired by rotaxane-like systems, Yang's group reported a poly(pseudorotaxane) supramolecular SMH *via* copolymerization of host (α -CD) and guest (PEG) monomers [34]. The use of acrylamide and acrylate comonomers avoided the rapid precipitation of α -CD/PEG inclusion complexes in the photoinitiated copolymerization process and afforded a mechanically tough physical hydrogel. Following a different synthetic approach, a mixture of poly- β -cyclodextrin and a polymer with adamantane groups in the side chains affords a physical hydrogel with a high self-healing efficiency [35]. Shape memory properties were added in both systems after being treated with FeCl_3 aqueous solution. The mechanism of the temporary crosslinking arisen from the coordination between carboxylate groups and Fe^{3+} ions and the methods for recovering the original shape are those that will be discussed more specifically in the next section.

With regard to hydrogels that display shape memory behavior induced by host-guest interactions, Li, Zhang and collaborators reported a pH sensitive SMH cross-linking β -CD-modified alginate and diethylenetriamine-modified alginate with Ca^{2+} ions [36]. At high pH values

(11.5), the material can be easily deformed to its temporary phase because the protonation of amino groups from diethylenetriamine prevents the formation of the inclusion complex. Deprotonation at neutral pH allows the system to recover its initial shape. Encouraged by the high recovery ratio ($> 95\%$), the biocompatibility of the polymeric backbone and the physiological pH in which the shape memory process takes place, and the SMH was evaluated as a promising candidate for biomedical applications. The chemical approach was later extended by the same research group to prepare redox-active SMHs. In this case, ferrocene-modified branched polyethylenimine (PEI) was used in combination with β -CD-modified chitosan. The reduced form of the ferrocene (Fe^{2+}) interacts with β -CD and permits the processing of this material into temporary shapes, whereas its oxidation leads to the shape recovery because the positively charged form is excluded from the CD cavity (**Figure 4**) [37].

Moving a step forward, the use of two different kinds of inclusion complexes acting simultaneously resulted in a SSMH with excellent self-healing and expansion-contraction properties [17]. Both ferrocene and adamantane guests and β -CD hosts were attached in polyacrylamide-based main chains to generate a dual temporary crosslinks. Oxidation of ferrocene groups leads to not only the shape memory behavior, but also to the expansion of the hydrogel. It is worth noting that different temporary shapes can be fixed through mechanical stress applied on the oxidized form taking advantage of the lability of β -CD/adamantane interactions.

2.4. Metal-ligand coordination bonds

This approach is based on the interactions established between the functional oxygen- or nitrogen-donor groups of the polymeric chains that act as ligands toward the transition metal ions that have been incorporated into the system. Coordination bonds are able to fix the temporary shape, whereas their removal by external chelating agent, the action of a reducing species and light- or electrically driven reactions leads back to the original state of the hydrogel. The addition of colorful, redox-, magnetically- and catalytically active transition metal cations can also confer the polymeric material with additional functionalities. It is worth noting that the temporary interactions could often show strong contributions from the electrostatic forces

