



Review Paper

Recent advances in polymer gels in oil and gas drilling and production engineering: A review



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ABSTRACT

Polymer gels are recognized as essential functional materials in oil and gas drilling and production engineering due to the design flexibility of their three-dimensional networks, the controllability of their mechanical properties, and their high adaptability to extreme environments. They are extensively utilized for profile control, water shutoff, wellbore stabilization, treatment of severe lost circulation, and enhanced oil recovery. This paper systematically reviews the latest research progress on crosslinked and non-crosslinked polymer gels in the field of oil and gas drilling and production engineering, with a particular focus on their synthesis principles, interfacial interactions, and engineering applications. Regarding crosslinked polymer gels, this paper summarizes structural design strategies for pre-crosslinked, in-situ crosslinked, and composite systems, elucidating the pivotal role of multi-scale crosslinked networks in enhancing thermal stability, salt tolerance, and shear resistance. For non-crosslinked polymer gels, this paper discusses diverse reversible interaction mechanisms, including hydrophobic association, hydrogen bonding, electrostatic interactions, and supramolecular assembly. Furthermore, it highlights their distinct advantages in environmental responsiveness, self-healing behavior, and rheological modulation. Furthermore, this paper analyzes the microscopic interfacial processes of polymer gels within porous media and fractures from three perspectives, interfacial adhesion, interfacial rheology, and mechanical response. This analysis clarifies the crucial role of interfacial interactions in governing dynamic transport, anchoring, gelation, and long-term stability. In critical application areas such as lost circulation control and enhanced oil recovery, gel systems have evolved from conventional single-function plugging materials to advanced high-performance systems characterized by stimuli-responsiveness, intrinsic self-healing capabilities, and multifunctional synergistic effects. This paper outlines the developmental directions of polymer gels in drilling fluids and enhanced oil recovery. The synergistic optimization of rational molecular design, composite network construction, and interfacial modulation strategies holds the promise for overcoming the performance limitations of gel materials in harsh environments, such as high temperature and high salinity, thereby facilitating their large-scale deployment in deep and ultra-deep oil and gas development.

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1. Introduction

Benefiting from their highly tunable three-dimensional cross-linked networks and pumpable, controllably curable characteristics, polymer gels have been recognized as efficient functional materials in oil and gas drilling and production engineering. Existing studies have demonstrated that their network frameworks can achieve adaptive filling and bridging within multiscale

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pore-fracture spaces, thereby simultaneously providing support and sealing functions and markedly overcoming the mechanical mismatch limitations of conventional rigid materials in highly heterogeneous, stress-sensitive formations (Han et al., 2022; Lei et al., 2022). As exploration and development targets continue to advance toward deep and ultra-deep reservoirs, reservoir temperature, pressure, and salinity increase exponentially, and the resulting extreme operating conditions impose much more stringent threshold requirements on the thermal stability, ionic tolerance, and viscoelastic response of gel materials (Al Brahim et al., 2022; Kang et al., 2021).

Crosslinked polymer gels can be broadly classified according to their synthetic route into two paradigms, namely pre-crosslinked and in-situ crosslinked systems. These two classes exhibit markedly different engineering responses and optimal application windows in oil and gas drilling and production engineering, which allows targeted matching to diverse operational environments. In pre-crosslinked systems, the entire reaction sequence is completed at the surface. Ma et al. (2024) proposed a pre-crosslinked particle plugging system that utilizes the swelling characteristics of pre-crosslinked particles and prioritizes plugging tests in high-permeability zones of the Daqing Oilfield, thus effectively enhancing the recovery of low-permeability oil layers. Based on the principle of size-controlled swelling, Tongwa and Bai (2015) developed a pre-crosslinked particle gel system suitable for deep-well injection, which has been successfully applied in fields with different porosities and permeabilities. In-situ crosslinked polymer gels are designed such that the crosslinking reaction is initiated during the injection process and gelation is completed downhole or within the reservoir. Non-crosslinked polymer gels in petroleum engineering have attracted increasing attention. Their formation mechanism does not rely solely on the traditional concept of constructing a three-dimensional network via covalent crosslinking, but instead emphasizes the use of physical interactions among polymer chains or their assemblies to build an injectable, swellable three-dimensional network structure (Revathi et al., 2025). Yang et al. (2023a) prepared a kind of block-type hydrophobically associating supramolecular gel through micelle copolymerization. This gel exhibited excellent rheological properties and had strong viscoelastic recovery ability. Appel et al. (2015) developed a self-assembled gel based on a selective adsorption mechanism between polymers and nanoparticles. By tuning the interfacial affinity between water-soluble polymer chains and functional nanoparticles, reversible physical adsorption of chain segments onto nanoparticle surfaces was induced. This interaction establishes a transient crosslinked network to yield a dynamic gel system featuring shear reversibility and self-healing capabilities. Basu et al. (2022) prepared a chemical-crosslinker-free hydrogel by blending sodium alginate with gelatin and regulating self-assembly via plasticizers and salts. This hydrogel exhibits excellent biocompatibility while eliminating the potential toxicity associated with residual chemical crosslinkers.

This study aims to clarify how factors including rock mineral composition, wettability, pore-throat structure, mineralization degree, and temperature influence interface adhesion, interface rheological properties, and mechanical responses, thus providing a theoretical basis for deepening the engineering applicability of interface mechanisms. The performance of polymer gels not only depends on their internal three-dimensional network structure, but is also significantly influenced by the properties of the gel–rock and gel–fluid interfaces. Interfacial adhesion is the basis for gel retention and solidification within pores and fractures (Lei et al., 2022). The adsorption between the gel molecular chains and the mineral surface, as well as the matching of wettability and surface energy, directly determine the adhesion ability and migration

behavior of the gel in the pores (Wang et al., 2023). Interfacial rheology plays a key role in controlling the stability and spatial distribution of gels during injection and displacement. When gels at interfaces are subjected to shear or extensional deformation, their viscoelastic response, interfacial layer deformation and slip behavior can markedly affect plugging efficiency (Malkin et al., 2023; Tang et al., 2022). External interfacial forces such as shear from downhole fluid flow, fracture stress fields, and gravity can alter the structure of the gel interfacial system and thereby affect its migration, adhesion, and solidification behavior (Duda et al., 2021; Luo et al., 2024). Overall, interfacial interactions of gels are central to their migration, adhesion, filling, and solidification processes and provide important guidance for optimizing material design (He et al., 2024).

Polymer gels and their derivative systems have been recognized as key functional materials for core aspects such as the control of severe wellbore fluid loss, the strengthening of wellbore mechanics, the restoration of mud properties, and the temporary sealing of downhole sections. After injection, the crosslinked gels undergo a sol-gel phase transition within seconds to minutes, generating a strongly coupled viscoelastic support layer in situ. This layer can precisely fill the millimeter- and micrometer-scale fracture networks, reducing the entry of drilling fluid into the lost channels, thereby lowering the lost circulation rate and enhancing the stress and structural integrity of the wellbore (Fang et al., 2022; Jiang et al., 2019). Concurrently, non-crosslinked or lightly crosslinked high-molecular-weight polymers play an increasingly pivotal role in drilling fluids, primarily functioning to improve rheological properties and control fluid loss (Hamad et al., 2020). Nanomodified copolymer gels have also been applied in the control of fluid loss in water-based drilling fluids under high-temperature and high-salt conditions. The formulation still exhibits excellent rheological and fluid loss properties in a 200 °C high-temperature and saturated salt environment (Li et al., 2022a).

The enhanced oil recovery principle of polymer gels mainly relies on their three-dimensional network for the selective blocking of high-permeability channels and the ability to redirect liquid flow. It reshapes the pressure field and saturation field of the reservoir, inhibits water-phase advancement, extends the front of flooding in the low-permeability zones, and thereby optimizes the spatial distribution of the oil–water interface, significantly improving the macroscopic sweep efficiency and microscopic oil-washing efficiency. Crosslinked polymer gels can construct a continuous three-dimensional network framework within the multi-scale space of reservoir pores and fractures. Through physical blocking, adsorption retention, and chemical coordination synergy mechanisms, they regulate the effective opening degree of the flow channels, inhibit the dominant advancement of the water phase, reduce the water–oil flow ratio, achieve synchronous expansion of the macroscopic sweep volume and improvement of the microscopic displacement efficiency, and ultimately significantly increase the oil recovery rate (Liu et al., 2023). Low-permeability oil reservoirs have small pore-throat sizes and high initial pressure gradients. Water flooding is highly likely to advance along local high-permeability zones. By introducing non-crosslinked polymer gels and coupling them with traditional water flooding, the high-viscoelastic properties can generate dynamic retention and reversible plugging at the pore scale. This instantly increases the flow resistance and reconfigures the pressure field, forcing the subsequent displacement fluid to shift to the low-permeability oil-bearing zones. Thus, it optimizes the spatial distribution of the oil–water interface, significantly expands the swept volume and improves the recovery rate (Lu et al., 2022).

Polymer gels have become indispensable functional materials throughout the entire life cycle of oil and gas drilling and

production engineering, with an application landscape that spans drilling, completion, stimulation, and enhanced oil recovery (Fig. 1). This paper systematically reviews recent advances in crosslinked and non-crosslinked polymer gels for oil and gas drilling and production engineering. It covers synthesis principles, interfacial interactions, and engineering applications, highlighting the key benefits of multiscale network designs in surface pre-crosslinking, in-situ downhole crosslinking, and hybrid crosslinking to enhance resistance to temperature, salinity, and shear. It also shows that reversible interactions such as hydrophobic association, hydrogen bonding, and supramolecular assembly endow physical gels with environmental responsiveness, self-healing behavior, and controllable flow regulation. Furthermore, this study analyzes gel migration, adhesion, and long-term stabilization in pore–fracture systems from the perspectives of interfacial adhesion, interfacial rheology, and mechanical response, highlighting the decisive role of interfacial processes.

2. Synthesis principles of polymer gels

This paper systematically reviews the synthesis principles of polymer gels, laying a material foundation for subsequent research on interfacial regulation mechanisms. Based on network formation mechanisms, gels can be classified into two categories: crosslinked and non-crosslinked types. The former constructs dense three-dimensional networks through radical polymerization and chemical crosslinking agents, which can be further divided into surface crosslinking and subsurface crosslinking according to the crosslinking location. The latter relies on physical interactions to form dynamic and reversible networks, encompassing functional systems such as environmentally responsive,

supramolecular, and self-healing gels. The differences in gel classification and synthesis mechanisms directly determine their interfacial characteristics and deep reservoir adaptability.

2.1. Crosslinked polymer gels

2.1.1. Surface crosslinked gels

2.1.1.1. Pre-crosslinked polymer gels. Pre-crosslinked polymer gels are prepared on the surface by polymerization and crosslinking of acrylamide in the presence of an initiator and a crosslinker. The resulting bulk gel is granulated, dried, crushed, and sieved to obtain particles with different sizes. After dispersion in the aqueous phase, the particles can swell up to 200 times their dry volume, thereby achieving high-strength plugging of fractures (Bai et al., 2015). Pre-crosslinked gel particles are highly sensitive to formation conditions and exhibit poor resistance to salinity and acidity (Bai and Sun, 2020). Zhou et al. (2021) used *N,N*-methylenebisacrylamide and dimethyldiallylammonium chloride as crosslinkers to carry out a free-radical polymerization with acrylamide. The resulting acid-resistant preformed particle gel (PPG) maintains its swelling capacity, viscoelasticity, and shear resistance in an acidic environment with pH of 3. To address the limitations of conventional PPGs, including high cost, low strength, and insufficient shear resistance, Kang et al. (2022) proposed a free-radical polymerization modification strategy that employs sawdust particles as a bio-based reinforcing phase. This study employed acrylic acid and acrylamide as comonomers, with *N,N*-methylenebisacrylamide as a chemical crosslinker and ammonium persulfate as an initiator. By adjusting the mass ratio between sawdust and gelant, the researchers prepared preformed sawdust-based polymer gel particles with an interpenetrating

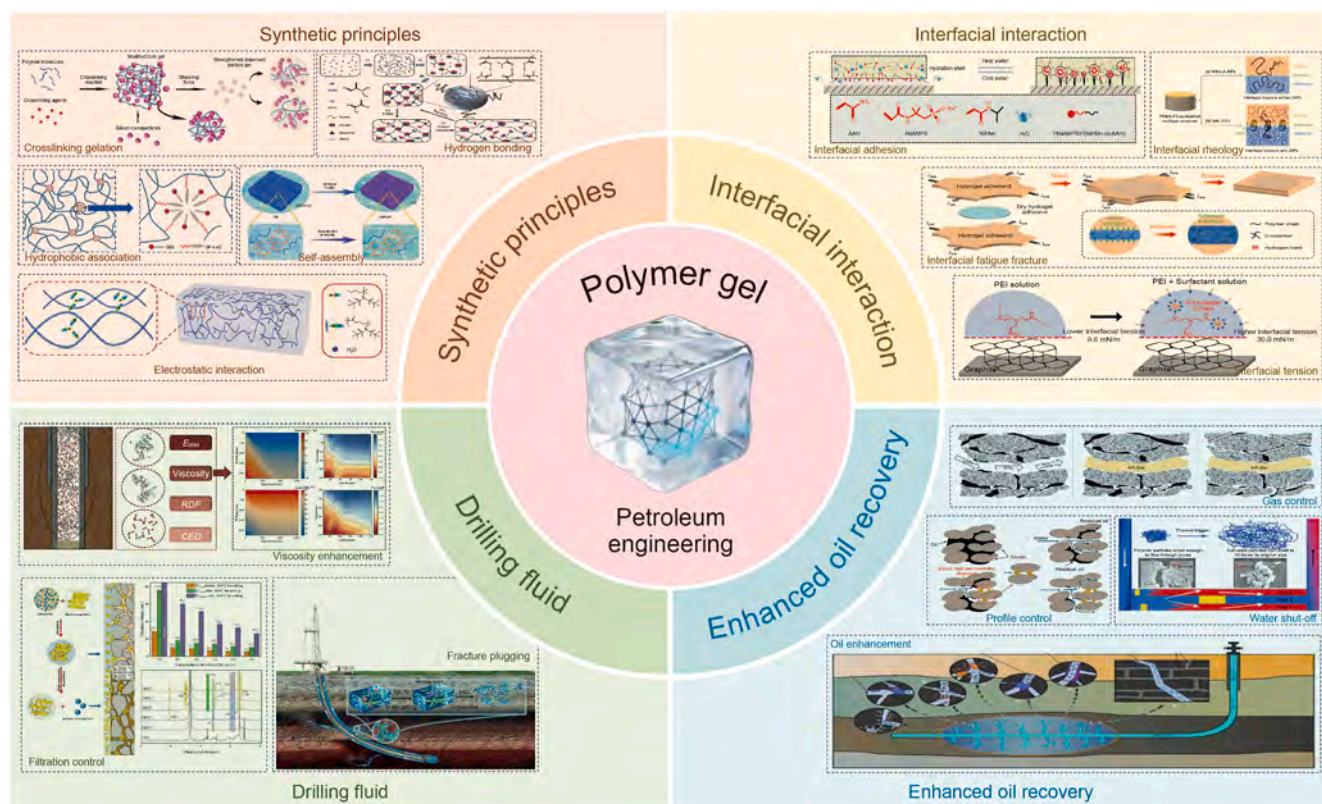


Fig. 1. The application of polymer gels in oil and gas drilling and production.

organic–inorganic network. The rigid lignocellulosic framework combined with the flexible polymer chains provided synergistic toughening, which enhanced compressive strength, shear resistance, and cost-effectiveness compared with conventional PPG systems.

Millimeter-scale PPGs are constrained by pore-throat size and are difficult to inject into porous media with permeabilities below several darcies. In contrast, dispersed particle gels (DPGs) have tunable particle size and strength, and are simple to prepare, inexpensive, and environmentally friendly. They have therefore become a major research focus in in-depth profile control and plugging in recent years (Dai et al., 2017). Compared with the conventional PPG route of “bulk gel synthesis followed by mechanical grinding and screening”, Liu et al. (2016a) proposed a one-step high-shear in-situ granulation strategy. In this approach, the polymer and crosslinker are blended and then exposed to a high shear-rate field so that crosslinking and fragmentation occur simultaneously, while the shear rate controls the particle size in real time, enabling the controlled preparation of DPG (Fig. 2). To optimize the performance of DPG under high-salinity conditions, Dai et al. (2016) prepared a strengthened DPG (SDPG) utilizing nano-silica as a reinforcing agent. This formulation effectively improved the high-temperature and high-salinity stability of the gel particles, endowing them with mechanical properties and viscoelasticity superior to those of conventional DPGs. To overcome the bottlenecks of the conventional “bulk synthesis–mechanical granulation” route for PPGs, which suffers from low efficiency, limited industrial scalability, and poor injectivity into low-permeability reservoirs. Zhao et al.

(2018) proposed a phenolic resin-dispersed particle gel (PR-DPG) system. Brine is used as the dispersion medium, an FL polymer serves as the backbone, and a phenolic resin acts as the crosslinking agent. A bulk gel is formed in a single step and then directly subjected to homogenizing shear, producing PR-DPG with controllable particle size and high resistance to temperature and shear. This process generated an in situ, scalable, high-performance solution for deep profile control and plugging in low-permeability oilfields.

