Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/136/2025.21026

A Review on the Molecule Structure Design Strategies of Self-healing Hydrogel

Yiyuan Chen[1,a,*]

[1]*Institute of Materials Science and Engineering, Hainan University, Haikou, China*
a. 3607462399@qq.com
**corresponding author*

Abstract: Self-healing hydrogels are a class of three-dimensional crosslinked polymer networks based on dynamic bond design, which can spontaneously restore the original structure and properties after being damaged by external forces. Currently, the design strategy and its optimization have become an important topic in the research of self-healing hydrogels. Self-healing hydrogels have shown strong advantages in the fields of biomedicine, energy storage and sensing, and geological exploration. In this paper, the design strategy of self-healing hydrogels and its mechanism, performance characteristics, application areas and development prospects are reviewed.

Keywords: Self-healing hydrogels, Dynamic bonds, Molecular design strategies, Biomedical applications.

1. Introduction

Hydrogel is a class of hydrophilic polymers formed by physical or chemical cross-linking of three-dimensional network structure materials [1], which can absorb a large amount of water, and does not dissolve, with soft, non-toxic, biocompatible and good elasticity [2], has been widely used in the field of biomedicine, food processing, environmental management, etc. [3]. However, the traditional hydrogel consists of a rigid covalent crosslinked network constituting the matrix, which is susceptible to aging after a long period of time and irreversible damage under external stress, thus affecting the integrity of the network structure and mechanical properties, limiting its service life, and resulting in a large amount of material waste [4].

The self-healing hydrogel can rely on the molecular structure design of reversible bonding of the hydrogel itself to spontaneously repair the cracks and restore the original structure and properties after damage, and it can realize unlimited self-healing, so it has realized a wide range of applications in the fields of biomaterials [5], flexible sensing [6], and geology and mining [7].

Inspired by the self-repair of biological tissues through cell proliferation and differentiation [8], researchers have developed hydrogels with dynamic bond cross-linking. When the material is fractured under external force, the dynamic bonds in the crosslinked network at the interface undergo reversible fracture; and under certain conditions (e.g., temperature, humidity, light, heat, acid and alkali, etc.) [9], the two parts of the fractured material are brought into contact, and the reversible bonds can be formed again, thus realizing in situ self-healing of the hydrogel.According to the type of dynamic bonding, self-healing hydrogels can be classified into two categories: covalently crosslinked and non-covalently crosslinked.

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/136/2025.21026

The choice of crosslink density and dynamic bonding determines the network structure of hydrogels, which is of great significance for improving the self-healing efficiency, enhancing the comprehensive performance of hydrogels, and expanding their application areas[10]. Mild and simple synthesis process, exploration of new dynamic bonds, and synthesis of two or more dynamic bonds to construct double or multiple crosslinked networks have become the hot spots in the design of molecular structure of self-healing hydrogels[11]. In this paper, we review the common self-healing hydrogel construction strategies, their principles, performance characteristics and applications, and look forward to the future trends of self-healing hydrogel molecular structure design[12-15].

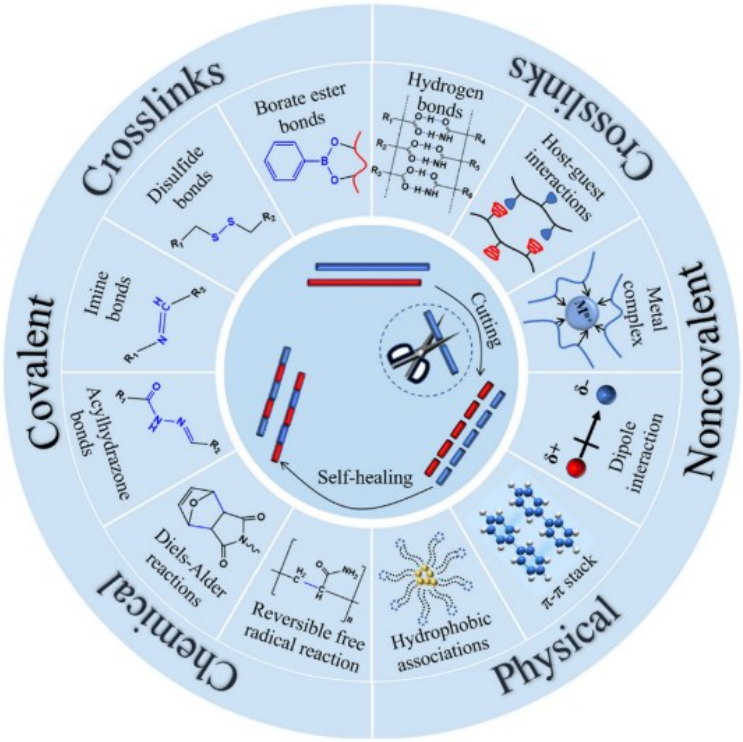

Figure 1: Various types of self-healing hydrogels based on corresponding design trategies

2. Design Strategies and Mechanism

2.1. Non-Covalent Bonds

The hydrogel synthesis process based on non-covalent dynamic bond design tends to be relatively simple to prepare, does not involve toxic or hazardous substances, and has a fast reconstruction rate and high self-healing efficiency. There are also new supramolecular interactions (e.g.,π-πstacking, etc.) [16] that continue to show attractive development prospects. [17] However, hydrogels based only on non-covalent dynamic bonds are often not strong enough. Several common dynamic noncovalent crosslinking strategies are briefly summarized below.