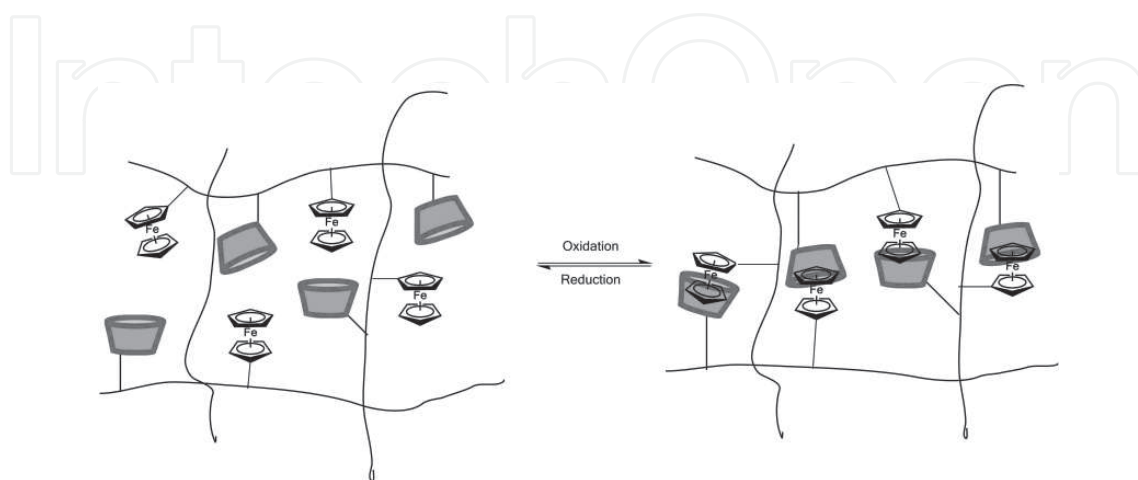


Figure 4. Schematic representation of the SME in redox-sensitive hydrogels based on host-guest interactions between ferrocene and CD groups.

between positively charged metal cations and negatively charged groups like phosphates or carboxylates. Examples including systems in which the electrostatic interactions have been identified as the origin of the shape memory behavior will be covered in the next section.

Metal-ligand coordination bonds have been applied in a variety of systems that cover from hard Lewis-bases like O-donor ligands in combination with hard Lewis-acids (Fe^{3+}) to N-donor ligands that interact with softer acids (Cu^{2+} , Zn^{2+}). The former strategy has been applied in cross-linked polyacrylamide/polyacrylic acid gels [38–40]. For instance, randomly distributed and physically cross-linked copolymer hydrogels showed high toughness and excellent processability in such a way that they could be fabricated by three-dimensional printing technologies. The metal coordination bonds could be easily removed through the light-induced reduction of the Fe^{3+} in the presence of citric acid or protonation of carboxylate groups under acidic pH. Conversely, chemical crosslink afforded a controllable self-deforming SMH: the original shape can be gradually modified as a function of the pH, whereas the transition-metal triggered shape memory behavior starts when the temporary form at basic pH is fixed by its immersion in an aqueous solution containing Fe^{3+} ions. Shape recovery takes place in a controllable way by sequential steps that imply the increase of H^+ concentration in the aqueous media.

When it comes to N-donor ligands pyridine, imidazole and cyanide groups have been employed with redox active Cu^{2+} and nonactive Zn^{2+} ions to lock the temporary shape. For redox sensitive Cu^{2+} -pyridine bonds (**Figure 5**), the reduction to Cu^+ *via* sodium metabisulphite was used as the external stimulus required to recover the original shape through a process that involved not only the cited shape memory behavior, but also changes in the color and mechanical properties of the material [41]. On the contrary, the polyacrylate chains with

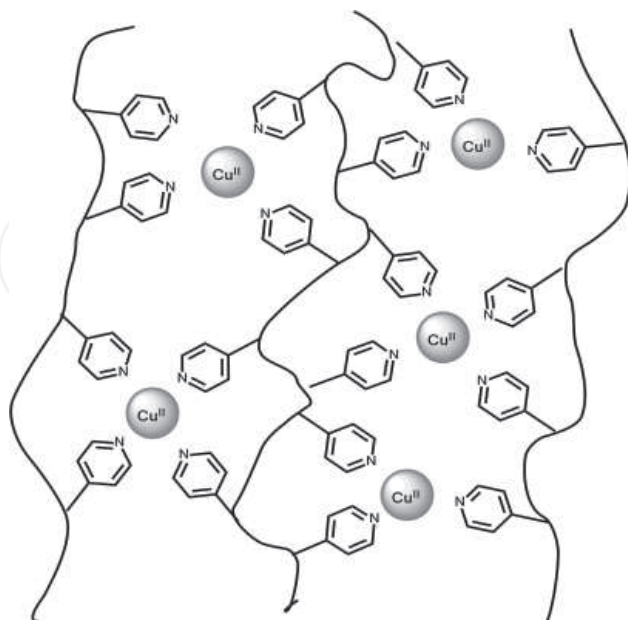


Figure 5. Schematic representation of the SME in redox-sensitive hydrogels based on metal-coordination bonds between copper cations and pyridine groups.