2.1.1.2. Secondary crosslinked gels. Conventional PPGs have inadequate cohesion between particles and lack effective adhesion to rock surfaces. In large fractures or high-permeability flow channels, they are readily eroded and carried away by high-velocity fluids, which leads to a significant reduction in plugging efficiency. Secondary crosslinked gels undergo an initial crosslinking step under surface conditions so that a weakly crosslinked network with moderate swelling is established already during the injection stage. The gel particles enter the target fractures and trigger a secondary crosslinking reaction under the reservoir temperature/ion concentration conditions. In situ, a dense three-dimensional polymer network is formed, achieving multiple bonds between the particles, the particles and the wall surfaces, and ultimately constructing a stable and complete sealing layer (Du et al., 2019). With the growing proportion of high-temperature and high-salinity reservoirs under development, the thermal and salinity stability of conventional pre-crosslinked polymer gels (RPPG) can no longer meet the requirements of deep plugging. Zhai et al. (2024) used a polyacrylamide polymer as the matrix

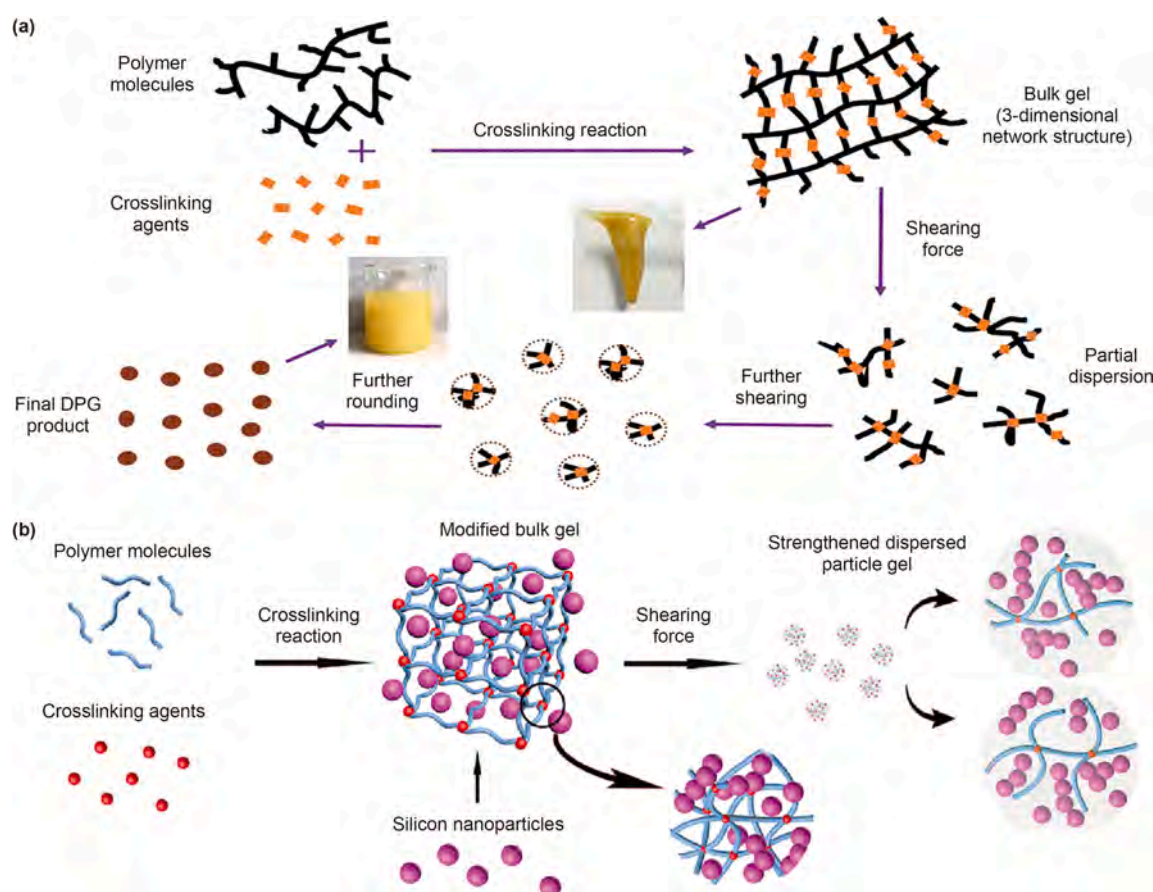


Fig. 2. Schematic diagram illustrating the synthesis principle of DPG. Adapted with permission from Liu et al. (2016a) and Dai et al. (2016).

and introduced sodium D-gluconate and polyvinyl alcohol as synergistic functional units. A multicomponent crosslinking network was constructed with *N,N'*-methylenebisacrylamide, poly(ethylene glycol) 400 diacrylate (PEG400DA), GA, and PVA, and a novel gel material with markedly enhanced temperature and salinity resistance was successfully obtained (Fig. 3). Song et al. (2023) developed a novel pre-crosslinked polymer gel suitable for high-salinity environments by employing acrylamide and 2-acrylamido-2-methylpropane sulfonic acid as comonomers, incorporating xanthan gum as a toughening component, and constructing a dual-network structure using *N,N'*-methylenebisacrylamide together with a pre-embedded Cr(III)-based crosslinker. The synergistic effect of the double network markedly enhances the toughness of both the primary and the re-crosslinked gels and effectively suppresses brittle failure and erosion-induced loss under high-salinity conditions. During gel injection, the strong permeability contrast between fractures and matrix drives extensive spreading of the gel solution along the fracture–matrix interface. This process leads to uncontrolled fluid loss, dilution of gel blocks, and solid-phase damage to the reservoir.

2.1.2. In-situ crosslinked gels

2.1.2.1. Covalently crosslinked polymer gels. Covalently crosslinked gels construct a three-dimensional network via the covalent

reaction between amide groups on polymer chains and organic crosslinkers (Zhao et al., 2015). Compared with metal-crosslinked systems relying on ionic coordination and hybrid gels containing metal-ligand covalent bonds, pure organic covalent crosslinked networks possess high bond energy and superior thermodynamic stability. They are resistant to rupture under high-temperature conditions, rendering them more suitable for in-depth profile control and plugging in high-temperature and high-salinity reservoirs (Zhu et al., 2017a). Common organic crosslinkers include phenolic compounds, polyethyleneimine, resorcinol, hexamethylenetetramine, and water-soluble phenolic resins. Among these, the crosslinking of phenolic gels primarily occurs through condensation reactions between phenolic or amide groups on the polymer chains and the crosslinker, resulting in the formation of a continuous bulk network (Zhang et al., 2020b). Polyethyleneimine, owing to its low cost and high amine-group density, can undergo nucleophilic substitution and transamidation reactions with amide groups on partially hydrolyzed polyacrylamide (HPAM) chains, thereby generating stable C–N covalent crosslinking sites and forming a three-dimensional gel network. Jayakumar and Lane (2013) developed a delayed crosslinking system using HPAM as the base fluid and PEI as the crosslinker, with 2-acrylamido-2-methylpropanesulfonic acid (AMPS) introduced as a reversible complexing retarder. This low-concentration, low-initial-viscosity system exhibits adjustable gelation time under high-temperature

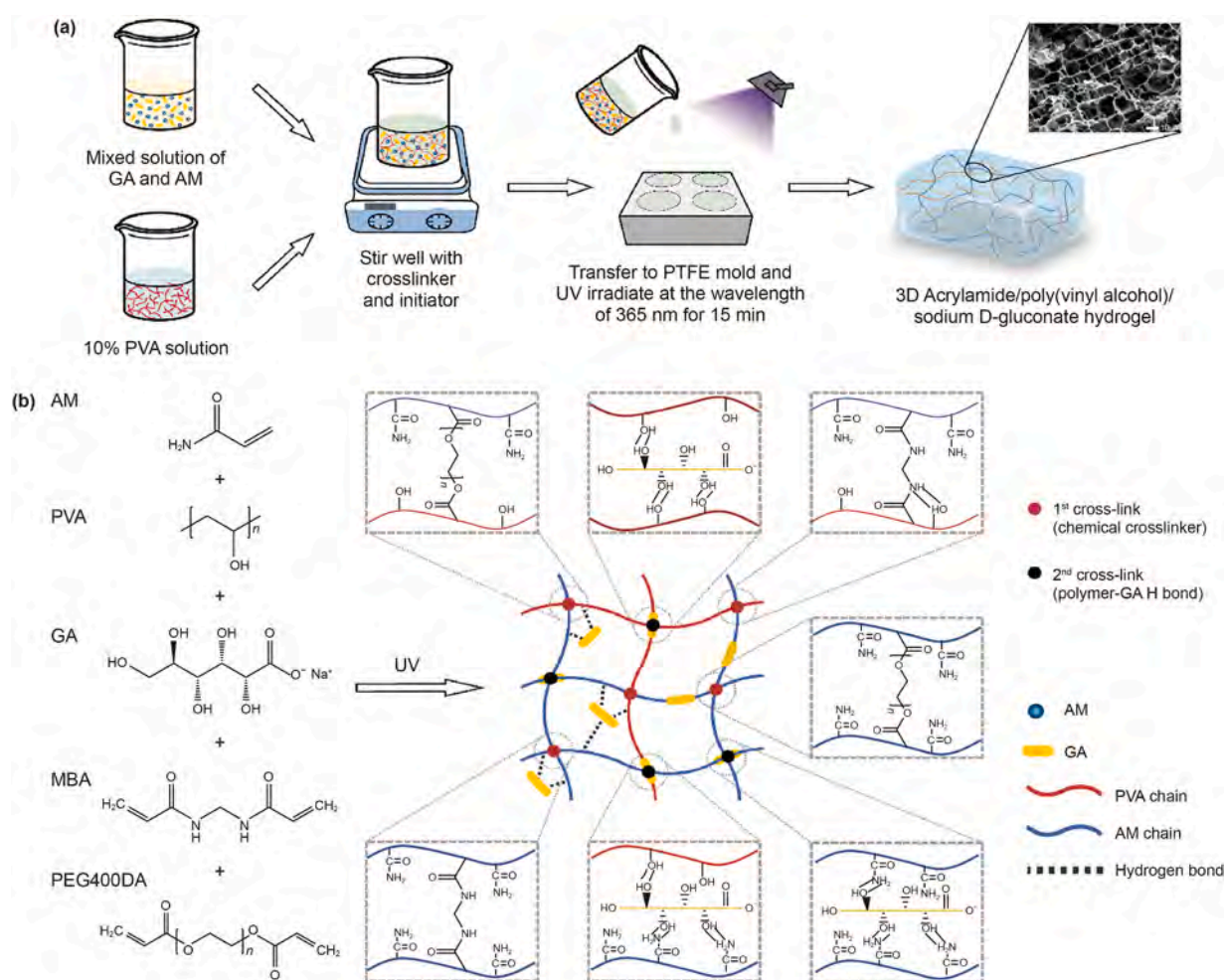


Fig. 3. Schematic illustration of the preparation mechanism of RPPG hydrogel. (a) Preparation process of RPPG hydrogel. (b) Crosslinking mechanism of hydrogel network. Adapted with permission from Zhai et al. (2024).

and high-salinity conditions, thus meeting the requirements for deep formation plugging. As the water cut of produced fluids continues to increase, there is an urgent need for temperature- and salinity-resistant gels to achieve deep water control. [Chen et al. \(2015\)](#) used an AM/AMPS copolymer as the backbone and a hexamethylenetetramine resorcinol phenol ternary system as a covalent crosslinker. They further introduced monoethanolamine as a dehydration inhibitor to obtain a polymer gel that remains stable under high temperature and high salinity, thereby providing an effective route for water production control in such reservoirs. Conventional polymers undergo rapid thermal degradation of the main chain above 90 °C and therefore fail to meet the plugging requirements of ultra-high temperature reservoirs. [Zhu et al. \(2017b\)](#) dissolved resorcinol, hexamethylenetetramine (HMTA), antioxidants, and thermal stabilizers in the polymer solution to construct an in-situ ternary co-crosslinking system. Resorcinol and the hydroxymethyl phenols released in situ from HMTA synergistically generate high-bond-energy C–N and C–C crosslinks. This mechanism significantly inhibits thermal degradation, allowing the resulting gel to retain a high elastic modulus even in high-temperature saturated brine, thus offering a feasible solution for

in-depth profile control in ultra-high-temperature reservoirs. [Lashari \(2020\)](#) developed a low-concentration amphiphilic polymer composite gel ([Fig. 4](#)) based on the HMTA/resorcinol in-situ crosslinking system, incorporating petroleum sulfonate as a surfactant and uniformly dispersed silica nanoparticles. This gel relies on the synergistic entanglement among nanoparticles, polymers, and surfactants, as well as on a dual crosslinked network formed by hydrogen bonds and covalent bonds. It maintains high elastic modulus and gel strength under high-temperature, high-salinity, and strongly acidic conditions, which improves sealing reliability and long-term thermal stability during CO₂ flooding under harsh conditions ([Liu et al., 2016b](#)).

2.1.2.2. Ionically crosslinked polymer gels. Ionically crosslinked gels construct their three-dimensional networks through the combined ionic and coordination interactions between ionized carboxyl groups on the polymer chains and multivalent metal cations. The metal ions first undergo hydrolysis to form polynuclear hydroxo complexes, which then coordinate with the carboxyl and amide groups of HPAM, generating stable multi-dentate crosslinking nodes ([Yang et al., 2013a](#)). Metal-crosslinked

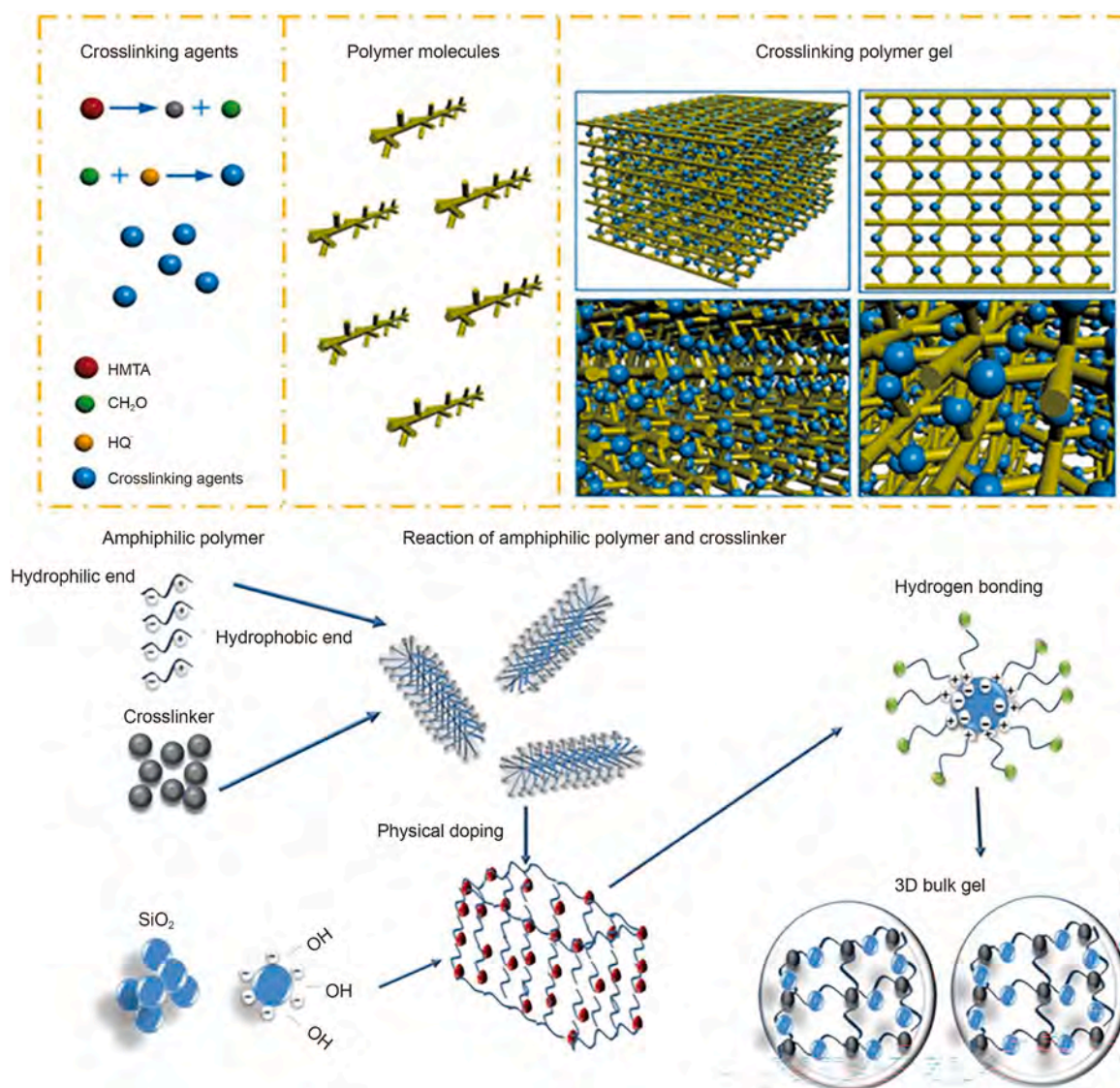


Fig. 4. Schematic diagram of the crosslinking mechanism of the covalently crosslinked polymer gel. Adapted with permission from [Liu et al. \(2016b\)](#) and [Lashari \(2020\)](#).

gel systems commonly employ crosslinkers such as Cr^{3+} , Al^{3+} , Fe^{3+} , and Zr^{4+} , all of which can efficiently complex with carboxyl groups (Zhang et al., 2019b). Among these, Cr^{3+} finds the most extensive application owing to its high complexation constant, rapid gelation kinetics, dense network structure, and cost-effectiveness. The Cr^{3+} -carboxyl three-dimensional network, constructed in-situ with polymers, effectively plugs high-permeability zones. Sharma and Kudapa (2022) used HPAM as the base fluid and a $\text{CH}_4\text{N}_2\text{S}$ /potassium dichromate in-situ reduction system as the organic chromium source to construct an HPAM- Cr^{3+} gel framework. This organic chromium crosslinking system exhibits superior complexation stability and lower ecological toxicity than conventional inorganic Cr^{3+} crosslinking systems, providing an environmentally friendly deep profile control material for high-temperature, high-salinity reservoirs. Targeting the low-temperature and high-salinity characteristics of fractured low-permeability reservoirs, Yang et al. (2013b) used $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$ as the chromium source, NaOH to control the degree of hydrolysis, and acetic acid/carrotic acid as coordination retarders to synthesize an organic chromium complex crosslinker in situ, which was then combined with HPAM to form a gel system. At a temperature of 27°C and a shear rate of 170 s^{-1} , this system maintains viscosity retention of above 85% and has a controllable gelation time of 4–6 h. It can significantly improve the sweep volume in low-permeability fractured formations. To address the challenges posed by high-temperature and high-salinity unconventional reservoirs to the thermal stability limits of polymers, Yang et al. (2019) introduced surface-quaternized SiO_2 nanoparticles in situ into an amphoteric polymer/organic chromium

crosslinking system. Hydroxyl groups on the nanoparticle surface form Si-O-Cr coordination bridges with Cr^{3+} ions, while electrostatic and hydrogen-bond interactions promote entanglement with polymer chains, thereby constructing an “organic–inorganic” hybrid double network (Fig. 5). The storage modulus of the gel increases from 45 to 120 Pa, and its strength retention remains above 90% after 30 d of high-temperature aging, which significantly enhances the long-term plugging reliability under extreme operating conditions. To achieve deep injection of low-viscosity polymer solutions and in-situ formation of high-strength gels in fractured reservoirs, delayed crosslinking technology has become a key approach. Sun et al. (2015a) developed a low-temperature delayed-crosslinking system using HPAM as the base fluid, thiourea as a thermal stabilizer, Na_2CO_3 for precise control of the degree of hydrolysis, and chromium acetate (Cr(III)-acetate) as the delayed crosslinker. This system is characterized by low initial viscosity, high stability, and extended gelation time in low-temperature reservoirs (Zhang et al., 2020a).