2.1.1. Hydrogen Bonds

In living organisms, the two strands of a DNA molecule are connected by multiple hydrogen bonds, and this connection gives the DNA molecule the ability to self-assemble. Inspired by this, hydrogen bonding has been widely used in the design of self-healing hydrogels. Hydrogen bonds are typically formed between hydrogen atoms and more electronegative atoms (e.g., nitrogen, oxygen, fluorine). While individual hydrogen bonds are weak, multiple hydrogen bonds formed in an oriented manner

DOI: 10.54254/2755-2721/136/2025.21026

can provide significant binding forces. In addition, hydrogen bonds bind and dissociate very quickly, giving self-healing hydrogels excellent properties such as fast self-healing rate, response to stimuli and [18].

Dang et al. prepared a self-healing hydrogel by one-pot free radical polymerization using carboxymethyl cellulose (CMC), acrylamide (AAm) and acrylic acid (AAc) as raw materials. The hydroxyl group of acrylic acid and the amino group of acrylamide form a hydrogen bond through the carbonyl oxygen. At 80℃, the broken hydrogen bonds can be regenerated within 1 h, completing the self-healing process. The hydrogel not only has excellent heat-induced self-healing ability, but also maintains high mechanical strength after healing, and remains intact without rupture even when stretched to 100% strain after healing; a hydrogel with a thickness of 1.8 mm and a width of 0.8 cm can withstand the weight of a 200 g water bottle without rupture. [19]

Zhao et al. prepared semi-interpenetrating polymer network (semi-IPN) hydrogels with a layered structure using sodium alginate (SA) and polyacrylamide (PAM) as raw materials, in which a large number of hydroxyl groups in the SA chains and abundant amino groups in the PAM chains could form multiple hydrogen bonds. The prepared hydrogels exhibited an excellent self-repair efficiency of 99% at room temperature, and the mechanical properties of the hydrogels were restored to the initial level after damage. [20]

2.1.2. Host-guest interaction

Subject-guest interactions refer to the phenomenon of specific recognition between subject and guest molecules. The subject molecules are usually cavity columnar macromolecular structures, and these subject molecules can selectively recognize specific guest molecules through non-covalent interactions such as hydrogen bonding, van der Waals forces, metal coordination, and hydrophobic interactions, thus forming relatively stable complexe. The reversibility of these non-covalent interactions provides the host-guest interactions with a dynamic self-healing capability, capable of spontaneous repair after rupture.

Yu et al. developed supramolecular hydrogels based on filipin protein (SF), acryloyl-β-cyclodextrin (Ac-CD) and 2-hydroxyethyl acrylate. In this system, CD acts as the main macromolecule and forms a reversible subject-object interaction with SF, endowing the hydrogel with excellent self-healing efficiency. The hydrogel cut into two parts was able to heal rapidly upon contact without any external stimulation. Compared with other hydrogels that require physical cross-linking, this subject-object interaction provided the hydrogel with more convenient and efficient self-healing properties, which enabled it to show promising application prospect in fields such as wound dressings. [21]

2.1.3. Metal complexation

Some transition metal ions can form reversible coordination bonds with ligands (e.g., carboxyl, hydroxyl, amino, etc.) with single electron pairs due to their empty d or f orbitals. When the hydrogel is damaged and cracked under external mechanical strain, the coordination bond can be quickly re-formed within a certain temperature range, thus realizing self-healing[22]. Notably, the doped ions conduct electricity, coordinate with the hydroxyl and carboxyl groups of the matrix, and also lower the freezing point. This provides ideas for the construction of strain-responsive, strongly adhesive, and low-temperature self-healing hydrogels, which opens up the possibility of their application in the fields of flexible sensing and wearable devices. Although metal coordination bonds are weaker than covalent bonds, they are stronger than hydrogen and van der Waals bonds, and the specific bond strength depends on the number of coordination bonds and the metal ions and ligand species.

DOI: 10.54254/2755-2721/136/2025.21026

Sun et al. designed ADC composite hydrogels from polyacrylic acid (PAAc), chitosan (CS), and polydopamine (PDA) for motion monitoring. In this system, Al3+ acts as a “bridge” to form a three-coordination structure with the carboxyl groups on the two PAAc chains, which constructs a hierarchical porous network with alternating rigid and elastic regions through reversible coordination bond-mediated interactions, improving the mechanical strength, adhesion, self-healing, and electrical conductivity of the hydroge. The fractured hydrogel can be completely healed after 24 hours hydrogel can be completely healed, and the mechanical properties recovered significantly, the tensile strength recovered to 81.6%, and the elongation at break recovered to 90.8%. In addition, the hydrogel showed excellent adhesion to a number of substrates. When the PDA content was 0.6%, the adhesion strength to steel was 213.8 kPa, and the adhesion strength to pig skin was 85.2 kPa.[23]

Fu et al. prepared CEC-PAA@Fe self-healing hydrogel by in situ free radical polymerization via the addition of N-carboxyethyl chitosan in an acrylic acid-Fe3+ system. Iron ions could coordinate with the carboxyl groups on the PAA and CEC chains to form a cross-linked network. The self-healing efficiency of the hydrogel was as high as 98% within 2.5 h. The self-healing efficiency of the CEC-PAA@Fe hydrogel was as high as 98%. In addition, due to the migration of Fe3+, the hydrogel not only had good electrical conductivity, but also excellent electrical reproducibility, and it was able to recover to the original conductivity of 87% after 2 h of self-healing. [24]