imidazole side groups generated a SMH based on Zn^{2+} /imidazole bonds whose shape can only be reversed by the addition of strong chelating agents such as EDTA [42]. In a closely related work, a UV-light triggered shape memory was described in a similar polymeric matrix. In this case, diphenyliodonium nitrate was incorporated which generates protons under UV light leading to the protonation of imidazole groups and consequent cleavage of coordination bonds [43]. Regarding cyanide containing materials, Liu et al. reported on dipole-dipole reinforced, acrylonitrile-based, ultra-high strength hydrogels that displays triple shape memory effect regulated by zinc ion concentration. Additional investigations by this group demonstrated that the temporary shape can be pre-programmed by surface micropatterning [12, 43].

2.5. Electrostatic interactions

Ionic temporary crosslink has been long used to induce self-healing behavior in covalently cross-linked hydrogels. Electrostatic forces between anionic functional groups and cationic metal cations can afford highly stretchable and tough self-healable hydrogels, as exemplified by photo-cross-linked polyacrylamide networks with Ca^{2+} -alginate interactions [44]. Following this approach and combining it with covalent boronate ester dynamic bonds, a dual shape memory/self-healing PVA hydrogel was developed where the incorporations/removal of Ca^{2+} ions was used to trigger the shape recovery process [45]. According to the authors, the temporary state can be fixed in 30 s, much faster than other shape memory hydrogels induced by metal ions, which need hours for that purpose. This is the case of acrylamide/isoprenyl phosphonic acid copolymers cross-linked by PEG diacrylate where the presence of Fe^{3+} ions allows the shape memory to take place [46]. In both systems, the extraction of metal ions with EDTA chelating agent completely recovers the original shape. Additionally, the reduction of Fe^{3+} with erythorbic acid for the later example and the removal of Ca^{2+} ions upon immersion of the hydrogel in basic aqueous media for the former can be applied as alternative recovering stimuli. Among the alginate-based shape-memory materials, it is worth highlighting the superelastic hydrogel that incorporates flexible SiO_2 nanofibers and exhibits pressure-dependent conductivity. Trivalent Al^{3+} cations facilitate complete recovery from 80% strain in this ultrahigh water content hydrogel (99.8 wt%) [47].

The electrostatic approach can be applied in combination with not only dynamic covalent bonds, but also another additional temporary interactions such as hydrogen bonds as was demonstrated by Ca^{2+} -triggered shape memory properties in PVDT-PAA (VDT = 2-vinyl-4,6-diamino-1,3,5-triazine) hydrogels synthesized *via* photo-polymerization [48]. The low cytotoxicity of the system encouraged the authors to evaluate biological aspects. It was proved that cells could adhere to the hydrogel surface, and afterward, they can be conveniently detached by simply adding calcium ions without influencing their viability. Thus, this dual strategy paves the way for the design of new multifunctional high strength hydrogels for biomedical applications.

Besides the addition of metal cations, charged groups can also be coexisting in zwitterionic copolymers. Classic examples include those in which anionic carboxylate or sulfonate monomers and cationic ammonium units are copolymerized with neutral comonomers. These hydrogels can show the shape memory behavior in the absence of any chemical cross-linker or addition of metal salts. Tong [49] have opted for synthesizing polyampholyte hydrogels by reacting

cationic 3-(methacryloylamino)propyltrimethylammonium, anionic *p*-styrenesulfonate and neutral methacrylic acid monomers in a one-step process. Apart from the pH-dependent shape memory effect that can be repeated over 10 times, the hydrogel showed a spontaneous shape change after the first cycle. Therefore, the hydrogel prepared was proposed as a starting point for the design of new soft actuators that require successive actions. However, the preparation of the desired shape memory material in polyampholyte hydrogels is often challenging. As shown by previous works, different authors were forced to incorporate Fe^{3+} ions or to induce salt-dependent hydrophobic association in order to fix the temporary shape [18].