Over several decades of development, metal-crosslinked gel systems have evolved into a multicomponent crosslinking framework centered on Cr^{3+} , Al^{3+} , and Zr^{4+} . Notably, Al^{3+} and Zr^{4+} are extensively utilized for near-wellbore profile control, owing to their low toxicity and favorable environmental compatibility. Dai et al. (2013) employed zirconium acetate as the crosslinking center and exploited its slow hydrolysis to prolong the gelation induction period, thereby developing a low-toxicity polymer gel with an adjustable gelation time of 2–8 h. This system effectively mitigates near-wellbore channeling while substantially reducing the environmental risks associated with chromium-based gels,

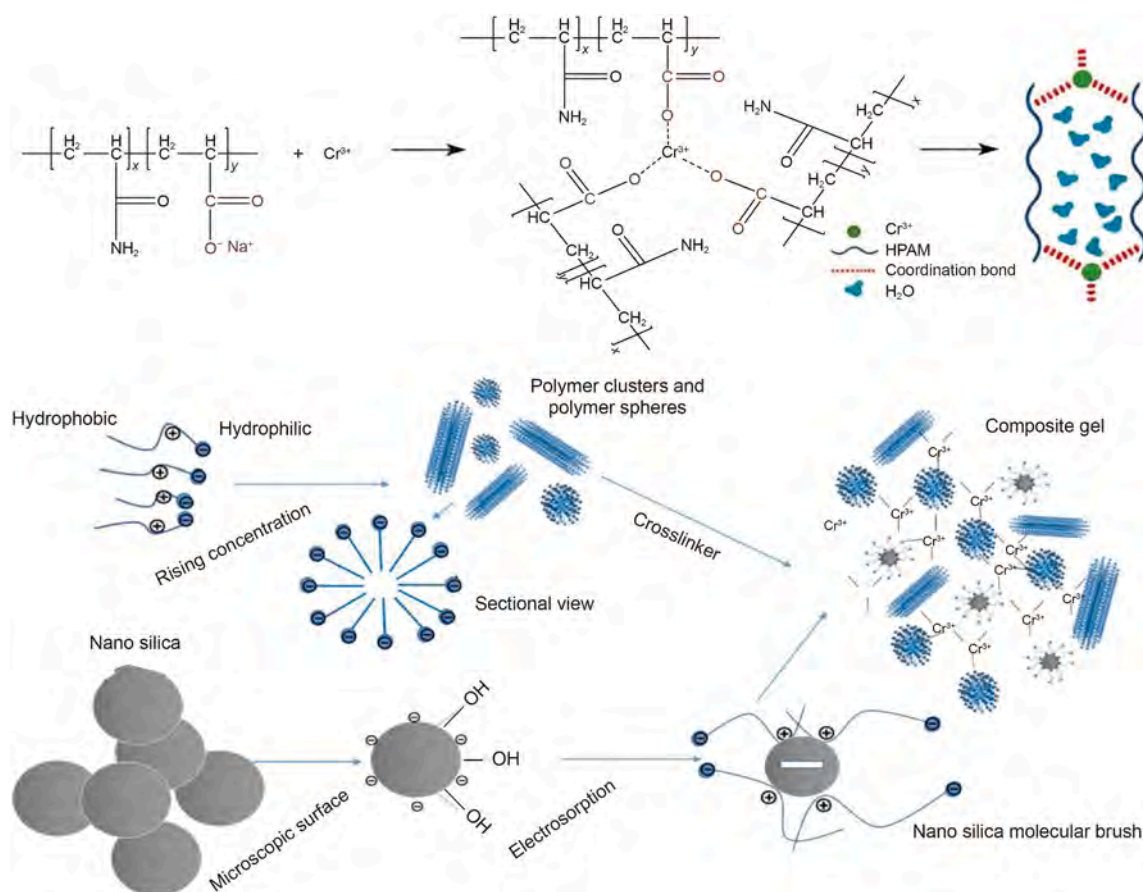


Fig. 5. Schematic diagram of the crosslinking mechanism of the organic chromium gel. Adapted with permission from Yang et al. (2019) and Zhang et al. (2020a).

and thus shows promise as an alternative to conventional chromium crosslinking systems. Compared with Cr^{3+} -based systems, Al^{3+} -crosslinked gels, owing to the moderate bond energy of Al–O coordination and a controllable hydrolysis rate, are better suited to medium-high-temperature (60–90 °C) reservoirs. Zhang et al. (2019a) used aluminum citrate (AlCit) as a retarded crosslinker and HPAM as the base fluid. By adjusting the Al^{3+} /Cit molar ratio (1:1–1:3), they precisely controlled the release kinetics of Al^{3+} , enabling the gelation time to be tuned between 4 and 20 h. At a temperature of 75 °C and a salinity of $1.5 \times 10^5 \text{ mg}\cdot\text{L}^{-1}$, the system achieves a storage modulus of 80 Pa, with a 30-d aging retention exceeding 90%. This provides a controllable and low-toxicity option for deep profile control in medium-temperature reservoirs.

2.1.2.3. Composite crosslinked polymer gels. In-situ crosslinked gels widely employ an “organic-metal” hybrid strategy (Pinho de Aguiar et al., 2020). Covalent organic crosslinking constructs a permanent three-dimensional framework that fixes the basic morphology and ultimate strength of the gel, while multivalent metal ions form reversible “dynamic hinges” through coordination interactions. Under load, bond breaking and reformation dissipate energy, relax stress at crack tips, and enhance fracture toughness, thereby achieving a synergistic combination of high strength and high toughness (Nakajima, 2017; Xin, 2022). Zhang et al. (2020a) established an ion-covalent sequential crosslinking mechanism. First, Cr^{3+} instantaneously coordinates with $-\text{COO}^-$ groups on HPAM chains, forming a pumpable weak network within several minutes and suppressing dilution of subsequent components by formation water. Subsequently, phenolic resin prepolymers slowly condense with $-\text{CONH}_2$ and other functional groups at elevated temperature, generating irreversible C–C and C–N covalent bonds that completely fix the primary network. This “ion-first-then-covalent” dual-stage crosslinking scheme endows the gel with long-term thermal and salinity stability under high-temperature, high-salinity conditions. However, the complexation rate between $\text{Cr}(\text{III})$ ions and HPAM is strongly affected by the coupled influence of temperature and salinity, so that under low-temperature, high-salinity conditions the gelation time becomes too short to achieve deep placement. In addition, purely metal coordination bonds are prone to rupture due to Cr^{3+} hydrolysis, precipitation or competitive complexation with $\text{Na}^+/\text{Ca}^{2+}$, leading to poor strength retention. Jin et al. (2014) introduced formaldehyde as a secondary crosslinker and, by exploiting its low-temperature hydroxymethylation reaction with amide groups, constructed a “metal-acetal” cooperative network together with chromium(III) acetate. Cr^{3+} first rapidly coordinates with carboxyl groups to form a pumpable weak gel, while formaldehyde subsequently generates $-\text{CH}_2-$ covalent bridges at a slower rate and converts the ionic crosslinking nodes into covalent ones, thereby extending the gelation time of the HPAM- $\text{Cr}(\text{III})$ -formaldehyde weak gel to 6–12 h and markedly improving the storage-modulus retention in low-temperature and high-salinity reservoirs. Addressing the bottlenecks of insufficient gel strength and poor long-term stability in high-temperature, low-permeability reservoirs, Yang et al. (2025) used a low-hydrolysis, medium-to high-molecular-weight polymer CX-305 as the base fluid and developed an ion-covalent sequential crosslinking system with aluminum citrate and phenolic resin, thus preparing an organic/metal composite crosslinked polymer gel (AR-Gel) (Fig. 6). Al^{3+} preferentially coordinates with carboxyl groups on the polymer chains, instantaneously forming the primary network, which provides the initial viscosity and suppresses subsequent fluid loss. Phenolic resin then undergoes condensation with amide groups at elevated temperature, generating an irreversible C–N/C–C covalent secondary network and markedly enhancing the mechanical strength.

The close interpenetration of the two networks enables AR-Gel to exhibit significantly improved storage-modulus retention during deep profile control and plugging in acidic, high-temperature, low-permeability reservoirs.

2.2. Non-crosslinked polymer gels

2.2.1. Non-crosslinked physical gels

Non-crosslinked physical gels are a class of polymer materials characterized by reversible non-covalent networks. Their three-dimensional skeletons are formed through the self-assembly driven by weak interactions between macromolecular chains (Wang et al., 2017). Unlike chemical gels that rely on crosslinking agents to form permanent covalent bonds, the network stability of physical gels is attributed to the combined contribution of hydrophobic association, hydrogen bonds, and electrostatic attraction (Kadam et al., 2015). A single force typically demonstrates instantaneous and reversible behavior under standard temperature conditions. However, when multiple weak interactions are spatially coupled and temporally synchronized, they induce the directional arrangement of polymer segments, constructing multiple self-assembled networks with high dynamic stability. Consequently, this unique structure endows the gel with recoverable mechanical properties and adaptive swelling behavior. Hydrophobic associative hydrogels are driven by hydrophobic side groups distributed on a hydrophilic main chain. In polar media, the hydrophobic moieties spontaneously aggregate due to hydrophobic repulsion, forming transient hydrophobic microdomains, which subsequently establish intermolecular or intramolecular physical crosslinking points (Bai et al., 2022). This reversible hydrophobic association network endows the gel with high toughness, rapid self-recovery, and shear dilution properties. It has become a typical construction mode of intermolecular physical gels that do not require chemical crosslinking agents. Liu et al. (2018) developed self-solubilizing composite micelles by employing two polymerizable amphiphilic monomers and subsequently fabricated hydrophobic associative physical gels via copolymerization. By comparing the electron microscopy images of the composite micelles, it was found that the synergistic effect between these amphiphilic monomers with large hydrophilic differences significantly improved the gel strength. Furthermore, the mechanical properties of the gel such as elongation at break and tensile strength (Fig. 7) could be adjusted over a wide range by simply varying the blending ratio. Gao et al. (2016) successfully synthesized a novel hydrophobic associative hydrogel using micellar copolymerization with sodium dodecyl sulfate (SDS) as the solvent. The resulting hydrophobic associative hydrogel exhibits tough mechanical strength, high elongation, and a low swelling degree. Its mechanical properties can be flexibly tuned by adjusting the proportion of hydrophobic monomers.

Hydrogen bonds as typical non-covalent interactions are often used to construct physical hydrogels with high ductility and excellent pressure-bearing capacity (Li et al., 2022b). The synergy of different types of hydrogen bonds can significantly enhance the bonding strength, enabling the material to maintain stable mechanical properties over a wide range of temperatures and pH values (Liu and Peng, 2023). Hu et al. (2015) obtained high-strength gels with single hydrogen bond cross-linking by copolymerizing DMAA and MAAC and utilizing amide-carboxylic acid hydrogen bonds (Fig. 8). However, a single energy-consuming mechanism is difficult to balance resilience and strength. Li et al. (2020) further designed a hydrogel containing a “soft-hard” double hydrogen bond domain. Carboxylic acid-amide forms a low bond energy “soft” region for energy dissipation, while carboxylic acid dimer constitutes a high bond energy “hard” region to provide

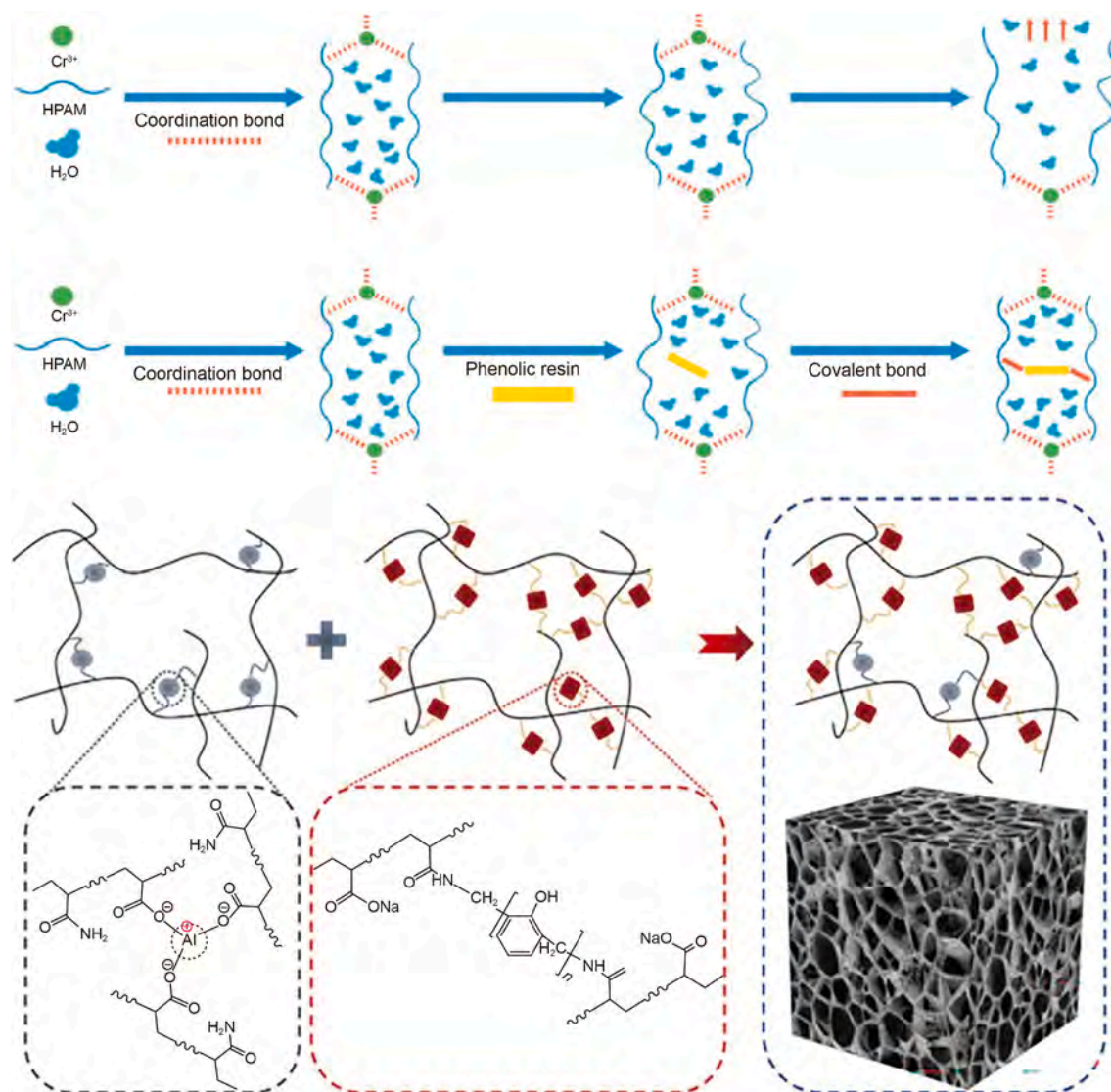


Fig. 6. Gelation mechanism of the composite crosslinked polymer gel system. Adapted with permission from Yang et al. (2025) and Zhang et al. (2020a).

crosslinking rigidity. The two components work synergistically to form a dual physical network, enabling the gel to simultaneously possess high mechanical strength, pH sensitivity, and a rapid shape-memory response. This allows for second-level shaping and recovery under temperature stimulation.

Physical gels driven by electrostatic interactions are synthesized via the charge-balanced copolymerization of oppositely charged monomers under high ionic strength conditions. This process facilitates the formation of multiple intermolecular and intramolecular ionic bonds with a broad distribution of bond strengths, thereby establishing a robust three-dimensional network structure (Sun et al., 2015b). Senbandith et al. (2023) mixed polyamphoteric electrolytes with controllable positive and negative charge segments in a stoichiometric ratio and prepared non-chemically crosslinked PEC gels using a self-assembled polyelectrolyte composite (PEC) strategy. This method avoids the residue of chemical crosslinking agents and biological toxicity, while retaining the adjustability of the proportion of chain segments. The obtained PEC gel is limited in swelling in the aqueous phase and exhibits high tensile strength and toughness as well as excellent morphological stability. Yu and Wu (2021) further

constructed an ionic gel based on the electrostatic interaction between fluorine-rich polyionic liquids and ionic liquids (Fig. 9). The material maintained high light transmittance while possessing excellent tensile mechanical properties.

2.2.2. Environmentally responsive gels

Environmentally responsive gels can be classified into various types such as temperature-sensitive, pH-sensitive, salt-sensitive, and stress-sensitive ones based on the differences in external stimulus signals (Han et al., 2022). This type of material is typically synthesized through free radical polymerization of monomers containing specific responsive functional groups, initiated by suitable initiators. It can sense changes in environmental parameters at the microscopic scale and respond by undergoing network reconstruction or modulating its performance. Although the type of stimulus is the same, different gels also show significant differences in their three-dimensional topological structures due to different synthetic routes and cross-linking mechanisms, which in turn leads to differentiation in macro behavior such as response rate, amplitude, and reversibility. It can be seen from this that the microscopic network configuration of the gel is the essential

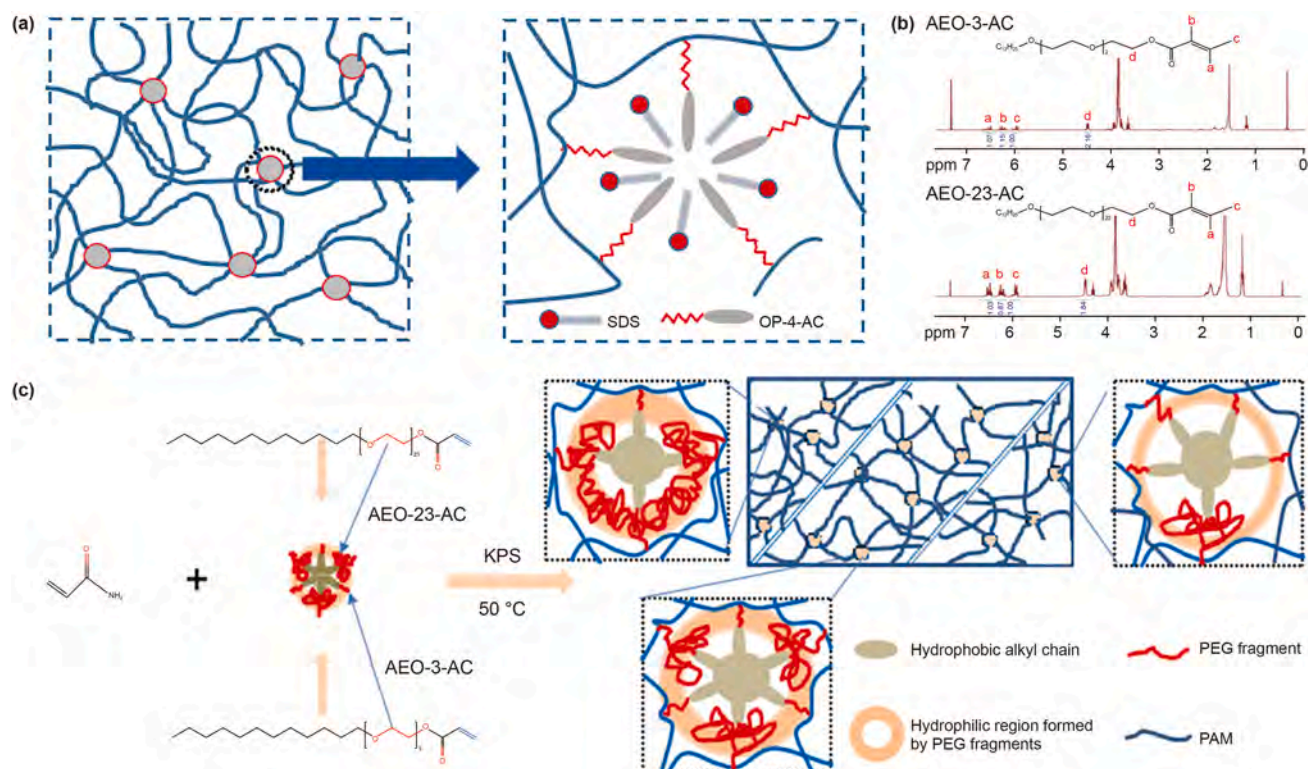


Fig. 7. Synthesis principle of the hydrophobically associating hydrogel. (a) Schematic illustration of the association network structure. (b) ¹H-NMR spectrum of the hydrogel. (c) Synthesis process of the hydrogel. Adapted with permission from Liu et al. (2018).

element that determines its stimulus-response characteristics and sensitivity.