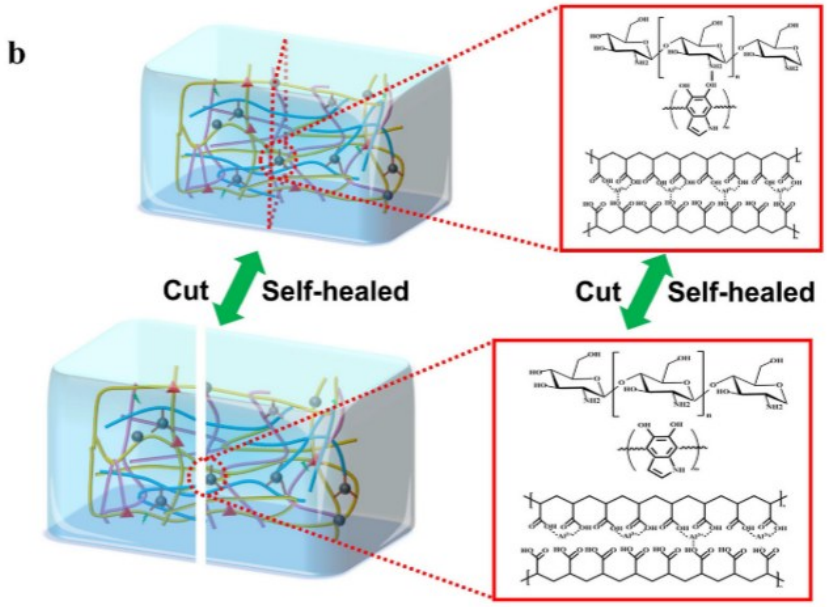

Figure 2: Self-healing mechanism of ADC hydrogel

2.1.4. Hydrophobic Association

The hydrophobic groups in the molecules will aggregate with each other to form micelles in order to avoid water molecules, and the environment inside the micelles is conducive to the entry of hydrophobic monomers to form polymerizable micelles. In this way, the hydrophobic monomers can provide the sites of association to copolymerize with the raw materials to form polymer chains, which in turn form cross-linked networks. When the hydrogel is cut and re-exposed, these micelles can re-form and link into molecular chains, restoring the three-dimensional network structure and realizing self-healing.

He et al. prepared self-healing polyacrylamide (PAM) hydrogels by reacting sodium dodecyl sulfate (SDS), sodium chloride (NaCl), and octadecyl methacrylate (SMA) to obtain polymerizable micelles, which were then copolymerized and condensed with acrylamide (AM). Under the action of

DOI: 10.54254/2755-2721/136/2025.21026

NaCl, a strong electrolyte, SDS formed micelles with SMA to expose the C=C bond as the site of attachment and formed a cross-linked network with PAM. The self-healing efficiency of this hydrogel was positively correlated with the amount of hydrophobic micelles formed by SMA.A hydrogel with 4% SMA content showed a self-healing efficiency of more than 70% after 24 h of exposure at 70 °C. The hydrogel was also characterized by a high degree of self-healing. [25]

2.2. Covalent Bonds

Compared to dynamic non-covalent bonds, dynamic covalent bonds retain the stability of covalent bonding properties and design hydrogels with better mechanical properties. In addition, some dynamic covalent bonds can also confer multiple stimulus responsiveness to hydrogels. However, some self-healing hydrogels based on dynamic covalent bonds require toxic substances to be involved in the synthesis process or relatively harsh conditions to induce self-healing behavior, which severely limits their applications.

2.2.1. Imine Bonds

Imine compounds, also known as Schiff bases, are named after the German chemist Hugo Schiff. Schiff bases contain a methylimine group (-RC=N-) and are usually formed by the dehydration condensation of a primary amine with a reactive carbonyl compound in an acidic anhydrous environment. When the hydrogel is cut, part of the imine bond is broken and the amino and aldehyde groups are freed. When the two parts of the hydrogel are contacted for a certain period of time, the free aldehyde and amino groups exposed at the interface can diffuse across the interface and re-form the imine bond, which can realize self-healing without external stimulation. In addition, the self-healing efficiency of imide-based hydrogels is controlled by temperature. Higher temperatures enhance the dynamic dynamics of reversible bonds, allowing the hydrogel network to be rebuilt faster at the molecular level. Imine bonds are stronger than acylhydrazone and disulfide bonds, with faster reactions and milder conditions [26], and are currently the most widely used strategy for designing self-healing hydrogels.