Although the field of shape memory hydrogels based on electrostatic assembly is basically limited to simple metal-ion containing systems, recent advances in self-healing hydrogels that incorporate another inorganic entities provide new ideas that could be promisingly exploited with the aim of pursuing shape-memory behavior. Indeed temporary ionic bonds are in the origin of (1) the rapid self-healing ability of mechanically robust hybrid PAA hydrogels that contain amino-derivatized nanometric polyhedral oligomeric silsesquioxanes (POSS) [50]; (2) the magnetic auto-repairing ability of a chitosan-based hydrogel loaded with magnetite (Fe_3O_4) nanoparticles that display coatings modified with carboxylic acid functionalities [51]; and (3) the combination of anionic polyoxometalate (POM) $[\text{EuW}_{10}\text{O}_{36}]^{9-}$ oxo-clusters with cationic triblock copolymers bearing guanidinium groups that result in hybrid hydrogels with both tunable luminescent and self-healing capability [52].

3. Multishape memory effect

Triple-shape or multishape memory hydrogels can be designed by a combination of two or more noninterfering dynamic switches incorporated in hydrogel's network [53]. In spite of the great variety of supramolecular interactions described above, triple/multiple shape memory effect still represents a great challenge. This class of SSMH is capable to store two or more metastable shapes in addition to the original shape. In contrast to conventional shape memory polymers in which temporally switches are based on temperature changes, SSMHs can respond to different stimuli (pH, redox...) through sequential changes at room temperature [54]. This kind of hydrogels is until now less studied, and only few examples have been reported. Xiao et al. have demonstrated the triple-shape and multishape memory effect by using two reversible interactions based on dynamic covalent interactions and metal–ligand coordination bonds. The hydrogel was prepared by the polymerization of acrylamide monomer in the presence of chitosan and oxidized dextran. The temporary shape could be obtained by multiresponsive Schiff base-type bonds established between the amino groups of chitosan and the aldehyde groups of the oxidized dextran. In addition, other secondary temporary shape could be fixed with the chelating capability of the chitosan with several metal cations [53]. More complicated studies have been devoted to the hydrogels based on three switchers based on metal-ligand coordination, dynamic covalent bonds and coil-helix transaction. Each of these interactions could fix one temporary shape in the hydrogel. The first temporary shape was achieved by coordination of acrylic acid moieties to Fe^{3+} cations. A second temporary shape was fixed by the reaction between phenylboronic acid (PBA) and 1,2-diols forming ester

bonds under basic pH (pH = 10). Finally, the third temporary shape was fixed by coil-helix transition of the agar structure that represents switch rarely used in the design of this kind of hydrogels [55]. A very similar approach was described by Le et al. where a triple-shape memory was based on PBA-diol bonds and the coordination interactions between alginate and calcium cations [56].

4. Conclusion

In summary, highly promising advances have been made in the development of supramolecular shape memory hydrogels, and a plethora of new hydrogels will be synthesized in the following years due to the versatility of the supramolecular interactions. In addition, the self-healable capability and their adequate biocompatible properties added great capability of adaptation to different requirements.

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Conflict of Interest

The authors declare no conflict of interest.