Thermosensitive gels are a class of smart polymer networks that undergo reversible phase transitions upon temperature perturbations. The essential feature is that when the system temperature crosses the critical threshold, the hydrophilic/hydrophobic balance of the molecular chain is instantaneously broken, the hydrogen bond network disintegrates and the hydration shell collapses. Macroscopically, this manifests as an abrupt change in swelling ratio, completing the reversible “sol-gel” transition (Lv et al., 2025). Thermosensitive gel molecules generally contain a certain proportion of hydrophilic and hydrophobic structures. Changes in temperature cause the disruption of hydrogen bonds, leading to an imbalance in the hydrophilic and hydrophobic balance, which is manifested as the swelling and contraction of the gel. This phenomenon is called the volume phase transition process of thermosensitive gels (Kang et al., 2021). Compared with traditional chemically crosslinked gels, thermosensitive gels can achieve in-situ sol-gel transition simply by using a temperature switch and they also possess advanced functionalities such as injectability and controllable molding (Fan et al., 2022). Liu et al. (2022a) constructed and characterized a thermosensitive hydrogel system loaded with IL-1ra. This material could complete the sol-gel phase transition within 5 min at 37 °C. After freeze-drying, it presented a porous structure with a pore size distribution of 5–70 μm. Yuan et al. (2024) employed aqueous free radical polymerization as the technical route, introduced lithium saponite nanosheets as physical cross-linking points and prepared a lithium saponite-reinforced (AM/NVCL) composite thermosensitive gel. Thanks to the inorganic–organic synergistic network, this gel exhibits a high-water absorption rate, enhanced mechanical strength, and sensitive thermosensitivity (Fig. 10).

Salt-sensitive gels are a type of polymer network that can reversibly regulate their water absorption and swelling ratios under salinity gradients. Their skeletons are usually constructed via one-step free radical polymerization of salt-sensitive copolymers (Chang et al., 2011). Generally, the salt response of salt-sensitive gels is primarily influenced by three factors: the three-dimensional gel matrix, the interstitial fluid, and the structure of charged particles (Taylor et al., 2017). Meanwhile, the swelling property of salt-sensitive gels is determined by the free exchange of mobile ions and water molecules between the gel matrix and the surrounding fluid. The electrostatic repulsion between fixed charges provides the driving force for swelling. Xiao et al. (2017) reported a polycation-ampholytic polyelectrolyte double-network salt-sensitive gel. By leveraging the synergy of interlayer charge shielding and anti-polyelectrolyte effects, it can achieve reversible bending-contraction deformation in a high-salt environment, highlighting the regulatory potential of charge interactions on macroscopic mechanical behavior. Shao et al. (2021) further adopted the random free-radical copolymerization strategy to precisely design the ratio and distribution of positive and negative charges along the polyampholytic chain. Under high-salinity conditions, the fixed charges are shielded, the electrostatic repulsion between chains is weakened and the gel volume rapidly collapses. In a low-salinity environment, the repulsive force recovers and the network rapidly reswells, thus exhibiting highly reversible and sensitive salt-responsive characteristics (Fig. 11).

pH-sensitive gel, as an intelligent polymer material, exhibits certain pH-sensitivity characteristics due to the presence of alkaline or acidic functional groups within its crosslinked hydrophilic network. The polymer chains of pH-sensitive gels consist of monomer units containing acidic or basic groups, which can ionize in solution through dissociation or protonation (Adelnia et al.,

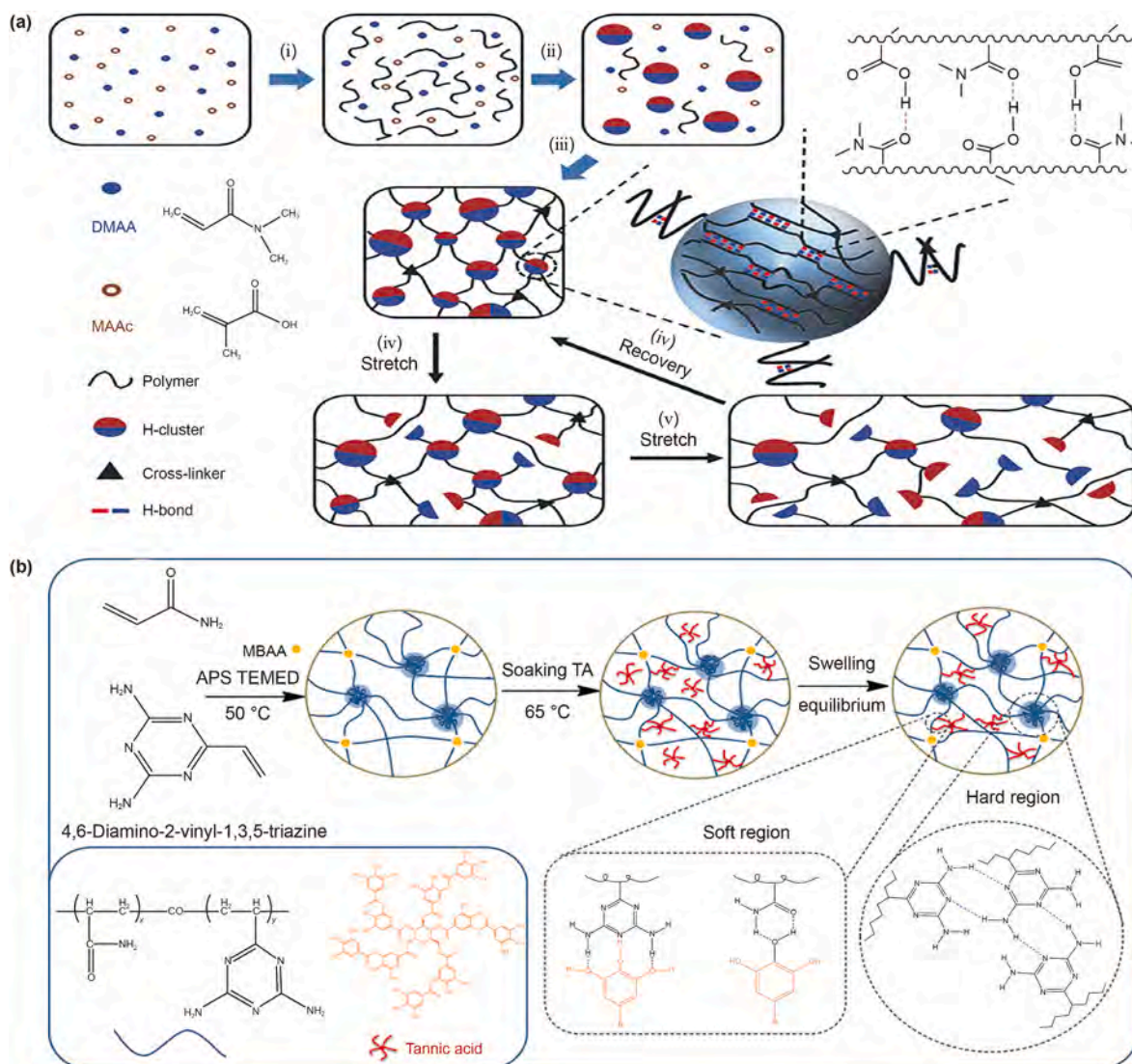


Fig. 8. Synthesis principle of hydrogels based on hydrogen bonding. (a) Preparation mechanism of the DMAA-co-MAAc hydrogel. Adapted with permission from Hu et al. (2015). (b) Schematic illustration of the formation of the P(Am-co-VDT)/TA hydrogel. Adapted with permission from Li et al. (2020).

2019). Typically, these functional groups are weak acids or weak bases and their ionization equilibrium shifts in response to variations in proton activity within the medium. Due to the stronger electrostatic repulsion between charged groups along the polymer chains, charged polymers exhibit a higher degree of swelling compared to neutral polymers (Philippova et al., 2013). For weakly acidic or weakly basic polymers, their swelling behavior will change with the variation of the pH value of the medium (Deng et al., 2012). Based on the synergistic effect of the lower critical solution temperature behavior of thermo-responsive polymers and the ionization behavior of pH-sensitive monomers, Khan et al. (2020) prepared heterogeneous pH/temperature dual-sensitive hydrogels composed of *N*-isopropylacrylamide, acrylic acid, and vinyl-terminated polydimethylsiloxane via gamma-ray irradiation copolymerization. This gel exhibits extremely high pH-sensitivity and can rapidly absorb or release free water in response to pH changes. Based on the synergistic regulation of hydrogen bonding interactions and electrostatic repulsion, Yue et al. (2019) prepared a temperature and pH dual-responsive hydrogel via aqueous free-radical copolymerization, using polyethylene glycol methyl ether

methacrylate and acrylic acid as monomers. This gel features facile preparation, high mechanical strength and dual environmental responsiveness (Fig. 12).

Stress-sensitive gels refer to a type of gel materials that exhibit changes in rheological properties, strain or swelling behavior under variations in the external environment (Khalesi et al., 2020; Wei et al., 2018). Due to the presence of solvent-affinitive groups in the gel structure, when exposed to external stimuli, the gel swells and eventually reaches a volumetric equilibrium state. The internally crosslinked network structure keeps the gel insoluble during the swelling process and maintains its shape (Warren et al., 2017). Currently, most stress-sensitive gels are fabricated via thermal treatment and blending of multiple components. Furthermore, polyvinyl alcohol, chitosan, and agarose primarily serve as the polymer backbones to construct the gel network. Utilizing the physical cross-linking mechanism of salt-induced chitosan chain entanglement, Cui et al. (2019) performed in-situ polymerization of acrylic acid in an acidic chitosan solution and incorporated tannic acid-modified cellulose nanocrystals (TA@CNC) as nano-reinforcers. Subsequently, high-strength, self-

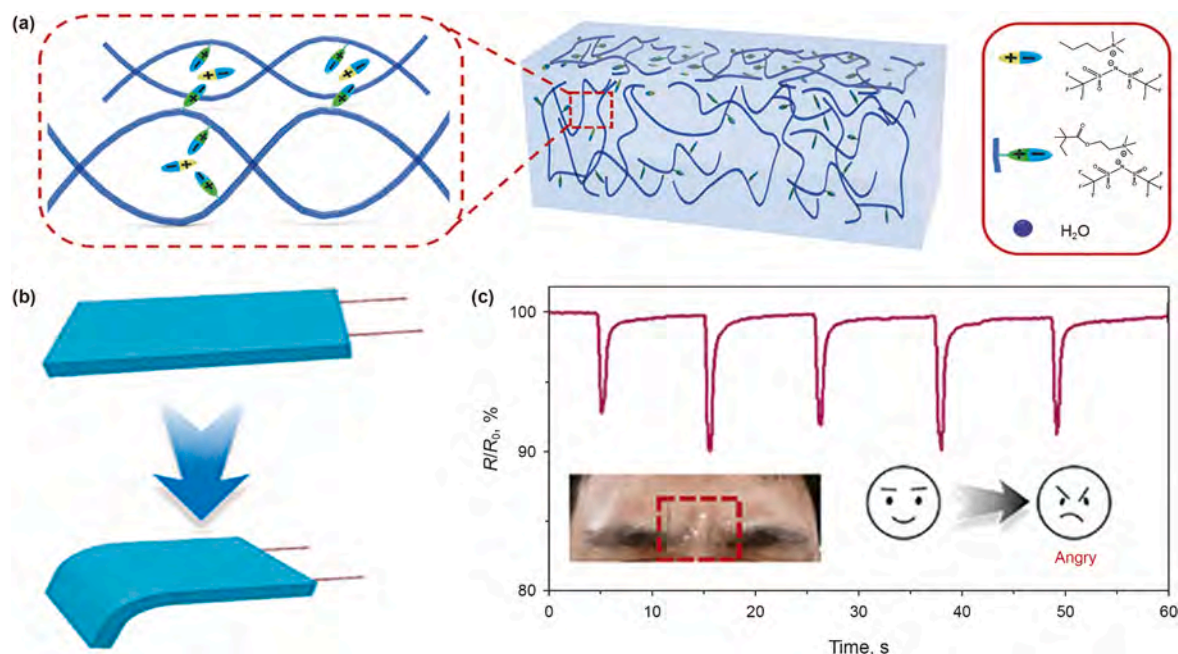


Fig. 9. High-performance ionic gels based on electrostatic interactions. (a) Schematic illustration of the ionogel structure. (b, c) Schematic illustrations of the ionogel-based sensors. Adapted with permission from Yu and Wu (2021).

adhesive, and strain-sensitive chitosan/polyacrylic acid double-network nanocomposite hydrogels were prepared via immersion in a saturated NaCl solution (Fig. 13). Based on a hybrid physical-chemical cross-linking strategy with tunable stress relaxation, Chaudhuri et al. (2016) fabricated a series of dual-network hydrogels exhibiting distinct stress relaxation rates but similar initial moduli by modulating the molecular weight and cross-linking density of sodium alginate and PEG spacer chains. This gel exhibits significant stress relaxation and energy dissipation under mechanical loading, effectively simulating the viscoelastic and plastic behavior of geotechnical media under sustained stress. This offers a novel strategy for modulating the mechanical properties of soft rock or geopolymer materials.

2.2.3. Supramolecular gels

Supramolecular gels are reversible, high-performance gel networks formed through the self-assembly of low-molecular-weight gelators or macromolecules driven by non-covalent interactions (Picchioni and Muljana, 2018; Xia et al., 2020). Unlike traditional chemically cross-linked polymer gels, they construct three-dimensional networks with diverse nanostructures via non-covalent interactions, thereby immobilizing the solvent. The primary non-covalent interactions involved include hydrogen bonding, electrostatic interactions, host-guest interactions, and metal-ligand coordination. Subtle variations in non-covalent interactions alter the equilibrium state of the gel system, triggering a gel-sol phase transition, thereby endowing supramolecular gels with unique dynamic reversibility. Constructing functional colloids via supramolecular non-covalent interactions is not only an effective strategy for gaining deep insights into biological self-assembly, but also a vital pathway for developing high-performance supramolecular materials. Based on the principle of urea-enhanced multiple hydrogen bonding cross-linking, Zhang et al. (2024) prepared supramolecular gels. These gels exhibit ultra-tough mechanical properties suitable for high-load bearing environments and allow for the construction of anisotropic microstructures via solvent exchange-induced hydrogen bond

reorganization (Fig. 14). Li et al. (2015) constructed a novel supramolecular gel by integrating DNA hybridization with host-guest interactions between CB and phenylalanine-functionalized carboxymethyl cellulose. This supramolecular gel can be fabricated via a facile “one-pot” mixing strategy and exhibits excellent tensile properties.

2.2.4. Self-healing physical gels

Self-repairing physical gels are constructed by hydrophilic macromolecules through dynamic and reversible physical cross-linking (hydrogen bonds, hydrophobic interactions, ionic coordination, etc.) to form a three-dimensional network. The chain segments are rich in hydrophilic groups, which can bind a large amount of free water, presenting typical soft wet characteristics (Bai et al., 2022). Under mild temperatures and without external force interference, the dynamic bonds at the broken chain interface can reform, achieving dual self-healing of structure and function (Perera and Ayres, 2020; Picchioni and Muljana, 2018). In particular, hydrophobic association has emerged as a pivotal strategy for fabricating high-efficiency self-healing gels, owing to its moderate bond energy and superior reversibility. By incorporating hydrophobic microdomains into hydrophilic backbones, transient hydrophobic cross-linking points are formed in aqueous environments. Upon fracture, these hydrophobic segments rapidly re-associate via hydrophobic interactions, endowing the gels with high healing efficiencies exceeding 90% and exceptional elongation rates greater than 1000%. Motivated by the superior elongation and strength of double-network systems, Li et al. (2018) fabricated a double-network self-healing hydrogel via the copolymerization of acrylamide (AM) and the hydrophobic monomer lauryl methacrylate (LMA), integrated with the ionic coordination between sodium alginate (SA) and ferric ions (Fe^{3+}). Its advantage lies in utilizing NaCl-induced SDS to form worm-like micelles, which can significantly enhance the solubility and polymerization activity of LMA, thereby constructing a hydrophobic associative network with excellent self-healing properties. Meanwhile, the ionic bonds between sodium alginate and Fe^{3+} as well as the

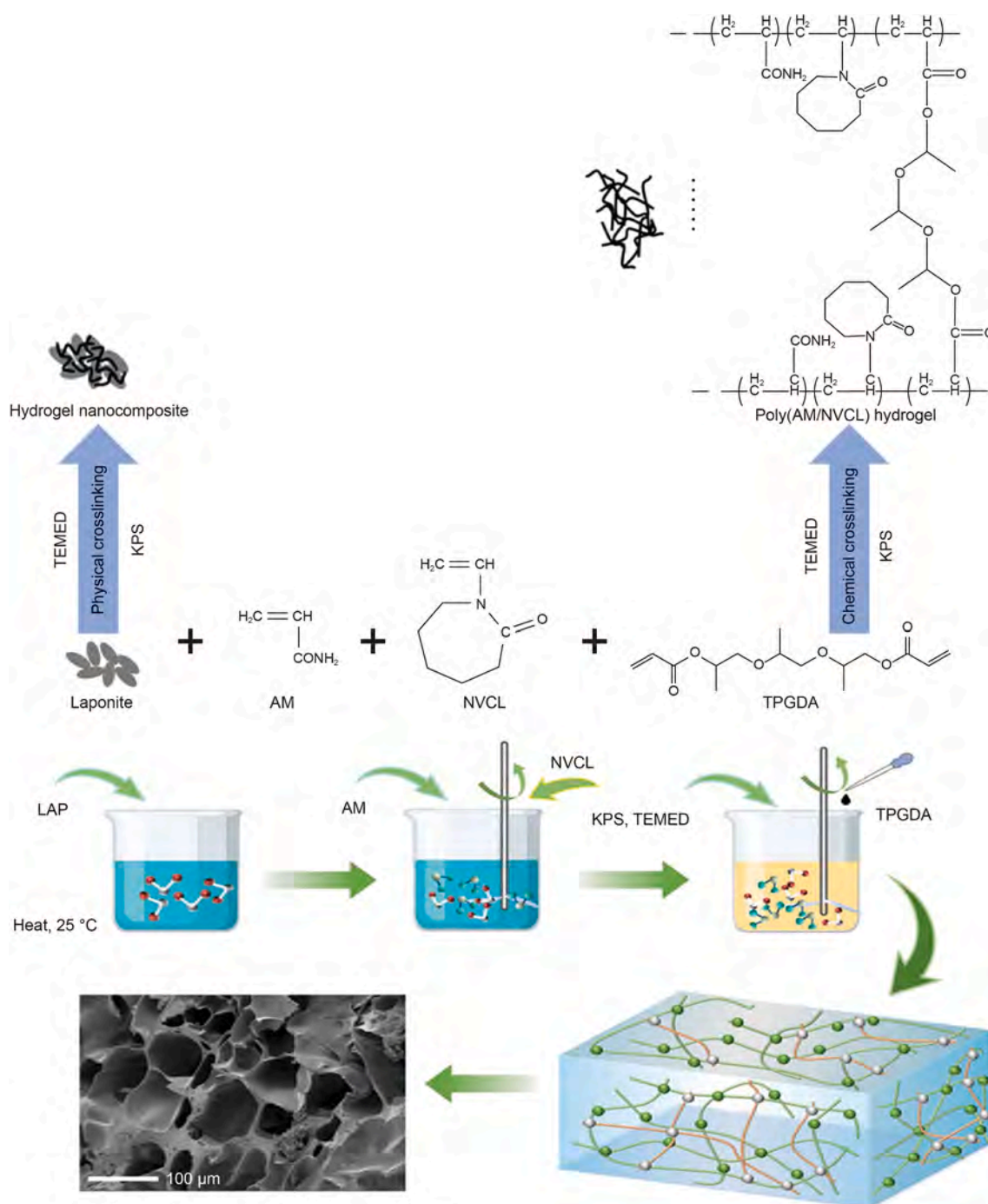


Fig. 10. Synthesis principle and microstructural characterization of the reaction process of the thermo-responsive hydrogel. Adapted with permission from [Yuan et al. \(2024\)](#).

hydrogen bonds between sodium alginate and acrylamide further enhance the compactness and mechanical strength of the network structure, endowing the resulting hydrogel with both excellent ductility and high strength. [Kamiyama et al. \(2022\)](#) prepared highly stretchable and self-healing polymer gels formed solely by physical entanglement of ultra-high-molecular weight (UHMW) polymers through a one-step method. This UHMW gel exhibits excellent high stretchability, high ionic conductivity, and recyclability. In addition, the gel can achieve self-healing at room temperature without any external stimulation ([Fig. 15](#)).