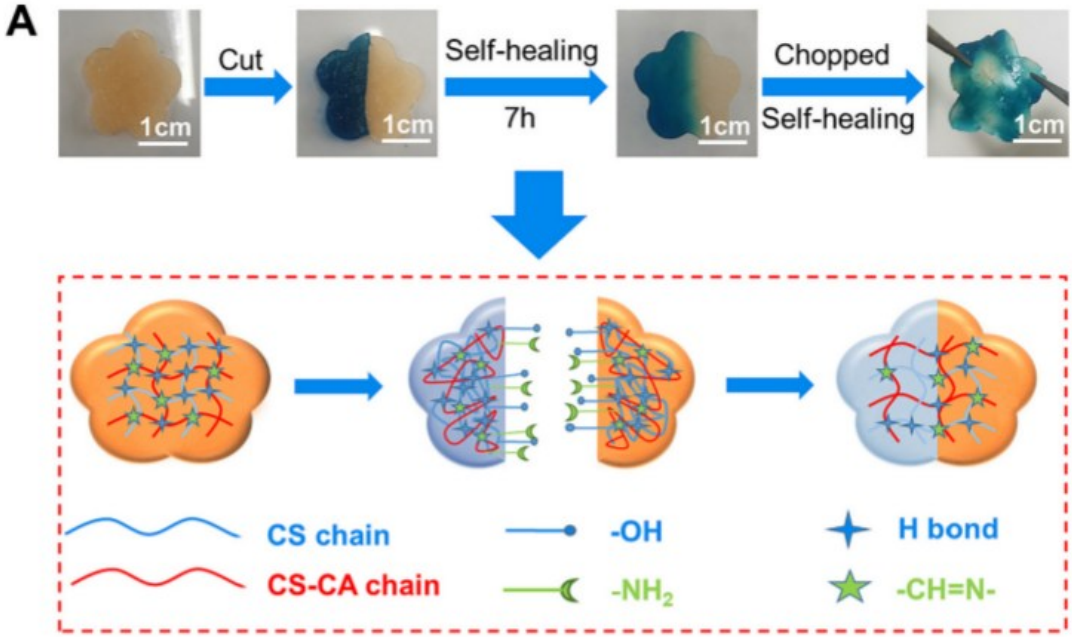

Figure 3: Self-healing behavior of CS-CA hydrogel

DOI: 10.54254/2755-2721/136/2025.21026

Huang et al. synthesized benzothiophene-capped, remotely clawed, four-armed poly(ethylene glycol) (PEG-BA) and crosslinked it with carboxymethyl chitosan (CMC) to form a dynamic hydrogel with strong mechanical properties for use as a hemostatic material. The imine bond was formed between the amino group on the CMC chain and the aldehyde group at the distal end of PEG-BA. Long strips of hydrogels placed side by side could be joined into a complete film after 5 min of contact at room temperature. The healing efficiency was 64 ± 3.8% after 6 h and increased to 80 ± 3.2% after 12 h. The hydrogels were also characterized by a high healing efficiency. Encouragingly, the hydrogel showed better self-healing properties at physiological temperature than at room temperature, with healing efficiencies as high as 80±8.6% and 94±9.8% after 6 and 12 h, respectively, which demonstrated its great potential for use as a hemostatic material. In addition, its energy storage modulus was as high as 3162.06±21.06 Pa, which was comparable to that of conventional native hydrogels, indicating that it combines excellent mechanical properties with efficient self-healing ability. [27]

In addition, changes in PH can affect the strength of imine bonds and thus induce their dynamic behavior [31]. This can endow the hydrogels with excellent PH responsiveness on the basis of their ability to achieve self-healing.Shi et al. constructed CA-CS hydrogels with Schiff base-hydrogen bonding double-crosslinked network by freeze-thawing and photo-crosslinking method using chitosan (CS) and coumarin (CA) as raw materials for controlled release of tachyphylium foetidum foliatum (TFL).The amino group of CS formed imine bonds with the aldehyde group of CA. When the hydrogel is fractured under external stress, the unreacted CA in it can react with CS to regenerate the Schiff base bond. The two parts of the cut hydrogel were spliced together and were initially fused after 3h and completely self-healed after 7h.The hydrogels were then cut and spliced together. The pKa values of glucosamine residues in chitosan were about 6.2-7.0 in an acidic buffer solution at pH = 4, at which time the amino group of CS was protonated and intermolecular repulsion was enhanced. As a result, the strength of the Schiff base bond becomes weaker and the cross-linking points of the hydrogel are easily decomposed, which can promote the release of TFL; in contrast, the amino group of CS is deprotonated in alkaline buffer at pH = 9.2, and thus the Schiff base bond is more stable, reducing the rate of drug release. This pH responsiveness shows the great potential of this hydrogel for drug controlled release applications. [28].

The acylhydrazone bond is an imine bond generated by the reaction of hydrazide and carbonyl groups, which is prepared under mild reaction conditions and in high yields. It undergoes reversible fracture under catalytic conditions at pH below 4 or high temperature and exhibits temperature and pH responsive properties. Sun et al. prepared a hydrogel of oxidized sodium alginate (OSA) crosslinked with hydrazone-modified poly-N-isopropylacrylamide (PNIPAM) copolymer. The formation of acylhydrazonium bond between the abundant aldehyde group on the chain of OSA and acylhydrazide group in the copolymer P(NIPAM-co-Hy) was shown by Sun et al. . After cutting the hydrogel into two parts and contacting them for 24 h, the samples successfully self-healed without any external stimuli; the hydrogel remained self-healing even after being cut into small pieces. In addition, the hydrogel was able to respond to changes in external pH with a reversible “sol-gel” transition. After adjusting the pH to 1, the hydrogel completely solubilizes within 1 hour; after precise acid neutralization, it can return to the gel state. This provides the conditions for its application in pH-responsive drug delivery systems. [29]

2.2.2. Disulfide/Diselenide Bonds

Inspired by the assembly process of protein molecules, disulfide bonds are also commonly used in the construction of dynamic hydrogels. Disulfide bond refers to a functional group with the structure of R-S-S-R', which can undergo a dynamic and reversible “oxidation-reduction” transition with thiol groups, in which the disulfide bond is in the oxidized state and the thiol is in the reduced state, which

DOI: 10.54254/2755-2721/136/2025.21026

is sensitive to reducing agents such as GSH. The disulfide bond is in the oxidized state and the thiol is in the reduced state, which is sensitive to reducing agents such as GSH. However, the self-healing process of hydrogels based on disulfide bonds often depends on relatively harsh external conditions, such as free radicals and radiation.