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References

- [1] Langer R, Peppas NA. Advances in biomaterials, drug delivery, and bionanotechnology. *AICHE Journal*. 2003;**49**:2990-3006. DOI: 10.1002/aic.690491202
- [2] Gupta P, Vermani K, Garg S. Hydrogels: From controlled release to pH-responsive drug delivery. *Drug Discovery Today*. 2002;**7**:569-579. DOI: 10.1016/S1359-6446(02)02255-9
- [3] Richter AA, Paschew G, Klatt S, Lienig J, Arndt KF, HJP A. Review on hydrogel-based pH sensors and microsensors. *Sensors*. 2008;**8**:561-581. DOI: 10.3390/s8010561
- [4] Gyarmati B, Szilágyi BA, Szilágyi A. Reversible interactions in self-healing and shape memory hydrogels. *European Polymer Journal*. 2017;**93**:642-669. DOI: 10.1016/j.eurpolymj.2017.05.020
- [5] Taylor DL, in het Panhuis M. Self-Healing Hydrogels. *Adv. Maternité*. 2016;**8**:9060-9093. DOI: 10.1002/adma.201601613
- [6] Löwenberg C, Balk M, Wischke C, Behl M, Lendlein A. Shape-memory hydrogels: Evolution of structural principles to enable shape switching of hydrophilic polymer networks. *Accounts of Chemical Research*. 2017;**50**:723-732. DOI: 10.1021/acs.accounts.6b00584
- [7] Zhao Q, Qi HJ, Xie T. Recent progress in shape memory polymer: New behavior, enabling materials, and mechanistic understanding. *Progress in Polymer Science*. 2015;**49-50**:79-120. DOI: 10.1016/j.progpolymsci.2015.04.001
- [8] Hu J, Zhu Y, Huang H, Lu J. Recent advances in shape-memory polymers: Structure, mechanism, functionality, modeling and applications. *Progress in Polymer Science*. 2012;**7**:1720-1763. DOI: 10.1016/j.progpolymsci.2012.06.001
- [9] Li G, Zhang H, Fortin D, Xia H, Zhao Y. Poly(vinyl alcohol)-poly(ethylene glycol) double-network hydrogel: A general approach to shape memory and self-healing functionalities. *Langmuir*. 2015;**31**:11709-11716. DOI: 10.1021/acs.langmuir.5b03474
- [10] Habault D, Zhang H, Zhao Y. Light-triggered self-healing and shape-memory polymers. *Chemical Society Reviews*. 2013;**2**:7244. DOI: 10.1039/c3cs35489j
- [11] Liu C, Qin H, Mather PT. Review of progress in shape-memory polymers. *Journal of Materials Chemistry*. 2007;**17**:1543. DOI: 10.1039/b615954k
- [12] Han Y, Bai T, Liu Y, Zhai X, Liu W. Zinc ion uniquely induced triple shape memory effect of dipole-dipole reinforced ultra-high strength hydrogels. *Macromolecular Rapid Communications*. 2012;**33**:225-231. DOI: 10.1002/marc.201100683
- [13] Xiao YY, Gong XL, Kang Y, Jiang ZC, Zhang S, Li BJ. Light-, pH- and thermal-responsive hydrogels with the triple-shape memory effect. *Chemical Communications*. 2016;**52**:10609-10612. DOI: 10.1039/C6CC03587F
- [14] Zhang H, Zhao Y. Polymers with dual light-triggered functions of shape memory and healing using gold nanoparticles. *ACS Applied Materials & Interfaces*. 2013;**5**:13069-13075. DOI: 10.1021/am404087q