In summary, the synthesis mechanism of crosslinked polymer gels involves initially forming reactive polymer chains through

free-radical polymerization at the surface or downhole, followed by the introduction of chemical cross-linkers (such as organic cross-linkers or metal ions). Through condensation, addition or coordination reactions, the active sites between chains are irreversibly bonded, forming a dense three-dimensional network structure. Specifically, surface crosslinked gels complete the cross-linking reaction at the surface to form bulk gel particles prior to injection, characterized by stable performance and high plugging strength. Downhole crosslinked gels involve injecting a low-viscosity polymer solution into the formation. The cross-linking reaction is then triggered at the target layer by temperature, pH or ions, in situ forming a high-strength gel suitable for plugging

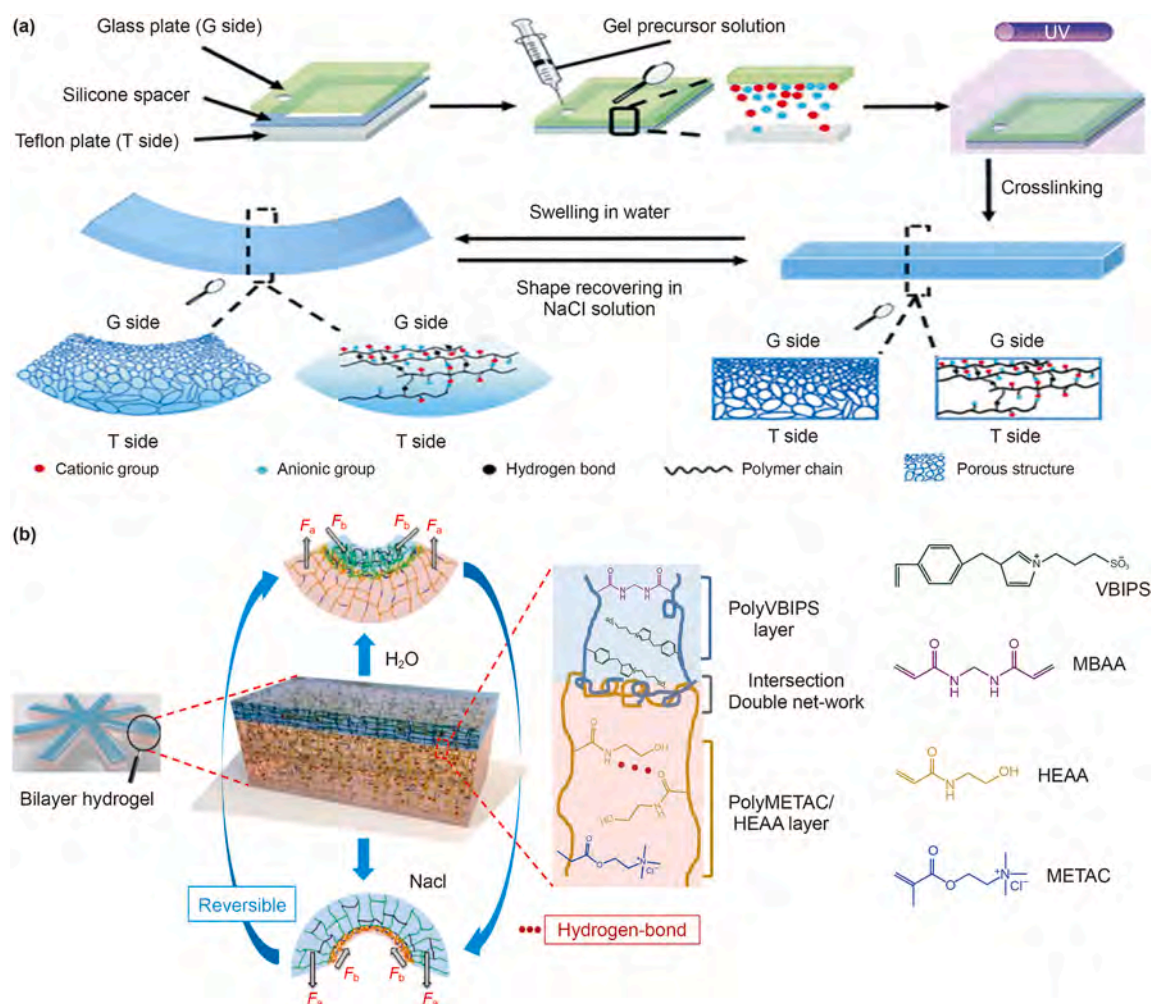


Fig. 11. Deformation mechanism and bending performance of the bilayer salt-responsive hydrogel. (a) Schematic illustration of the fabrication process and deformation mechanism of the hydrogel actuator. Adapted with permission from Shao et al. (2021). (b) Schematic illustration of the microstructure and bending behavior of the bilayer hydrogel in water and salt solutions. Adapted with permission from Xiao et al. (2017).

complex formations. The synthesis principle of non-crosslinked polymer gels involves constructing a dynamic and reversible three-dimensional network structure through physical interactions, such as hydrophobic association, hydrogen bonding, electrostatic interaction and host-guest recognition, without the need for chemical cross-linking agents. The network is formed through weak intermolecular interactions, exhibiting functionalities such as self-healing and environmental responsiveness. The synthesis process is relatively straightforward and the material demonstrates high adaptability. However, its stability deteriorates under high-temperature, high-salt or extreme pH conditions. Different types of polymer gels and the corresponding synthesis principles are summarized in Table 1.

3. Interfacial interactions of polymer gels and rocks

In oil and gas drilling and production projects, the effectiveness of a polymer gel to truly “penetrate, seal, and stabilize” depends not on its bulk strength but on its interfacial strength. Lost channels in deep and ultra-deep wells are often formed by interwoven fractures and pores ranging from millimeter to micrometer scale. After the gel is injected, it must first “anchor” to the rock wall before it can be said to be capable of subsequent plugging and pressure-bearing. If the interfacial adhesion force is insufficient,

the gel will slide off as a whole under the combined effects of pressure difference and shear force, causing the plugging layer to fail instantly. Improper interfacial rheological matching can cause high-elastic-modulus network to crack brittly under pumping disturbance, resulting in secondary lost circulation. If the interfacial fracture fatigue threshold is too low, microcracks will rapidly propagate under cyclic stress, leading to “short-term effectiveness, long-term failure”. Therefore, the interfacial strength is not only an extension of the material’s mechanical properties, but also the “life-or-death threshold” that determines whether the gel can adapt to the deep, high-temperature, high-salt, and high-stress environments. Only by achieving “chemical anchoring at the molecular scale–topological interlocking at the mesoscopic scale–resilience dissipation at the macroscopic scale” can ensure that the gel can remain in the well for a long time and continuously perform plugging and stimulation control functions.

3.1. Interfacial interactions of crosslinked polymer gels and rocks

3.1.1. Interfacial adhesion

The core mechanism of gel interfacial adhesion lies in a “dual-scale synergistic effect”. At the molecular scale, polymer chain segments at the interface form reversible or irreversible specific bonds with functional groups on the substrate surface via

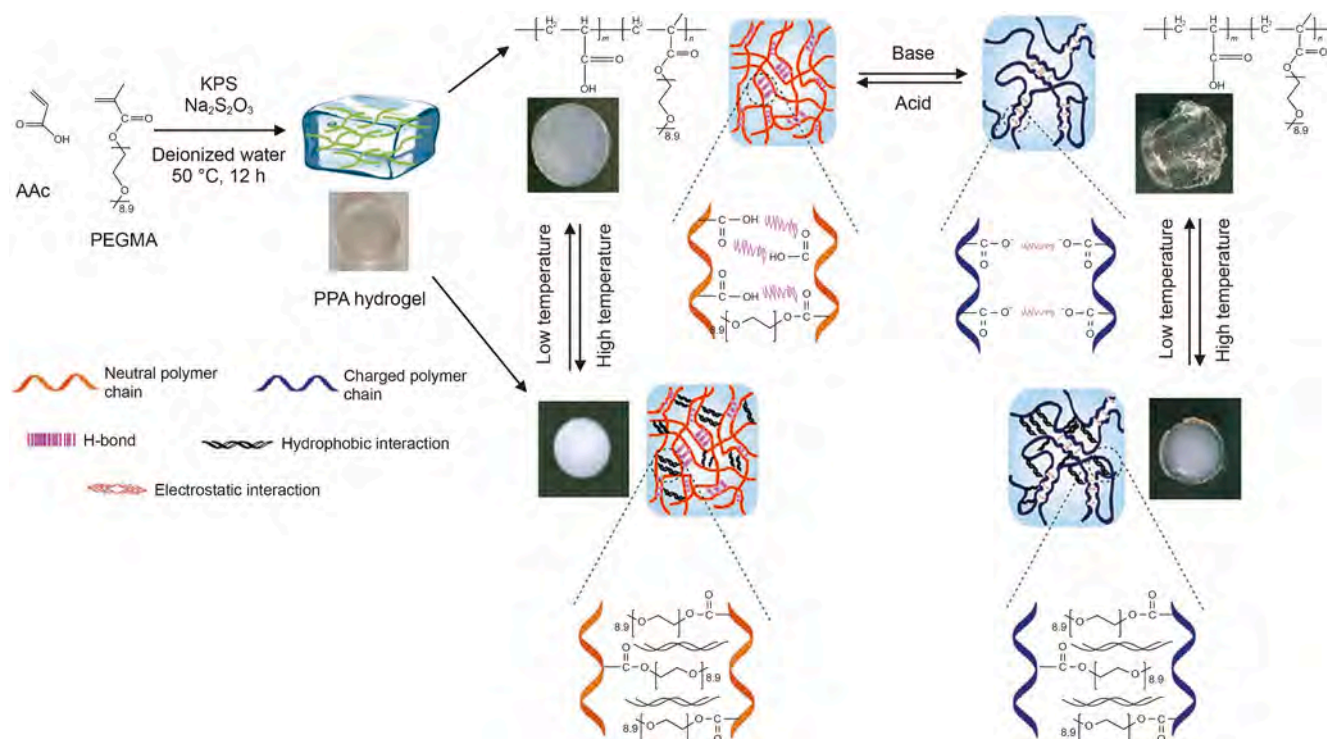


Fig. 12. Schematic illustration of the synthesis of the pH-responsive and temperature-responsive PPA hydrogel. Adapted with permission from Yue et al. (2019).

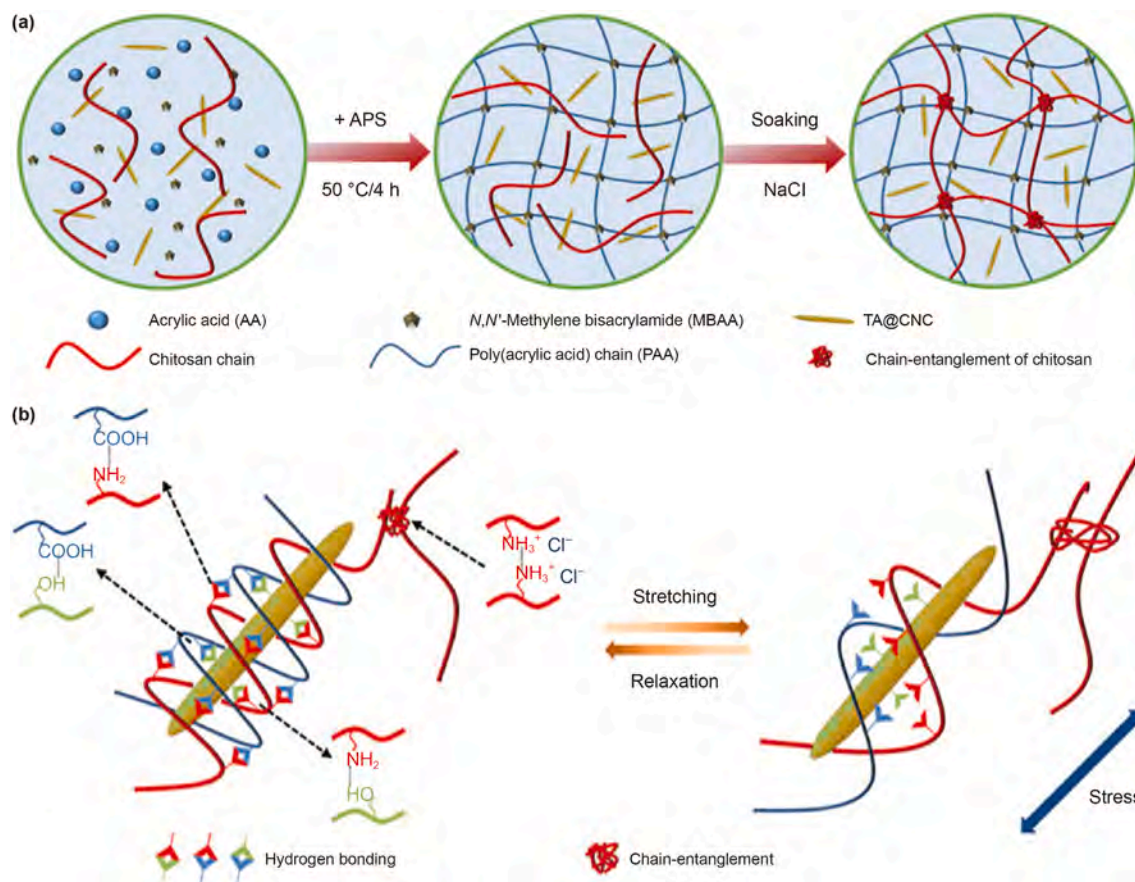


Fig. 13. Synthesis principle of the stress-sensitive hydrogel. (a) Preparation process of the nanocomposite hydrogel. (b) Reversible network changes within the hydrogel during stretching and relaxation. Adapted with permission from Cui et al. (2019).

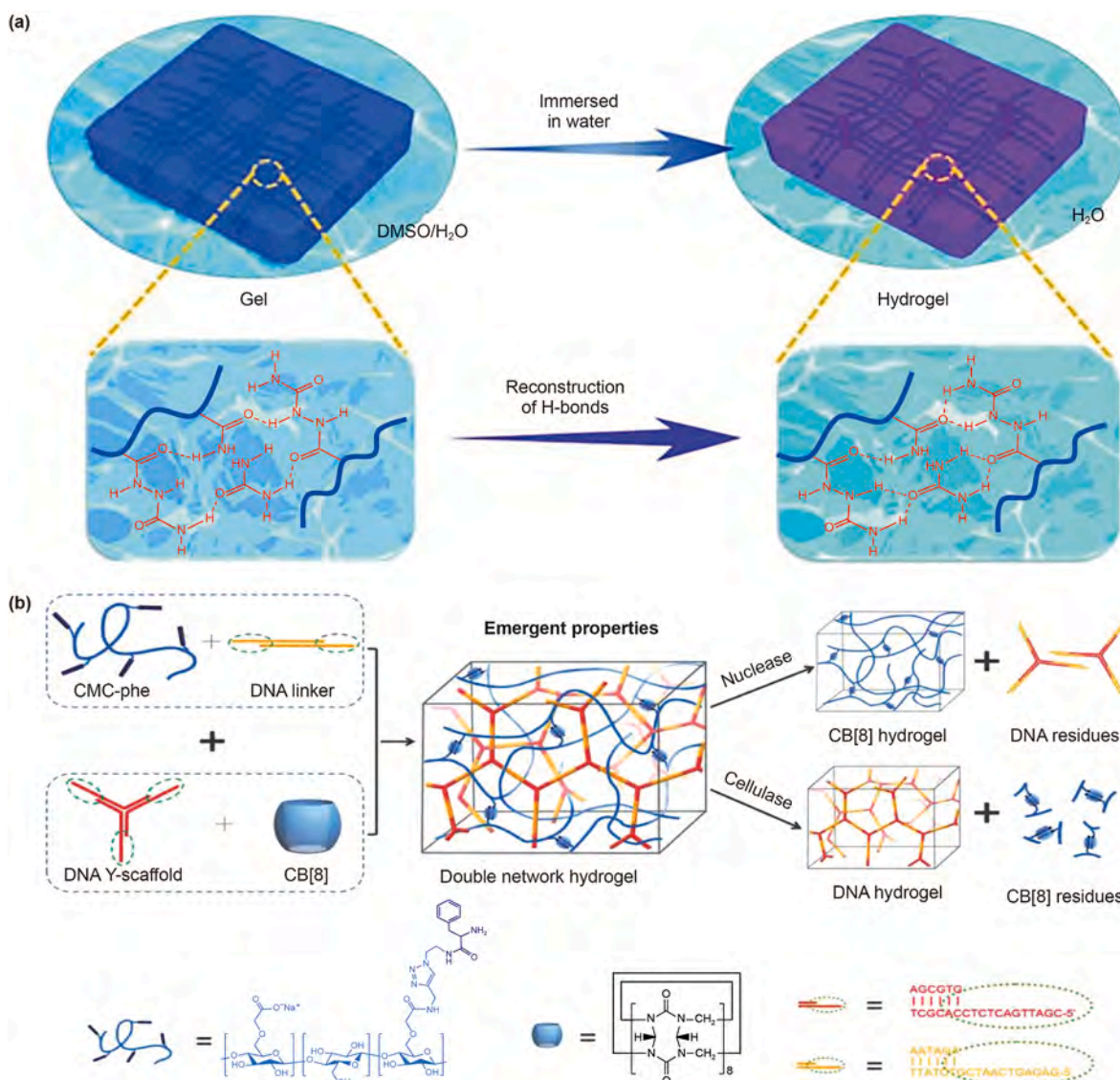


Fig. 14. Synthesis principles of the supramolecular gel. (a) Network structure of the PNASC gel. Adapted with permission from Zhang et al. (2024). (b) Formation of the double-network gel via host-guest interactions. Adapted with permission from Li et al. (2015).

hydrogen bonding, electrostatic pairing, metal coordination or dynamic covalent bonds, thus achieving “chemical anchoring”. At the mesoscopic scale, the gel network undergoes local swelling and reconstruction in the contact region. Chain segments penetrate into micropores or surface asperities of the substrate, giving rise to topological interlocking and capillary interlocking, which can be viewed as “physical riveting” (Bovone et al., 2021; Yuk et al., 2016). The coupling of these two scales endows the interface with high work of adhesion and self-healing capability. When sacrificial bonds or dynamic crosslinks are introduced, interfacial debonding can dissipate energy through bond breaking and reformation, reconciling high toughness with reversible detachment. Chen et al. (2023) developed a thermosensitive double-network hydrogel using a combined free-radical and photo-initiated strategy, in which rigid, brittle poly(2-acrylamido-2-methyl-1-propane-sulfonate) (PAMPS) serves as the first network and ductile poly(*N*-isopropylacrylamide-co-acrylamide)(P(NIPAM-co-AM)) as the second network. After interpenetration of the two networks, immersion in multivalent metal ions yields a TDN-metal ion gel (Fig. 16). The interfacial work of adhesion can be tuned in real time

through reversible association/dissociation of metal–ligand coordination bonds, enabling concurrent hydrophilic–hydrophobic switching and thermoresponsive adhesion. Sim et al. (2020) grafted bismaleimide (DIMI) onto silica surfaces and carried out a Diels–Alder (DA) reaction with poly(furfuryl methacrylate) (PFMA) brushes, forming a covalently crosslinked network at 70 °C. Upon heating to 110 °C, the retro-Diels–Alder (rDA) reaction is triggered and the crosslinking points are cleaved. Combination with light-controlled disulfide exchange, this process enables reversible “on-off” control of surface wettability and adhesion strength.