Bi et al. crosslinked thiolated galactomannan mannan (GGMSH) and TEMPO oxidized cellulose nanofibers (T-CNF) and constructed a disulfide-hydrogen bonded dual network self-healing hydrogel for bovine serum albumin (BSA) controlled release by utilizing the thiol-disulfide exchange reaction triggered by UV light. In this, sulfhydryl groups from two GGMSH chains formed disulfide bonds under UV illumination. After the hydrogel was cut into two parts and then contacted with each other, it was able to self-heal after UV irradiation for 160 s and remained intact and did not separate when immersed in water. [30]

In the periodic table, the element selenium is located in the same main group in the next cycle of the element sulfur, and the two are highly similar chemically, so the diselenide bond possesses a similar dynamic behavior as the disulfide bond. Jia et al. designed an AHA-Sel/LiCl (ASCL) hydrogel. The Schiff base bond with diselenide bond was formed by acid-catalyzed between encapsulated hyaluronic acid (AHA) and aminated diselenide cross-linker 2,2 ′-diselenadiyldiethylamine dihydrochloride (Sel). Under the low temperature of -20°C, the ASCL hydrogel was able to self-heal without external stimulation in merely 5 minutes, much swifter than hydrogels reported in recent years to require hours of self-healing. [31]

2.2.3. Borate Ester Bond

Borate esters are reversibly formed between boric acid and diols. Borate ester-based self-healing materials have the advantages of high self-healing ability, flexibility, and recyclability, and can effectively self-heal without external stimulation at room temperature. The borate ester bond is formed only at pH>pKa, and the reversible sol-gel transition of the hydrogel is realized through the collapse and reconstruction of the network structure, which endows the excellent pH responsiveness. [31]

Tang et al. constructed self-healing gel electrolytes for supercapacitors by combining a polymer precursor of 3-acrylamidophenylboronic acid (AAPBA) with 3,4-dihydroxyaniline (P4-AC).The two phenolic hydroxyl groups in the P4-AC polymer precursor and the -B(OH)2 group on the benzene ring in the AAPBA polymer precursor were esterified and crosslinked in alkaline environments, resulting in the formation of the gel's of dynamic borate bonds. It can be quickly restored to its original state after stress damage. Even after ten self-repairs, the gel still has the same mechanical properties as undamaged gels, and the supercapacitor maintains 100% of its initial performance at all angles or strains. After 10,000 cycles of charging and discharging, supercapacitors using the gel can maintain 90% of their initial capacity after 20 self-healing processes, which is only 4% lower than that of undamaged supercapacitors, showing high self-healing ability. [32]

Lin et al. prepared bionic skin with tannic acid (TA), Ag nanoparticle-modified CNC and crosslinked with polyvinyl alcohol (PVA) nanohybrids. The abundant catechol groups in tannic acid and the diol groups in PVA both formed borate bonds with B(OH)4- ions, which synergized with the multiple hydrogen bonds between the CNC nanoparticles and the PVA chains and tannic acid molecules to endow the PB-Ag/TA@CNC hydrogel with excellent self-healing ability. And the test results showed that the borate bonds played a major role in the self-healing process of this system. In the macroscopic self-healing efficiency test, the hydrogel that was cut in half could be re-healed after keeping the contact in the environment for 10 min. [33]

DOI: 10.54254/2755-2721/136/2025.21026

2.2.4. D-A Reaction

The Diels-Alde reaction, or dienophile synthesis, is a ring-forming addition reaction between a dienophile and a pro-dienophile. Its thermal reversibility is characterized by a low temperature for forward ring-forming reactions and a higher temperature for reverse ring opening. The reaction possesses the advantages of high yield, few side reactions, can increase the gel cross-linking density, fast rate and good selectivity [30]. Self-healing at room temperature can be achieved by optimizing the molecular structure design.

Li et al. prepared a self-healing hydrogel for drug release based on a reversible D-A reaction between fructose and chitosan. Furfural-modified pectin (PF) was used as the conjugated diene portion, and 6-maleimidocaproic acid was grafted onto chitosan to obtain CA, which acted as a pro-dienophile. The two were mixed and hybridized hydrogels were prepared by D-A reaction. After cutting the hydrogel into two halves, it was already significantly self-healing after 5 hours of exposure at 37 degrees Celsius and was able to withstand a weight of 500 g without being damaged.

Shao et al. constructed thermally reversible self-healing hydrogels by covalent DA reaction between furfural-modified CNCs (dienophiles) and maleimide end-functionalized PEG (pro-dienophiles). The healing hydrogels were exposed to a nitrogen atmosphere at 90 °C for a defined period of time without any external intervention, and then cooled to room temperature and stretched again with no splitting observed, confirming that the two pieces merged to form a complete hydrogel and that the interfacial layer was strong enough to withstand the tensile stress. Evaluated from the mechanical property indexes, the self-healing efficiency has reached 35% after 1 hour and 78% after 24 hours. [31]

3. Prospects and Challenges

The advantages of self-healing hydrogels are remarkable and promising. However, the reconstruction of some dynamic bonds after breakage depends on more stringent external conditions, and higher self-healing efficiency and better overall performance have become the goals of molecular structure design of self-healing hydrogels.

3.1. Dual-Network(DN) & Multi Network(MN)

Single-network crosslinked hydrogels tend to have insufficient mechanical strength, and even if they are self-healing, the low self-healing efficiency greatly limits their application [32]. In addition, dual- or multi-network crosslinked hydrogels can integrate the advantages of different dynamic bonds to optimize the comprehensive performance of hydrogels, which has become the most common structural design strategy today.