- [15] Ratna D, Karger-Kocsis J. Recent advances in shape memory polymers and composites: A review. *Journal of Materials Science*. 2008;**43**:254-269. DOI: 10.1007/s10853-007-2176-7
- [16] Bilici C, Can V, Nöchel U, Behl M, Lendlein A, Okay O. Melt-processable shape-memory hydrogels with self-healing ability of high mechanical strength. *Macromolecules*. 2016;**49**:7442-7449. DOI: 10.1021/acs.macromol.6b01539
- [17] Miyamae K, Nakahata M, Takashima Y, Harada A. Self-healing, expansion-contraction, and shape-memory properties of a preorganized supramolecular hydrogel through host-guest interactions. *Angewandte Chemie International Edition*. 2015;**54**:8984-8987. DOI: 10.1002/anie.201502957
- [18] Fan Y, Zhou W, Yasin A, Li H, Yang H. Dual-responsive shape memory hydrogels with novel thermoplasticity based on a hydrophobically modified polyampholyte. *Soft Matter*. 2015;**11**:4218-4225. DOI: 10.1039/C5SM00168D
- [19] Li Z, Lu W, Ngai T, Le X, Zheng J, Zhao N, Huang Y, Wen X, Zhang J, Chen T. Mussel-inspired multifunctional supramolecular hydrogels with self-healing, shape memory and adhesive properties. *Polymer Chemistry*. 2016;**7**:5343-5346. DOI: 10.1039/C6PY01112H
- [20] Nieuwenhuizen MML, TFA DG, Der Bruggen RLJ V, Paulusse MJJ, Appel WPJ, Smulders MMJ, Sijbesma RP, Meijer EW. Self-assembly of ureido-pyrimidinone dimers into one-dimensional stacks by lateral hydrogen bonding. *Chemistry – A European Journal*. 2010;**16**:1601-1612. DOI: 10.1002/chem.200902107
- [21] Chen H, Li Y, Tao G, Wang L, Zhou S. Thermo- and water-induced shape memory poly(vinyl alcohol) supramolecular networks crosslinked by self-complementary quadruple hydrogen bonding. *Polymer Chemistry*. 2016;**7**:6637-6644. DOI: 10.1039/C6PY01302C
- [22] Zhang G, Chen Y, Deng Y, Ngai T, Wang C. Dynamic supramolecular hydrogels: Regulating Hydrogel properties through self-complementary quadruple hydrogen bonds and thermo-switch. *ACS Macro Letters*. 2017;**6**:641-646. DOI: 10.1021/acsmacrolett.7b00275
- [23] Xu B, Zhang Y, Liu W. Hydrogen-bonding toughened hydrogels and emerging CO₂-responsive shape memory effect. *Macromolecular Rapid Communications*. 2015;**36**:1585-1591. DOI: 10.1002/marc.201500256
- [24] Chen YN, Peng L, Liu T, Wang Y, Shi S, Wang H. Poly(vinyl alcohol)-tannic acid hydrogels with excellent mechanical properties and shape memory behaviors. *ACS Applied Materials & Interfaces*. 2016;**8**:27199-27206. DOI: 10.1021/acsami.6b08374
- [25] Skrzyszewska PJ, Jong LN, de Wolf FA, Cohen Stuart MA, van der Gucht J. Shape-memory effects in biopolymer networks with collagen-like transient nodes. *Biomacromolecules*. 2011;**12**:2285-2292. DOI: 10.1021/bm2003626
- [26] Huang J, Zhao L, Wang T, Sun W, Tong Z. NIR-triggered rapid shape memory PAM-GO-gelatin hydrogels with high mechanical strength. *ACS Applied Materials & Interfaces*. 2016;**8**:12384-12392. DOI: 10.1021/acsami.6b00867
- [27] Guo W, Lu CH, Orbach R, Wang F, Qi XJ, Cecconello A, Seliktar D, Willner I. pH-stimulated DNA hydrogels exhibiting shape-memory properties. *Advanced Materials*. 2015;**27**:73-78. DOI: 10.1002/adma.201403702