3.1.2. Interfacial rheological behavior

The interfacial rheological behavior is governed by the synergistic action of three factors—stiffness of the interfacial glassy layer, dynamics of viscous junctions, and network energy dissipation—which directly controls the plugging strength, erosion resistance, and reversible adhesion of gels. Tang et al. (2013) systematically investigated the interfacial rheology of pre-crosslinked particle gels using interfacial tension relaxation techniques. Increasing particle concentration led to the formation of a

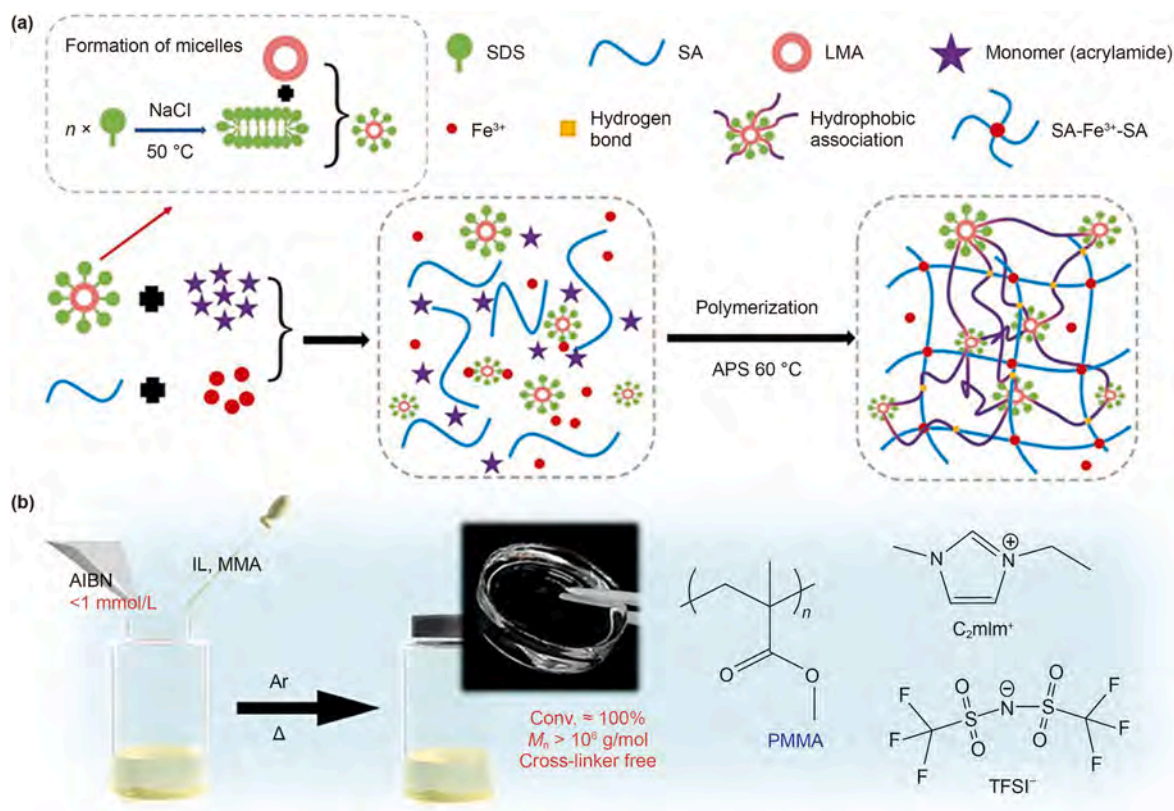


Fig. 15. Synthesis principle of the self-healing physical gel. (a) Synthesis and network structure of the double-network hydrogel. Adapted from Bai et al. (2022). (b) Synthesis process of the UHMW gel. Adapted from Kamiyama et al. (2022).

percolated network at the interface, accompanied by simultaneous increases in interfacial dilational modulus and viscous components. Addition of electrolyte causes counterions to screen residual surface charges on particles, reducing electrostatic repulsion. The brittle network converts to a flexible structure and interfacial film strength decreases markedly, confirming the “charge–rigidity” regulatory mechanism. Tang et al. (2019) constructed ionically dual-crosslinked sodium alginate gels by leveraging the strong coordination between carboxyl groups and multivalent metal ions. They found that the reinforcing efficiency of Ca²⁺, Cu²⁺, Al³⁺, and Fe³⁺ increases with cation valence. In particular, Fe³⁺ increased the storage modulus by 6.5 times and the fracture toughness by 4.8 times, confirming a positive correlation between valence state, crosslinking density, and mechanical performance. Liu et al. (2022b) reported that an Ag⁺/Fe³⁺ catalytic system can trigger rapid gelation of acrylic acid and its comonomers at damaged interfaces at room temperature, forming a covalently crosslinked PAA network and enabling multiple healing cycles without external energy input. After healing, the interfacial shear strength is restored, and subsequent coating with a hydrophobic polymer layer leads to higher tensile strength, improved toughness and better water-retention capacity (Fig. 17). These studies collectively reveal how the synergistic interplay of interfacial charge, metal coordination, and dynamic covalent crosslinking governs the rheological and mechanical properties, as well as the self-healing efficiency, of gels. This insight offers new design ideas for highly tough, repairable, and environmentally adaptive polymer gel systems.

3.1.3. Interfacial tension effects

Under external force, the dynamic coordination bonds and hydrogen bonds within the interfacial layer of crosslinked polymer

gels undergo instantaneous breaking and reformation, dissipating shear energy while maintaining structural integrity. Meanwhile, the ultra-long main chains and topological entanglements disperse localized stress to the micrometer scale, suppressing the initiation of interfacial microcracks. The charge–network–electrolyte ternary synergy enables interfacial tension to increase with rising particle concentration; upon electrolyte shielding, the network softens and tension decreases, achieving reversible switching between “high-elasticity and low-tension” states. This mechanism provides a controllable rheological boundary for deep reservoir profile control and flooding. Gong et al. (2003) prepared poly(2-acrylamido-2-methylpropanesulfonic acid) hydrogels (PAMPS) by free-radical polymerization of 2-acrylamido-2-methylpropanesulfonic acid (AMPS) and, for the first time, proposed the concept of “sacrificial bonds”. In their design, a highly chemically crosslinked PAMPS network served as the primary network, while a lightly crosslinked polyacrylamide network acted as the secondary network. Upon stretching, chains in the primary network preferentially fractured and dissipated energy, whereas the secondary network, stabilized by topological entanglements, suppressed crack propagation and thus imparted high toughness to the material. However, this strategy relies on irreversible covalent crosslinks, so the sacrificial bonds cannot be re-formed after rupture and the strength decays permanently (Fig. 18) (Chen et al., 2013). Sun et al. (2012) used a one-pot method to copolymerize acrylamide (AM) with sodium alginate (SA), with *N,N'*-methylenebisacrylamide (MBAA) serving as the chemical crosslinker. Ca²⁺ was then introduced to form ionic coordination domains, and a chemically and ionically double-crosslinked network was constructed by photo-initiation. Under external loading, Ca²⁺-carboxylate coordination bonds undergo reversible breakage and reformation, effectively dissipating energy and markedly increasing the fracture strain.

Table 1

Classification, synthesis principles, and advantages and disadvantages of different types of polymer gels.

Category	Classification	Representative product	Synthesis principle	Advantages	Disadvantages	References
Crosslinked polymer gels	Surface-crosslinked polymer gels	Pre-crosslinked polymer gels	At the surface, gels are produced by free-radical aqueous or inverse microemulsion polymerization with controlled chemical crosslinker to form an integral three-dimensional network through a diffusion–reaction process.	Surface crosslinking gives stable properties before injection. Swollen gels sustain high pressures and provide effective plugging. Particles are easy to screen and their size can be tailored to pore–throat scales.	Pre-crosslinked particles are limited by particle size and permeability and their performance declines under high temperature, high salinity, and chemically harsh conditions.	Bai and Sun (2020); Bai et al. (2015); Kang et al. (2022); Zhou et al. (2021)
		Secondary crosslinked polymer gels	Low-viscosity weakly crosslinked or pre-crosslinked particles are injected first. In the target zone, formation temperature, pH or ions trigger secondary dense crosslinking and generate a high-strength network.	Low initial viscosity ensures good pumpability and low fluid loss and protects the matrix. In-situ strengthening densifies the network and greatly enhances fracture residence and erosion resistance.	The process window is narrow and coupling particle size with crosslinking rate is difficult. High temperature and high salinity may cause premature gelation or strength decay and increase field control risk.	Du et al. (2019); Ma et al. (2024); Zhai et al. (2024)
		PLC polymer crosslinked gels	Using cellulose or nanofibers as the backbone, vinyl monomers are grafted through free-radical copolymerization while multifunctional organic crosslinkers build a secondary network. Additional aldehyde–phenol and aldehyde–lignin condensation with phenolic hydroxyl groups produces an interpenetrating covalent dual network that enhances thermal and salt stability.	Low-temperature gelation is fast and controllable. It is compatible with drilling fluids and loss-control materials and works synergistically. The cellulose backbone is fully degradable and environmentally benign. The fluid is strongly shear thinning before gelation and highly viscoelastic afterward.	Gelation is strongly coupled to pH, temperature, and crosslinking ratio, so field fluctuations can cause under-crosslinking or embrittlement. Nano-reinforcement or composite modification is needed to ensure long-term plugging under high-temperature high-salinity conditions.	Alam et al. (2019); Kabir et al. (2018)
	In-situ crosslinked gels	Covalently crosslinked polymer gels	Reactive macromolecules are initially formed by radical polymerization. Multifunctional organic crosslinkers are then introduced, so that condensation and addition reactions lock interchain active sites into irreversible covalent bonds and yield a dense three-dimensional network in a single step.	Covalent bonds have high bond energy and resist salt and heat, so they are suitable for high-temperature, high-salinity reservoirs. The resulting three-dimensional network is stable and strong and ensures durable plugging performance.	Gelation time and the injection process require precise control. After swelling and degradation, chemical cleanup becomes difficult.	Zhang et al. (2020b); Zhao et al. (2015); Zhu et al. (2017a)
		Ionically crosslinked polymer gels	Carboxyl- or hydroxyl-containing polymers are mixed with metal crosslinkers or injected in stages. Metal ions instantly coordinate into multidentate ionic bridges and rapidly build a three-dimensional network.	Gelation is controllable and operation is simple. The system has good mobility and injectivity and provides high mechanical strength with stable plugging performance. It is low cost and highly adaptable.	Under high temperature or high salinity, gels readily degrade and undergo syneresis. Gelation time is highly sensitive and difficult to control.	Yang et al. (2013a, 2019); Zhang et al. (2019b)
		Composite crosslinked polymer gels	Metal–carboxylate coordination is first used to build a weak gel network. Subsequent covalent crosslinking with phenolic, PEI, or HMTA produces a dense network structure that synergistically enhances strength and thermal resistance.	These gels combine high strength with toughness, and their layered crosslinking enable precise control over gelation time and location while enhancing resistance to salinity and acidity.	Costs and scale-up challenges are greater than those for single-network systems, and both formulation and processing are more complex. Failure of any single component can lead to a widespread decline in performance.	Nakajima (2017); Pinho de Aguiar et al. (2020); Zhang et al. (2020a)

(continued on next page)

Table 1 (continued)

Category	Classification	Representative product	Synthesis principle	Advantages	Disadvantages	References
Non-crosslinked gels	Non-crosslinked physical gels	Hydrophobically associating gels	Micelles are constructed using surfactants, and hydrophobic and hydrophilic monomers copolymerize within the micelles. The resulting physically crosslinked network is formed through the association of hydrophobic groups.	Mechanical properties can be controlled and tuned by adjusting the monomer ratio, and the materials also possess self-healing capabilities.	Gels synthesized with branched hydrophobic monomers exhibit reduced mechanical strength and poor swelling stability.	Bai et al. (2022); Gao et al. (2016); Liu et al. (2018)
		Hydrogen-bonded gels	Spontaneously associates through intermolecular hydrogen bonds such as chain-end $\text{-COOH}\cdots\text{O=C-}$ and $\text{-NH}\cdots\text{O=C-}$, forming a dynamically reversible double physically crosslinked network.	Superior mechanical performance, excellent toughness, high self-healing capability, and a relatively simple synthesis process.	Hydrogen bonds are susceptible to environmental factors such as water and pH, resulting in limited stability.	Li et al. (2020, 2022b); Liu and Peng (2023)
		Electrostatic-interaction gels	Electrostatic interactions are utilized to construct a physically crosslinked network through methods such as monomer copolymerization, polyelectrolyte complexation, or ionic crosslinking. This network is partially supplemented with topological entanglement or covalent crosslinking to enhance stability.	Strong performance tunability is achieved by modulating parameters such as monomer concentration, charge ratio, and salt concentration, enabling wide-range regulation of modulus and strength.	Insufficient stability; electrostatic interactions are readily disrupted under high humidity or extreme pH conditions, leading to excessive gel swelling or degradation.	Senebandith et al. (2023); Sun et al. (2015b); Yu and Wu (2021)
	Environmentally responsive gels	Thermo-responsive gels	Based on thermo-responsive polymers, a physically crosslinked three-dimensional network is formed through temperature-induced dissociation of intermolecular hydrogen bonds, enhanced hydrophobic interactions, or micelle aggregation, achieving a sol-gel phase transition.	The materials exhibit good biocompatibility; natural polymer substrates are low in toxicity and biodegradable; they also demonstrate excellent thermal responsiveness and have a wide range of applications.	Weak mechanical properties are observed because purely physically crosslinked networks are prone to rupture. Furthermore, high salinity and pH variations can affect the phase transition temperature and overall stability.	Fan et al. (2022); Liu et al. (2022a); Lv et al. (2025)
		Salt-responsive gels	By copolymerizing or compounding polyelectrolytes, a crosslinked network is formed through ionic bonding and electrostatic interactions, allowing swelling and shrinking in response to changes in salt concentration.	Highly sensitive to salt, rapidly contracting as salt concentration increases. performance is adjustable, with swelling rate controlled by the monomer ratio or the valence state of salt ions.	Highly dependent on the environment, prone to agglomeration under high salt conditions. The ionic valence significantly affects stability.	Ali et al. (2015); Chang et al. (2011); Shao et al. (2021); Taylor et al. (2017); Xiao et al. (2017)
		pH-responsive gels	By copolymerizing or blending monomers containing ionic groups, and forming networks through covalent or physical crosslinking, the ionization of groups can respond to changes in environmental pH, thereby triggering gel swelling or contraction.	The preparation process is environmentally friendly and can be carried out using non-toxic residual methods such as aqueous solution free radical polymerization, without the need for organic crosslinking agents.	Highly dependent on the environment. High salt concentrations can shield electrostatic interactions and weaken pH responsiveness.	Adelnia et al. (2019); Deng et al. (2012); Khan et al. (2020); Philippova et al. (2013); Yue et al. (2019)
		Stress-responsive gels	Construct a three-dimensional network through dynamic physical crosslinking, introducing stress-responsive microdomains between polymer chains. Under external force, the weak crosslinking points	Sensitive to stress, it can accurately detect slight stress and quickly generate current, deformation, or capacitance changes, with a response time of just a few seconds.	High humidity and electrolytic environments can weaken stress response sensitivity.	Chaudhuri et al. (2016); Cui et al. (2019); Khalesi et al. (2020); Warren et al. (2017); Wei et al. (2018)

Supramolecular gels	PNASC hydrogels	can reversibly break and reform, enabling the network topology to instantly reorganize. Using NASC as a monomer, a three-dimensional network is constructed through free radical polymerization, with intermolecular hydrogen bonds and potential microphase separation working synergistically to form an ultra-rigid and ultra-tough gel structure.	High hydrogen bond density, strong environmental stability. Performance can be tuned through copolymerization or blending, and it also possesses dynamic functions such as shape memory and self-healing.	In low-temperature environments, the dynamics of hydrogen bonds decrease, affecting mechanical flexibility and ion transport efficiency.	Zhang et al. (2024)
	Host-guest supramolecular double network gels	The first network is formed through base hybridization, and the second network is formed through host-guest interactions. The two networks physically interpenetrate to construct a double network structure.	Mechanical properties are synergistically enhanced, thermal stability is improved, dynamic response is excellent, with shear thinning and thixotropy.	High-temperature or high-salt environments may disrupt supramolecular interactions; during large-scale production, it is challenging to control the uniformity of the network.	Li et al. (2015)
Self-healing physical gels	Soft-hard synergistic dual physically crosslinked gels	A free radical copolymerization produces the PAAc main chain, with hydrophobic microdomains self-associating into a soft network, while Fe^{3+} and $-\text{COO}^-$ are simultaneously introduced for instantaneous coordination to form an ionic hard network, creating a synergistic soft-hard dual physical crosslinking structure.	Excellent mechanical properties, strong self-healing ability, capable of healing at room temperature without external stimuli, easy to prepare, and with adjustable component ratios.	High temperature and high humidity may disrupt hydrophobic interactions and ion coordination, significantly affecting the distribution of Fe^{3+} .	Li et al. (2018)
	UHMW gels	Initiate the free radical polymerization of vinyl monomers with an extremely low concentration of initiator, forming a three-dimensional network gel through physical entanglement between polymer chains.	Strong self-healing ability at room temperature; excellent recyclability with performance remaining unchanged after hot-press regeneration; easy to prepare through a single-step in-situ polymerization.	Different combinations of ionic liquids exhibit significant variations in compatibility. Ultra-high molecular weight polymers have poor solubility, are prone to phase separation, and make it difficult to obtain homogeneous gels.	Kamiyama et al. (2022)

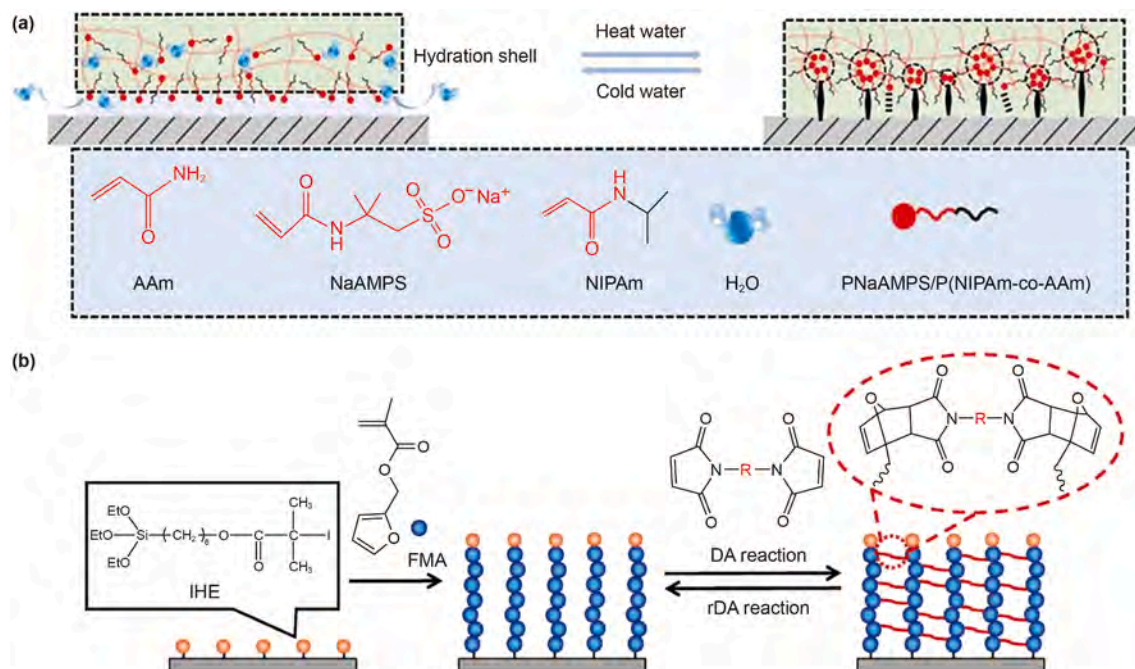


Fig. 16. Schematic illustration of thermo-responsive adhesion and reversible crosslinking in intelligent hydrogels. (a) Adhesion mechanism of TDN hydrogels and schematic of the monomer molecular structures. Adapted with permission from [Chen et al. \(2023\)](#). (b) Synthesis of PFMA brushes and schematic representation of reversible crosslinking and de-crosslinking via DA and rDA reactions. Adapted with permission from [Sim et al. \(2020\)](#).