DOI: 10.54254/2755-2721/136/2025.21026

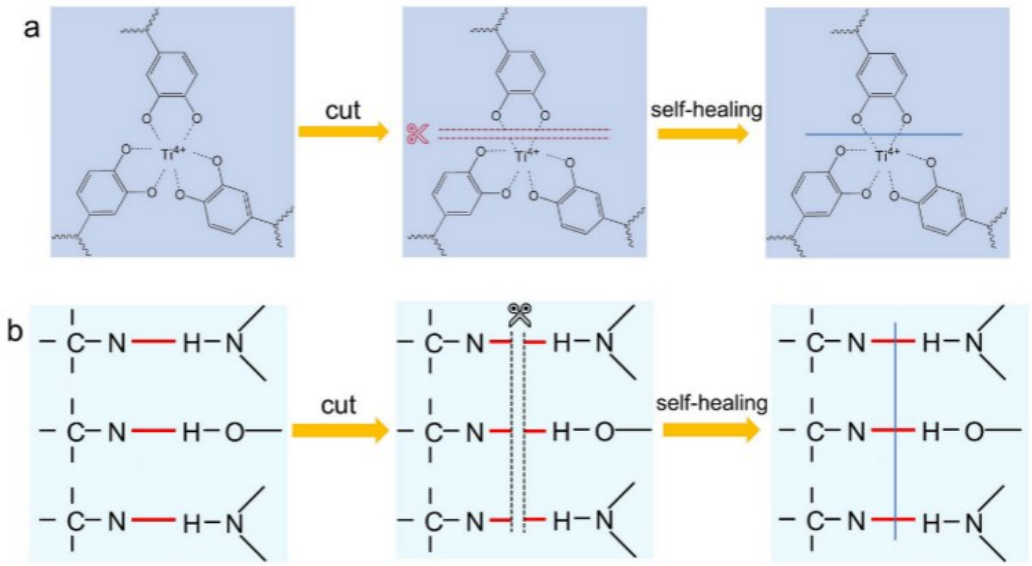

Figure 4: Schematic diagrams of destruction and regeneration of (a) metal coordination bond and (b) hydrogen bond during the self-healing process of CMC/DA@Ti hydrogel

Niu et al. constructed non-covalent double crosslinked self-healing hydrogels as flexible wearable sensors by grafting DA onto carboxyl-activated CMC chains to form amide bonds and crosslinking different CMC chains with titanium ions. The introduction of titanium ions enabled the hydrogels to realize efficient self-healing while greatly improving the mechanical properties, adhesion and conductivity. [33]Hydrogen bond formation occurs mainly between amide groups (C-N, N-H) and hydroxyl groups (O-H), while titanium ions form a three-coordination network with the hydroxyl oxygen of DA (Fig.) The best self-healing effect was observed at a molar mass ratio of Ti to DA of 1; 3. The self-healing efficiency was able to reach 93.66% within 3 h and 97.78% after 6 h, which was higher than that of other reported self-healing polymers. At the same molar mass ratio of titanium ion doping, the conductivity of this hydrogel was about 4.9 times higher than that of CMC/PDA hydrogel without Ti 4+, which was also higher than that of most reported conductive polymers. This indicates its promising prospect in the field of flexible sensors. [29]

Bai et al. prepared a hydrophobic-conjugated, metal-liganded dual-network self-repairing (DNSA) hydrogel based on hydrophobic conjugation for sealing formation pores and cracks in oil and gas drilling and production engineering. In this system, hydrophobic linkage constitutes the first crosslinked network, which is formed by simple micellar copolymerization of the hydrophobic monomers lauryl methacrylate (LMA), SDS, and hydrophilic monomer(AM), and the second network is formed by the reversible coordination crosslinks between iron ions and carboxyl groups of sodium alginate. In addition, there was an abundance of multiple hydrogen bonds between the sodium alginate and polyacrylamide chains, which could be reversibly connected after breakage and thus repair the incision. The hydrogel healed after 12 hours of contact at 70 °Cand remained intact under bending and stretching. [31]

3.2. Novel Dynamic Bonds

The exploration of novel dynamic bonds also possesses importance in today's molecular structure design work of self-healing hydrogels. For example, Knoevenagel condensation (KC), a reaction in which one molecule of water is removed to form a C=C bond between an aldehyde or ketone and a reactive methylene compound, has been reported as a novel dynamic hydrogel construction strategy.

DOI: 10.54254/2755-2721/136/2025.21026

The reaction can be readily carried out in aqueous solution independently of the presence of a catalyst. [27] It has been shown that temperature changes, near-infrared radiation, etc. can induce its dynamic behavior, endowing it with good prospects for development in areas such as drug release.