- [28] Hu Y, Lu CH, Guo W, Aleman-Garcia MA, Ren J, Willner I. A shape memory acrylamide/DNA hydrogel exhibiting switchable dual pH-responsiveness. *Advanced Functional Materials*. 2015;**25**:6867-6874. DOI: 10.1002/adfm.201503134
- [29] Hu Y, Guo W, Kahn JS, Aleman-Garcia MA, Willner I. A shape-memory DNA-based hydrogel exhibiting two internal memories. *Angewandte Chemie International Edition*. 2016;**55**:4210-4214. DOI: 10.1002/anie.201511201
- [30] Lu CH, Guo W, Hu Y, Qi XJ, Willner I. Multitriggered shape-memory acrylamide–DNA hydrogels. *Journal of the American Chemical Society*. 2015;**137**:15723-15731. DOI: 10.1021/jacs.5b06510
- [31] Strandman S, Zhu XX. Self-healing supramolecular hydrogels based on reversible physical interactions. *Gels*. 2016;**2**:16. DOI: 10.3390/gels2020016
- [32] Webber MJ, Langer R. Drug delivery by supramolecular design. *Chemical Society Reviews*. 2017;**46**:6600-6620. DOI: 10.1039/C7CS00391A
- [33] Sliwa W, Girek T. CD-based rotaxanes and polyrotaxanes as representative supramolecules. In: Sliwa W, Girek T, editors. *Cyclodextrins*. Weinheim: Wiley-VCH Verlag; 2017. pp. 9-50. DOI: 10.1002/9783527695294.ch1
- [34] Feng W, Zhou W, Dai Z, Yasin A, Yang H. Tough polypseudorotaxane supramolecular hydrogels with dual-responsive shape memory properties. *Journal of Materials Chemistry B*. 2016;**4**:1924-1931. DOI: 10.1039/C5TB02737C
- [35] Cai T, Huo S, Wang T, Sun W, Tong Z. Self-healable tough supramolecular hydrogels crosslinked by poly-cyclodextrin through host-guest interaction. *Carbohydrate Polymers*. 2018;**193**:54-61. DOI: 10.1016/j.carbpol.2018.03.039
- [36] Dong ZQ, Cao YY, Yuan QJ, Wang YF, Li JH, Li BJ, Zhang S. Redox- and glucose-induced shape-memory polymers. *Macromolecular Rapid Communications*. 2013;**34**:867-872. DOI: 10.1002/marc.201300084
- [37] Han XJ, Dong ZQ, Fan MM, Liu Y, Li JH, Wang YF, Yuan QJ, Li BJ, Zhang S. pH-induced shape-memory polymers. *Macromolecular Rapid Communications*. 2012;**33**:1055-1060. DOI: 10.1002/marc.201200153
- [38] Zhang T, Silverstein MS. Doubly-crosslinked, emulsion-templated hydrogels through reversible metal coordination. *Polymer*. 2017;**126**:386-394. DOI: 10.1016/j.polymer.2017.07.044
- [39] Zheng SY, Ding H, Qian J, Yin J, Wu ZL, Song Y, Zheng Q. Metal-coordination complexes mediated physical hydrogels with high toughness, stick–slip tearing behavior, and good processability. *Macromolecules*. 2016;**49**:9637-9646. DOI: 10.1021/acs.macromol.6b02150
- [40] Le X, Zhang Y, Lu W, Wang L, Zheng J, Ali I, Zhang J, Huang Y, Serpe MJ, Yang X, Fan X, Chen T. A novel anisotropic hydrogel with integrated self-deformation and controllable shape memory effect. *Macromolecular Rapid Communications*. 2018:1800019. DOI: 10.1002/marc.201800019
- [41] Harris RD, Auletta JT, Motlagh SAM, Lawless MJ, Perri NM, Saxena S, Weiland LM, Waldeck DH, Clark WW, Meyer TY. Chemical and electrochemical manipulation of