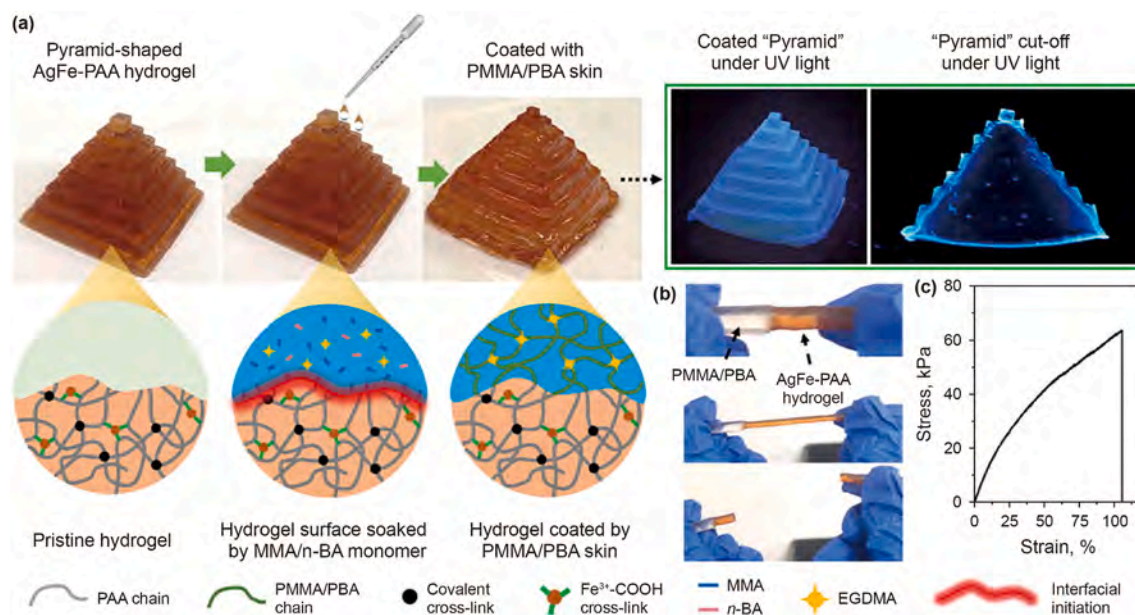


Fig. 17. Preparation and properties of the high-strength core-shell structured gel. (a) Preparation process of the high-strength core-shell structured gel. (b) Interfacial strength of the gel under stretching. (c) Stress-strain curves of the gel. Adapted with permission from [Liu et al. \(2022b\)](#).

3.2. Interfacial interactions of non-crosslinked polymer gels and rocks

3.2.1. Interfacial adhesion

Interfacial adhesion is defined as the capacity of a gel to combine and interact with an external interface. The strength and stability of this interaction serve as the key indicators for evaluating adhesion performance. The interfacial adhesion of non-crosslinked polymer gels relies primarily on non-covalent

interactions, including hydrogen bonding, electrostatic interactions, hydrophobic association, host-guest recognition, and metal-ligand coordination ([Chelu and Musuc, 2023](#)). These interactions are dynamically reversible and can be influenced by factors such as the interfacial water layer, chain segment conformation, and substrate roughness ([Bovone et al., 2021](#)). The free water layer often weakens the intermolecular contact, thereby reducing the initial adhesion force. The penetration and entanglement of polymer chain segments on rough

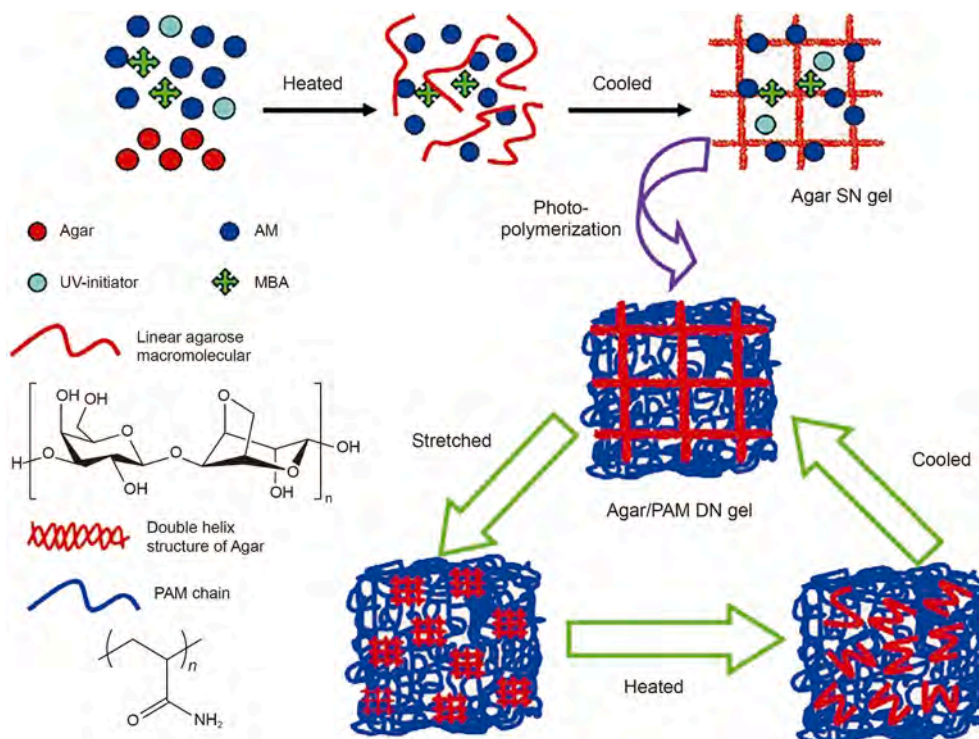


Fig. 18. Preparation of the physical/chemical dual-crosslinked agar/polyacrylamide double-network gel. Adapted with permission from [Chen et al. \(2013\)](#).

surfaces or porous substrates can significantly enhance energy dissipation and improve adhesion strength ([Zhang et al., 2019c](#)). In recent years, researchers have sought to improve the interfacial adhesion performance of non-crosslinked gels by employing structured design strategies. [Wang et al. \(2022b\)](#) proposed a dual-network approach to construct a composite interface layer on the gel surface, comprising energy-dissipating networks and dynamically adhesive networks. The former provides sufficient mechanical support to resist external force damage, while the latter achieves dynamic reorganization and self-repair through reversible bonds (such as hydrogen bonds and coordination bonds), thereby maintaining long-term stable adhesion in a humid environment. This design imparts high adhesion energy and long-term stability to the hydrogel, offering a novel design strategy for achieving robust and durable interfacial bonding in non-crosslinked systems ([Fig. 19](#)). [Yang et al. \(2023d\)](#) started from the interface topological structure and achieved programmable control of adhesion energy by regulating the arrangement mode and energy distribution of polymer chains. Overall, non-crosslinked gels can achieve strong, controllable, and long-term stable interface bonding while maintaining softness due to their reversibility, self-healing, designability, and environmental responsiveness.

3.2.2. Interfacial rheological behavior

Interfacial rheology characterizes the viscoelastic response of a gel subjected to external forces at the interface, reflecting the energy storage and dissipation behavior of the interfacial layer under shear, extensional, or oscillatory loading. For non-crosslinked polymer gels, due to the high activity of the chain segments and the reversibility of the bonding bonds, their interfaces exhibit viscoelastic behavior with adjustable time scales. The advantages of non-crosslinked systems in terms of interfacial rheology lie in their high energy dissipation and environmental responsiveness. Reversible interactions provide additional energy

dissipation pathways at the interface. Through chain segment slippage and the dynamic breaking and reformation of bonds, stress concentration can be effectively mitigated, thereby reducing the risk of catastrophic debonding. Meanwhile, its interfacial mechanical response can be modulated by external stimuli, thereby enabling switchable adhesion or anti-slip properties. [Ollier and Webber \(2025\)](#) investigated the influence of reversible bond kinetics on the shear-thinning behavior of hydrogels, revealing that the dynamic breaking and reformation of reversible bonds induce the shear-thinning phenomenon. Studies have revealed that bond dissociation kinetics significantly influence shear-thinning behavior. Specifically, a lower dissociation rate facilitates the maintenance of structural integrity, thereby enhancing the shear resistance of the gel ([Fig. 20](#)). [Bi et al. \(2023\)](#) investigated the rheological properties of hydrogels containing reversible disulfide bonds, revealing that these gels undergo a solid-to-liquid transition under applied stress and recover their initial state upon removal of the load, thereby demonstrating excellent self-healing capabilities. Studies have demonstrated that the incorporation of disulfide bonds endows hydrogels with excellent self-healing capabilities. Furthermore, their storage modulus and loss modulus can be modulated by adjusting the concentration and type of reversible linkages, thereby achieving precise control over the gel's rheological properties. Consequently, judicious control over the kinetics of reversible bonds through molecular design enables the precise tuning of both the injectivity of the gel system and its ultimate gelation strength within the reservoir formation. This capability is paramount for achieving effective deep conformance control.

3.2.3. Interfacial fracture fatigue

Interfacial fracture fatigue refers to the process where a hydrogel, in contact with a substrate, undergoes crack initiation, propagation, and ultimate failure under the action of external forces. This phenomenon is a key limiting factor for the

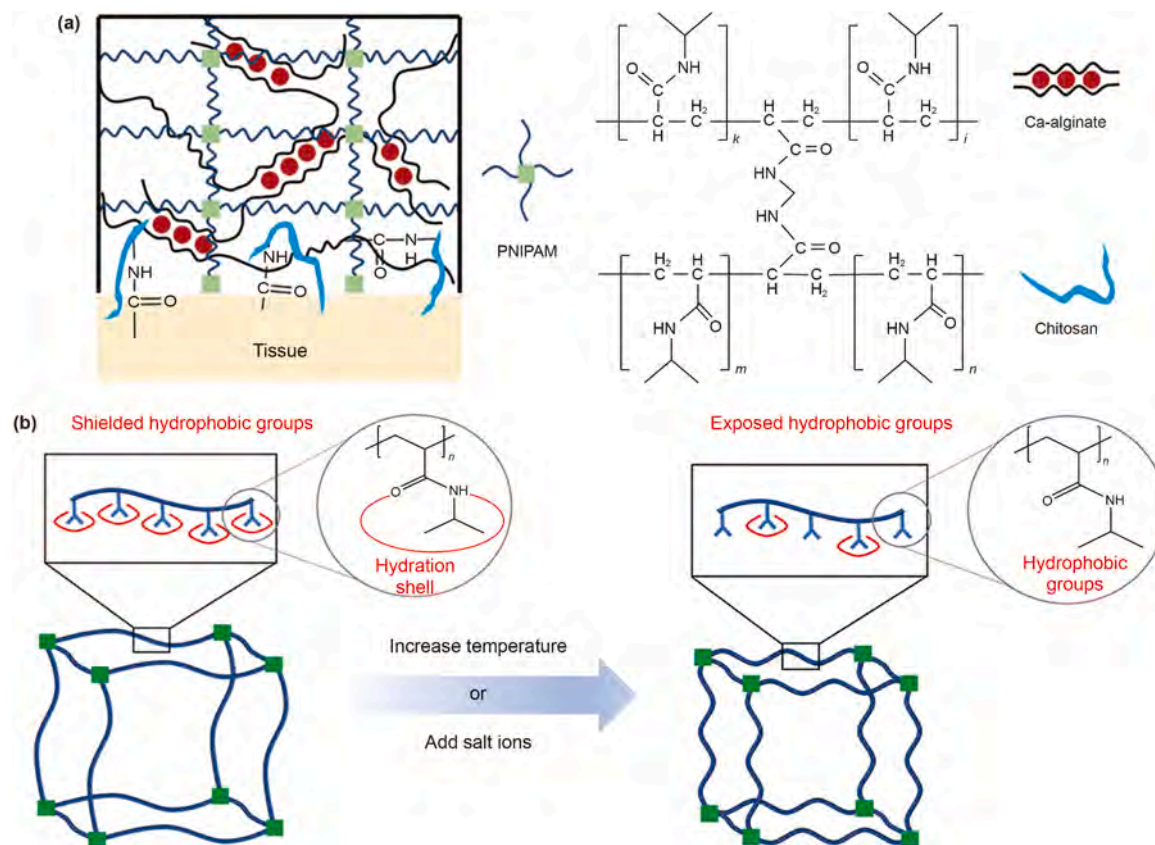


Fig. 19. Network crosslinking and response mechanisms of PNIPAM-based composite hydrogels. (a) Network crosslinking mechanism of PNIPAM. (b) Response mechanism of the PNIPAM network. Adapted with permission from Wang et al. (2022b).

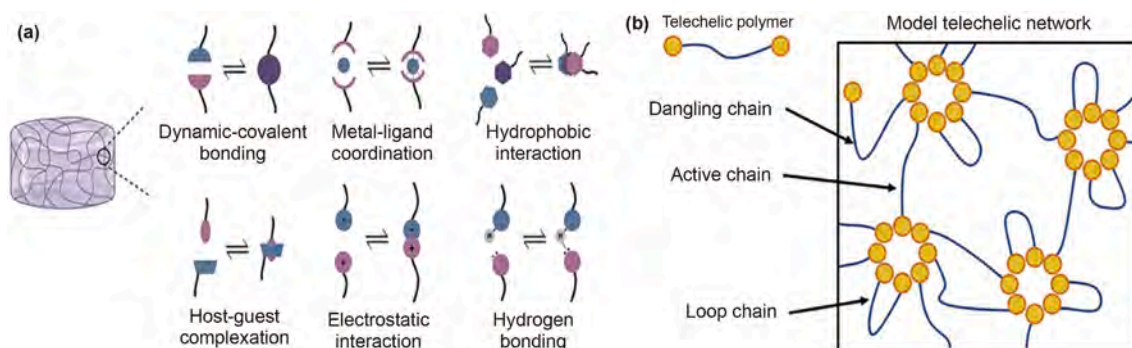


Fig. 20. Schematic illustration of the dynamic non-covalent interaction network model of the gel. (a) Gel network structure formed by dynamic non-covalent interactions. (b) Polymer network model under shear behavior. Adapted with permission from Ollier and Webber (2025).

performance of hydrogels in applications involving soft material interfaces. Due to their brittle network structures, conventional chemically crosslinked hydrogels frequently suffer from low interfacial fracture toughness and are prone to adhesive failure. In recent years, researchers have effectively enhanced the interfacial fracture toughness and fatigue resistance of hydrogels by incorporating dynamic reversible interactions, such as hydrogen bonds, ionic bonds, and disulfide bonds. Under external loading, hydrogels containing these reversible bonds can dissipate energy through the dynamic dissociation and reassociation of the bonds, thereby retarding crack propagation and improving interfacial fatigue tolerance. Specifically, under external shear or tensile

loading at the interface, the continuous dissociation and re-association of reversible bonds facilitates local stress dissipation, thereby mitigating stress concentration and inhibiting crack propagation. Li et al. (2021) reported that the interfacial fatigue threshold of hydrogels incorporating hydrogen bonds can reach 382 J/m², significantly exceeding that of conventional hydrogels. This finding underscores the critical role of hydrogen bond kinetics in interfacial fatigue resistance (Fig. 21). Zhong et al. (2024) modulated the chain segment density and degree of chain entanglement of loosely crosslinked polyacrylamide hydrogels via mild dehydration. This approach significantly enhanced the fracture toughness and fatigue threshold of the material while

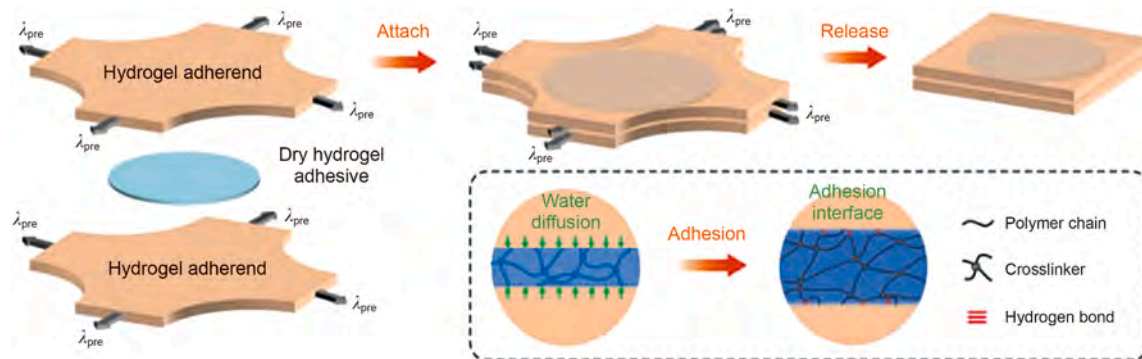


Fig. 21. Schematic illustration of the formation mechanism of gel interfacial adhesion. Adapted from Li et al. (2021).

maintaining a high-water content. In summary, reversible bonds endow the hydrogel interface with high energy dissipation capability, superior fatigue resistance, and environmental responsiveness.

4. Applications of polymer gels in drilling and production

Polymer gels have become essential materials in the oil and gas drilling and production industry for addressing challenges such as lost circulation control, wellbore instability, and enhanced oil recovery. In drilling fluids, gels facilitate fracture plugging and wellbore stability through a process known as “deep migration and in-situ gelation”. In enhanced oil recovery, they improve water control and increase oil production through deep profile control and fluid flow redirection. This paper systematically reviews the current applications of crosslinked and non-crosslinked polymer gels in drilling fluid loss prevention and enhanced oil recovery, analyzes their mechanisms of action and application effectiveness, and provides engineering application for the advanced design of gel materials tailored to specific subsurface conditions.