Wang et al. used cyanoacetate, benzimidazole-functionalized dextran (DEX-CA and DEX-BA) to form a dynamic hydrogel filler by KC reaction for wound management. In this case, a C=C bond was formed between the cyano group of DEX-CA and the benzaldehyde group of DEX-BA. Under NIR irradiation, the C=C bond was reversibly broken and the loaded drug was released with the decrease of crosslink density; after withdrawal of the radiation, the C=C bond was restored, the density of the hydrogel crosslinked network increased, and the structure and properties were fully restored. [31]

Ding et al. constructed thermosreversible dynamic hydrogels by capping methoxypolyethylene glycol (denoted as mPEG-BA, mPEG-CA, respectively) with benzaldehyde and cyanoacetate and cross-linking the two. The C=C bonds were broken at high temperatures and reformed upon cooling. In the macroscopic self-healing test, the self-healing efficiency was already close to 100% after 4 h at 37 °C, and the healed hydrogel could withstand stretching without rupture; and the dynamic conversion of the C=C bond was accelerated after warming, which was favorable for its self-healing efficiency. [29]

3.3. Functional Modification of Molecules

Since warming accelerates the rate of molecular thermal motion, and the reconstruction of dynamic covalent bonds depends on the thermal motion of the pre-molecules at the interface, for some (especially those constructed based on dynamic disulfide bonding, D-A reactions, etc.) self-healing hydrogels, they only possess high self-healing efficiency at higher temperatures. This severely limits their applications in biomedical fields. Therefore, how to realize efficient self-healing under mild conditions through molecular structure design and modification is a hot topic in today's research.

It has been demonstrated that it is feasible to achieve thermal equilibrium of DA reaction at room temperature by appropriate modification, such as DA reaction between cyano-functionalized pro-dienophile and furan, or DA reaction between anthracene and aromatic azido pro-dienophile, etc. Zhao et al. prepared a self-healing reaction using alkene-rich aedo-glucan as a dienophile and dichloro-maleic acid modified aedo-glucan as a pro-dienophile under physiological conditions. self-healing hydrogels were prepared under physiological conditions. After contacting the fractured hydrogels for 7 h at 37℃, the cracks were almost completely healed. [34]

4. Conclusion

Self-healing hydrogels are emerging materials that have flourished in recent years, and their molecular structure design and optimization strategies have become a research hotspot. Both non-covalent and covalent cross-linking have unique performance advantages. Self-healing hydrogels based on imine bonding, metal ion coordination bonding, etc. can realize efficient self-healing under mild conditions without complex modification, and at the same time, they are endowed with multiple stimulus responsiveness, which has become a widely used design strategy. In addition, the comprehensive use of multiple dynamic bonds, the design of dual-network/multi-network structures, and the exploration of novel dynamic bonds show a broad application prospect, especially in the fields of biomedicine and flexible electronics.

Although the structural design of self-healing hydrogels endows them with many excellent properties and a large number of results have been obtained, there are still many challenges in enhancing the mechanical properties, improving the long-term stability, and realizing large-scale production. Future research needs to further address these issues to promote the widespread use of self-healing hydrogels in practical applications.

DOI: 10.54254/2755-2721/136/2025.21026

References

[1] Zhang Yongyue, Shi Jiangtao, Fu Zongying, et al. Research progress of cellulose self-healing hydrogels [J]. Scientia Siluricae, 2019,60(02):128-138.

[2] Xu Hongtao, Shen Yong, Pan Hong, et al. Progress in preparation and application of self-healing hydrogels based on dynamic reversible covalent bonds [J]. New Chemical Materials, 2019,51(11):87-92.

[3] Chenxi Niu, Zhibo Lin, Qian Fu, Yutao Xu, Youhui Chen, Lingbin Lu, An eco-friendly versatile superabsorbent hydrogel based on sodium alginate and urea for soil improvement with a synchronous chemical loading strategy, Carbohydrate Polymers, Volume 327,2024,121676,

[4] Wei Z, Yang J H, Zhou J X, et al. 2014. Self-healing gels based on constitutional dynamic chemistry and their potential applications. Chemical Society Reviews, 43(23): 8114−8131.

[5] Jiman Jin, Chuchu Sun, Keyuan Xu, Xiaoliang Sun, Lingling Cao, Liangle Liu, Multifunctional self-healing peptide hydrogel for wound healing, International Journal of Biological Macromolecules, Volume 261, Part 1,2024,129734,

[6] Jia Yang, Qiong Kang, Bin Zhang, Xiyu Tian, Shuzheng Liu, Gang Qin, Qiang Chen, Robust, fatigue resistant, self-healing and antifreeze ionic conductive supramolecular hydrogels for wearable flexible sensors, Journal of Industrial and Engineering Chemistry, Volume 115,2022,Pages 162-170,

[7] LIU Jiayin, Li Yining, Wei Zhiyi, et al. Application progress of self-healing gel in petroleum engineering [J/OL]. Fine Chemical Industry,1-15[2024-09-11].

[8] Wang Chunyao. Research progress of self-healing hydrogels for biomedical purposes [J]. Fine and Special Chemicals,2023,31(06):40-45.

[9] Wenya Xu, Wen Wang, Simou Chen, Rui Zhang, Yuxin Wang, Qi Zhang, Lihui Yuwen, Wen Jing Yang, Lianhui Wang, Molybdenum disulfide (MoS2) nanosheets-based hydrogels with light-triggered self-healing property for flexible sensors, Journal of Colloid and Interface Science,2021,586: 601-612.

[10] Liu Mengmeng, Qiu Liwei, Wan Zhiwei, et al. Design principle and application of self-healing hydrogels [J]. Advances in Chemical Industry,2024,43(03):1350-1362.