- mechanical properties in stimuli-responsive copper-cross-linked hydrogels. *ACS Macro Letters*. 2013;**2**:1095-1099. DOI: 10.1021/mz4004997
- [42] Nan W, Wang W, Gao H, Liu W. Fabrication of a shape memory hydrogel based on imidazole–zinc ion coordination for potential cell-encapsulating tubular scaffold application. *Soft Matter*. 2013;**9**:132-137. DOI: 10.1039/C2SM26918J
- [43] Feng W, Zhou W, Zhang S, Fan Y, Yasin A, Yang H. UV-controlled shape memory hydrogels triggered by photoacid generator. *RSC Advances*. 2015;**5**:81784-81789. DOI: 10.1039/C5RA14421C
- [44] Sun JY, Zhao X, Illeperuma WRK, Chaudhuri O, Oh KH, Mooney DJ, Vlassak JJ, Suo Z. Highly stretchable and tough hydrogels. *Nature*. 2012;**489**:133-136. DOI: 10.1038/nature11409
- [45] Meng H, Xiao P, Gu J, Wen X, Xu J, Zhao C, Zhang J, Chen T. Self-healable macro-/microscopic shape memory hydrogels based on supramolecular interactions. *Chemical Communications*. 2014;**50**:12277-12280. DOI: 10.1039/C4CC04760E
- [46] Yasin A, Li H, Lu Z, ur Rehman S, Siddiq M, Yang H. A shape memory hydrogel induced by the interactions between metal ions and phosphate. *Soft Matter*. 2014;**10**:972-977. DOI: 10.1039/C3SM52666F
- [47] Si Y, Wang L, Wang X, Tang N, Yu J, Ding B. Ultrahigh-water-content, superelastic, and shape-memory nanofiber-assembled hydrogels exhibiting pressure-responsive conductivity. *Advanced Materials*. 2017;**29**:1700339. DOI: 10.1002/adma.201700339
- [48] Ren Z, Zhang Y, Li Y, Xu B, Liu W. Hydrogen bonded and ionically crosslinked high strength hydrogels exhibiting Ca^{2+} -triggered shape memory properties and volume shrinkage for cell detachment. *Journal of Materials Chemistry B*. 2015;**3**:6347-6354. DOI: 10.1039/C5TB00781J
- [49] Zhang Y, Liao J, Wang T, Sun W, Tong Z. Polyampholyte hydrogels with pH modulated shape memory and spontaneous actuation. *Advanced Functional Materials*. 2018:1707245. DOI: 10.1002/adfm.201707245
- [50] Pu W, Jiang F, Chen P, Wei B. A POSS based hydrogel with mechanical robustness, cohesiveness and a rapid self-healing ability by electrostatic interaction. *Soft Matter*. 2017;**13**:5645-5648. DOI: 10.1039/C7SM01492A
- [51] Zhang Y, Yang B, Zhang X, Xu L, Tao L, Li S, Wei Y. A magnetic self-healing hydrogel. *Chemical Communications*. 2012;**48**:9305. DOI: 10.1039/c2cc34745h
- [52] Wei H, Du S, Liu Y, Zhao H, Chen C, Li Z, Lin J, Zhang Y, Zhang J, Wan X. Tunable, luminescent, and self-healing hybrid hydrogels of polyoxometalates and triblock copolymers based on electrostatic assembly. *Chemical Communications*. 2014;**50**:1447-1450. DOI: 10.1039/C3CC48732F

- [53] Xiao H, Lu W, Le X, Ma C, Li Z, Zheng J, Zhang J, Huang Y, Chen T. A multi-responsive hydrogel with a triple shape memory effect based on reversible switches. *Chemical Communications*. 2016;**52**:13292-13295. DOI: 10.1039/C6CC06813H
- [54] Zhang J, Chen T. A multiple shape memory hydrogel induced by reversible physical interactions at ambient condition. *Polymer*. 2017;**9**:138. DOI: 10.3390/polym9040138
- [55] Le X, Lu W, Xiao H, Wang L, Ma C, Zhang J, Huang Y, Chen T. Fe³⁺-, pH-, thermoresponsive supramolecular hydrogel with multishape memory effect. *ACS Applied Materials & Interfaces*. 2017;**9**:9038-9044. DOI: 10.1021/acsami.7b00169
- [56] Le X, Lu W, Zheng J, Tong D, Zhao N, Ma C, Xiao H, Zhang J, Huang Y, Chen T. Stretchable supramolecular hydrogels with triple shape memory effect. *Chemical Science*. 2016;**7**:6715-6720. DOI: 10.1039/C6SC02354A

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