[11] Xugang Dang, Yuntao Fu, Xuechuan Wang, A temperature and pressure dual-responsive, stretchable, healable, adhesive, and biocompatible carboxymethyl cellulose-based conductive hydrogels for flexible wearable strain sensor, Biosensors and Bioelectronics, Volume 246,2024,115893,

[12] ingwei Zhao, Mi Feng, Ling Zhang, Bin He, Xinyan Chen, Jian Sun, Facile synthesis of self-healing and layered sodium alginate/polyacrylamide hydrogel promoted by dynamic hydrogen bond,Carbohydrate Polymers,Volume 256,2021,117580

[13] Rui Yu, Yutong Yang, Jiahui He, Meng Li, Baolin Guo,Novel supramolecular self-healing silk fibroin-based hydrogel via host–guest interaction as wound dressing to enhance wound healing,Chemical Engineering Journal,Volume 417,2021,128278,

[14] Yafei Sun, Vijay Kumar Thakur, Rong Luo,High mechanical strength, strong adhesion, self-healing and conductive ionic hydrogels for motion detection,Polymer, Volume 299,2024,126946,

[15] Fu B, Cheng B, Bao X, et al. Self-healing and conductivity of chitosan-based hydrogels formed by the migration of ferric ions[J]. Journal of Applied Polymer Science, 2019, 136(34): 47885.

[16] He Meiling, Huang Min, Zhang Mengjiao, et al. Preparation and self-healing mechanism of hydrophobic association polyacrylamide hydrogels [J]. Polymer Materials Science and Engineering, 2019,36(05):127-135.

[17] Talebian, S., Mehrali, M., Taebnia, N., Pennisi, C. P., Kadumudi, F. B., Foroughi, J., et al.(2019). Self-healing hydrogels: The next paradigm shift in tissue engineering? Advancement of Science, 6(16), 1801664.

[18] Huang W, Wang Y, Chen Y, et al. Strong and rapidly self-healing hydrogels: Potential hemostatic materials[J]. Advanced healthcare materials, 2016, 5(21): 2813-2822.

[19] Haolei Shi, Dongxu Ma, Di Wu, Xiao Qiu, Shuai Yang, Yingying Wang, Lei Xiao, Xinyao Ji, Wei Zhang, Shuaiyuan Han, Pengfei Huo, Jidong Dong, Xianzhi Kong, Xue Guan, Dawei Zhang,A pH-responsive, injectable and self-healing chitosan-coumarin hydrogel based on Schiff base and hydrogen bonds,International Journal of Biological Macromolecules,Volume 255,2024,128122

[20] Sun C, Jia H, Lei K, et al. Self-healing hydrogels with stimuli responsiveness based on acylhydrazone bonds[J]. Polymer, 2019, 160: 246-253.

[21] Bi H, Zhang X, Wang Q, et al. Dynamic reversible disulfide bonds hydrogel of thiolated galactoglucomannan/cellulose nanofibril with self-healing property for protein release[J]. Industrial Crops and Products, 2023, 206: 117615.

[22] Jia L, Jiang J, Ren A, et al. Ultra-fast cryogenic self-healing ionic hydrogel for flexible wearable bioelectronics[J]. Chemical Engineering Journal, 2024, 495: 153734.

[23] Zhang Yanni, Gao Yan. Research progress of self-healing materials based on borate ester bond in electrolytes [J]. Chinese and Foreign Energy, 2019,29(02):31-38.

DOI: 10.54254/2755-2721/136/2025.21026

[24] Tang L, Ma Y, Yang C, et al. A self-healing hydrogel derived flexible all-solid-state supercapacitors based on dynamic borate bonds[J]. Journal of Industrial and Engineering Chemistry, 2023, 118: 511-518.

[25] Lin F, Wang Z, Shen Y, et al. Natural skin-inspired versatile cellulose biomimetic hydrogels[J]. Journal of Materials Chemistry A, 2019, 7(46): 26442-26455.

[26] Li D, Wang S, Meng Y, et al. Fabrication of self-healing pectin/chitosan hybrid hydrogel via Diels-Alder reactions for drug delivery with high swelling property, pH-responsiveness, and cytocompatibility[J]. Carbohydrate Polymers, 2021, 268: 118244.

[27] Shao C, Wang M, Chang H, et al. A self-healing cellulose nanocrystal-poly (ethylene glycol) nanocomposite hydrogel via Diels–Alder click reaction[J]. ACS Sustainable Chemistry & Engineering, 2017, 5(7): 6167-6174.

[28] Wang C, Zhang J, Fu Q, et al. Construction of strain responsive Ti-containing carboxymethyl cellulose hydrogel with transitional coordination precursor[J]. International Journal of Biological Macromolecules, 2024, 261: 129865.

[29] Bai Y R, Zhang Q T, Sun J S, et al. Double network self-healing hydrogel based on hydrophobic association and ionic bond for formation plugging[J]. Petroleum Science, 2022, 19(5): 2150-2164.

[30] H. Kiyani, F. Ghorbani, Sodium ascorbate as green and efficient catalyst for Knoevenagel condensation of aryl aldehydes with meldrum's acid in aqueous media, Jordan J. Chem. 8 (2013) 191–198,

[31] Wang L, Ding X, Fan L, et al. Self-Healing Dynamic Hydrogel Microparticles with Structural Color for Wound Management[J]. Nano-Micro Letters, 2024, 16(1): 232.

[32] Ding X, Li G, Zhang P, et al. Constructing thermally reversible dynamic hydrogels via catalysis-free knoevenagel condensation[J]. ACS Macro Letters, 2020, 9(6): 830-835.

[33] Nie Fengmin. Design, synthesis and properties of self-healing materials based on ion interaction [D]. Tianjin University,2022.

[34] Wei Z, Yang J H, Du X J, et al. Dextran-based self-healing hydrogels formed by reversible Diels–Alder reaction under physiological conditions[J]. Macromolecular rapid communications, 2013, 34(18): 1464-1470.