4.1. Applications of polymer gels in drilling fluids

4.1.1. Applications of crosslinked polymer gels in drilling fluids

Incorporating crosslinked polymer gel lost-circulation materials into drilling fluids enables a “deep migration and in-situ gelation” plugging mode. In this process, particles or weakly crosslinked precursors accumulate at fracture tips and, upon activation by temperature, pH, or ionic strength, rapidly form a three-dimensional network. The resulting plug, characterized by high viscoelastic modulus and low permeability, establishes a “pressure barrier” that blocks pressure transmission, suppresses further fracture propagation, and reduces fluid loss. An ideal plugging gel must be compatible with the drilling fluid system and exhibit adequate thermal stability and bearing strength. Its backbone should contain degradable units, such as ester or acetal linkages, so that after well completion, the plug can be removed by weak acids or chelating agents to restore permeability and achieve safe, efficient, and environmentally friendly drilling. Zhu et al. (2020) developed a degradable preformed particle gel (DPPG) with excellent hydrophilicity (Fig. 22). After entering fracture-based loss channels, the gel rapidly swells by water uptake, then fills and seals the channels, achieving plugging pressures up to 21.12 MPa. Xu et al. (2018) formulated nano-polymer microspheres for water-based drilling fluids that, under differential pressure, can enter and fill shale pores and microfractures to form a sealing layer. After high-temperature aging, more than half of their original particle size is retained, which helps maintain the stability of the sealing layer. During the oil and gas drilling process, drilling

fluid easily invades the formation due to the presence of pores or micro-cracks. Wellbore instability occurs under the combined effects of formation clay hydration swelling and hydraulic pressure. To mitigate wellbore instability induced by drilling fluid invasion, Gao et al. (2025) proposed a weak-gel structure in which modified nano-SiO₂ and P(AM-AAC) form a dynamically hydrogen-bonded crosslinked network. This dynamic network effectively improves plugging performance of the drilling-fluid and markedly increases fluid viscosity. At the same time, the combined effects of enhanced liquid-phase viscosity and physical plugging effectively suppress wellbore instability caused by clay hydration and hydraulic penetration.

During drilling, fluctuations in formation pressure and the need for wellbore stability require drilling fluids to exhibit excellent rheological and plugging performance. By adjusting fluid viscosity, optimizing gelation time, and strictly controlling fluid loss, it is possible to improve hole-cleaning efficiency, stabilize the wellbore, and mitigate reservoir damage. Tao et al. (2018) used the hexenyl monomer TDED as a self-crosslinking unit and, with NaHCO₃/K₂S₂O₈ as the initiator system, carried out free-radical copolymerization with AM, AMPS, and TEAC to prepare a weak gel named PTAPT. The product forms a three-dimensional network in both fresh water and mixed brines, retains 86.5% of its apparent viscosity, and maintains more than 40% of its viscosity after aging at 180 °C for 16 h, exhibiting both shear-thinning behavior and high-temperature thickening performance. Du et al. (2020) employed an (NH₄)₂SO₄/PEG aqueous two-phase dispersion system, using AM-AA-DMC as comonomers, APS/NaHSO₃ as the initiator pair, and MBA as the crosslinker to prepare hydrophilic amphoteric crosslinked polymer microspheres. As the dosages of acrylamide and crosslinker in the polymerization system increased, the microsphere size decreased, and their thickening effect on drilling fluids became more pronounced. The polymer microspheres can swell under elevated temperatures while exerting only a minor effect on drilling fluid viscosity, exhibit good thermal stability, and provide a pronounced plugging-strengthening effect. Consequently, they are suitable for nano-to microscale synergistic plugging in highly fractured formations. Deng et al. (2018) addressed the problem of excessively short gelation times caused by thermally accelerated initiation by preparing a microencapsulated initiator in which 2,2'-azobis(2-methylpropionamide) dihydrochloride (AIBA) is coated with ABS (Fig. 23). At 80 °C, the core material is released over approximately 30 min, thereby prolonging the gelation time of polyacrylamide and satisfying the “pumpable and controllable” operational requirements of long open-hole sections in deep wells. Taken together, these studies demonstrate that the synergistic use of self-crosslinking units, amphoteric polymer microspheres, and slow-release initiators enables integrated weak-gel thickening,

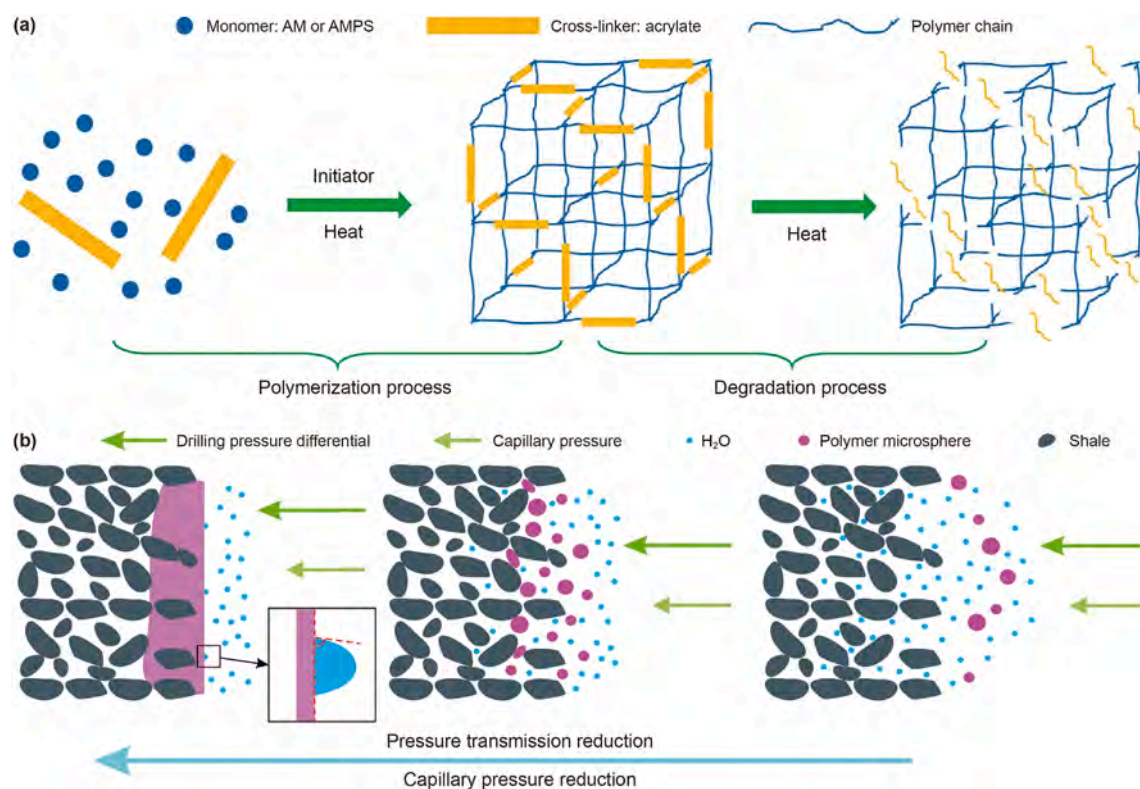


Fig. 22. Synthesis, degradation, and shale plugging mechanisms of polymer microspheres. (a) Mechanisms of synthesis, swelling, and self-degradation of DPPG. Adapted from [Zhu et al. \(2020\)](#). (b) Plugging mechanism of nano-polymer microspheres in shale pores and fractures. Adapted from [Xu et al. \(2018\)](#).

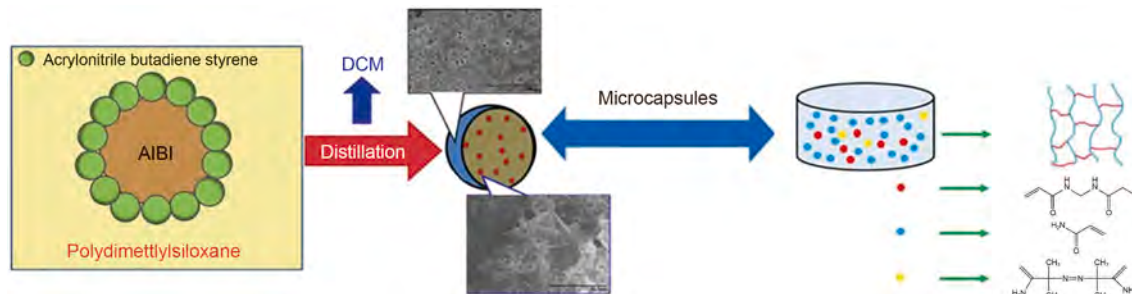


Fig. 23. Preparation mechanism of the microencapsulated initiator. Adapted with permission from [Deng et al. \(2018\)](#).

fluid-loss reduction, and plugging. This approach provides new ideas for drilling-fluid formulations suited to high-temperature, high-salinity, and highly fractured formations.

4.1.2. Applications of non-crosslinked polymer gels in drilling fluids

The functions of non-crosslinked polymer gels within a system vary significantly depending on their field of application. In drilling fluid systems, non-crosslinked polymer gels are typically used as plugging agents ([Bai et al., 2023](#)). During drilling operations, fluids readily infiltrate the formation through these pathways, inducing hydration swelling, dispersion, and even migration of clay minerals. This process alters the rock's structural integrity and mechanical properties, ultimately leading to wellbore instability ([Zhang et al., 2022](#)). The incorporation of plugging agents into drilling fluids effectively seals pores and micro-fractures, thereby reducing the rate of pressure transmission between the wellbore and the formation. This mechanism inhibits further fluid invasion, ensuring wellbore stability. Conventional rigid plugging agents are characterized by high plugging strength but limited adaptability,

whereas flexible plugging agents exhibit the opposite traits. Consequently, achieving optimal plugging performance that combines both attributes simultaneously remains a significant challenge ([An et al., 2015](#); [Liu et al., 2019](#)). Plugging agents based on self-healing nano-silica composite microgels hold promise for integrating the advantages of traditional plugging materials while overcoming their inherent limitations. [Yang et al. \(2023c\)](#) fabricated P(MPTC-co-NaSS)@SiO₂ composite microgels via a one-step inverse emulsion polymerization. In this system, nano-SiO₂ serves as rigid cores to provide high-temperature stability, while the synergy of hydrogen bonding, electrostatic attraction, and cation- π interactions between polyampholyte chains constructs a dynamic reversible network. This architecture endows the microgels with intrinsic self-healing properties and toughness, ensuring excellent pressure-bearing plugging capacity even after high-temperature aging ([Fig. 24](#)).

Lost circulation remains a critical bottleneck limiting the efficiency and safety of oil and gas exploration and development. Supramolecular gels, characterized by dynamic network

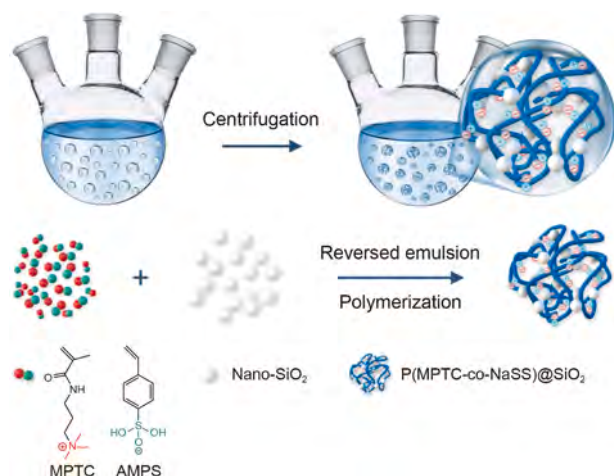


Fig. 24. Schematic illustration of the synthesis of self-healing microgels via oil-in-water (O/W) emulsion polymerization. Adapted with permission from Yang et al. (2023c).

structures formed through non-covalent interactions, exhibit superior mechanical properties, thermal stability, and plugging capabilities, making them as key materials for addressing drilling fluid loss. These gels are fabricated via micellar copolymerization, where self-assembly is driven by non-covalent interactions such as hydrophobic association and hydrogen bonding. This process generates a dense, interconnected, high-strength 3D network tailored for plugging pores and fracture leakage channels in complex formations (Yang et al., 2023b). Dai et al. (2025) synthesized a CNF/laponite-reinforced supramolecular polymer hydrogel (Fig. 25) using acrylamide (AM) and poly(vinyl alcohol) (PVA) as the primary monomers, combined with cellulose nanofibrils (CNF) and laponite as auxiliary reinforcing components. Before gelation, the system exhibits low viscosity and can undergo gelation at formation temperatures ranging from 80 to 120 °C. Furthermore, the gelation time can be precisely tuned between 30 and 120 min by adjusting the compounding ratio of CNF to laponite, thereby satisfying the operational requirements for field applications. The low viscosity and controllable gelation time of the supramolecular gel facilitate the smooth penetration of leak-stopping materials into relatively narrow cross-cracks, enabling effective filling and plugging. Furthermore, underpinned by a double network structure formed via hydrogen bonding and physical cross-linking, the gel possesses excellent elongation at break and deformability. This allows the material to undergo elastic deformation without

rupture during fracture closure, effectively preventing structural damage. Pressure-bearing plugging experiments demonstrate that the material achieves a plugging pressure capacity of up to 12.16 MPa at 120 °C. Moreover, even in high-salinity environments containing 70,000 mg/L Na⁺ and 16,000 mg/L Ca²⁺, the gel maintains a storage modulus of 6396 Pa. Notably, this corresponds to a plugging strength 1.8 times greater than that of conventional polyacrylamide (PAM) gels.

4.2. Applications of polymer gels in EOR

4.2.1. Applications of crosslinked polymer gels in EOR

The average water content in mature oil fields worldwide has exceeded 75%. This is primarily due to reservoir heterogeneity and the imbalance in the relative flow rates of the displacing and displaced fluids. High water content not only inhibits oil production but also doubles the cost of water treatment. Polymer gel technology redirects liquid flow through deep well profile modification, thereby reducing water production. It is currently the most widely used method for controlling water production and enhancing oil recovery. Polymer gels are mainly classified into in-situ crosslinked polymer gels and pre-formed gels (Xue et al., 2023). In-situ crosslinked polymer gels are prepared from polymers, crosslinkers, and additives, and are injected at low viscosity from the surface. Under the combined effects of formation temperature and ionic environment, delayed gelation occurs in high-permeability channels, forming a three-dimensional network that achieves deep plugging and flow diversion. Cui et al. (2020) developed a weak gel using ultra-high-molecular-weight HPAM and a water-soluble phenolic resin to reduce heterogeneous shear and expand the sweep volume. After large pores are plugged, oil droplets in smaller pores coalesce into larger oil slugs within narrow throats and are produced as a continuous oil stream. Wang et al. (2019a) synthesized a titanium-based nano-crosslinker (Ti-NC) via Ti⁴⁺ hydrolysis–condensation. Guar gels crosslinked with Ti-NC exhibit superior thermal stability, rheological behavior, and proppant-carrying capacity, enabling integrated fracturing and displacement in low-permeability reservoirs (Huang et al., 2020). Nanogels can adsorb at the oil–water interface, reduce interfacial tension, and modify wettability, thereby further enhancing microscopic oil displacement efficiency. Roussennac and Toschi (2010) studied the Brightwater® submicron delayed expansion gel. At 120 °C, it expanded by 6–8 times, effectively sealing the deep sealing layer and reducing water content by 18% in field tests. Yang et al. (2025) developed an AR-Gel system based on a low-hydrolysis, medium-to-high molecular weight polymer and a phenolic–aluminum citrate crosslinking framework. This system

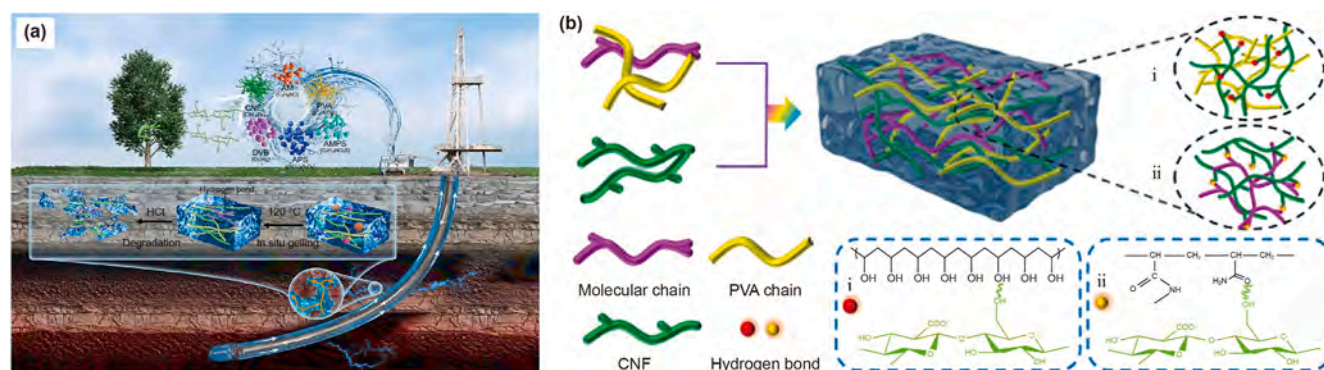


Fig. 25. CNF/laponite-reinforced supramolecular polymer gel. (a) Schematic illustration of cellulose nanofiber (CNF)-reinforced supramolecular gels for temporary fracture plugging in oil and gas reservoirs. (b) Schematic illustration of the chemical structure of the supramolecular gel. Adapted with permission from Dai et al. (2025).

achieved a plugging efficiency of 97%, suppressed CO₂ channeling by 92% during subsequent CO₂ flooding, and increased oil recovery by 34.5%, thereby realizing a synergistic “water plugging–gas control–oil enhancement” effect (Fig. 26).

Typical representatives of preformed polymer gels (PPG) include pre-crosslinked particle gels and polymer microspheres. These are prepared through free radical polymerization and crosslinking in a grinding reactor using monomers such as AM, followed by drying, grinding, and sieving to obtain particles of different sizes. They are injected on-site in slurry form on-site, allowing the particles to migrate deeply along high-permeability channels. Upon contact with formation water, the particles rapidly absorb water and expand, effectively blocking dominant channels and increasing flow resistance. Consequently, the displacement fluid is redirected toward the unimpacted oil-bearing layers, achieving well control and enhanced oil recovery. Wang et al. (2022a) reported that after 90 days of aging, the elastic modulus of weakly basic ASP pre-crosslinked gel particles increased by 8 times compared to conventional particles. The non-homogeneous composite drive recovery rate was 24.85% higher than that of the ternary composite drive, and the absolute value of the final recovery rate increased by 7.30%. Zhao et al. (2018) prepared a phenolic resin dispersed particle gel PR-DPG with excellent temperature and shear resistance. It can withstand temperatures up to 180 °C and shear rate of 10^5 s^{-1} . After entering the formation, the gel performs functions such as interception, adsorption, bridging, and blocking, thereby reducing water production in high-permeability layers and improving the formation profile. This gel has been successfully applied in the Changqing Oilfield, demonstrating a validity period of over 500 days. The particle size of preformed crosslinked gel affects their migration behavior. Nanometer-sized phenolic crosslinked polymer gels can

accumulate in large pore spaces or directly seal pore throats (Fig. 27). DPG can achieve deep profile control by utilizing the elastic deformation and migration properties of reservoir porous media. Liu et al. (2016a) prepared gel particles using resorcinol-formaldehyde as the crosslinking agent and oxalic acid-chloride ammonium as the stabilizer. These gel particles form a tight sealing layer at 200 °C, achieving a sealing rate of 98% in sandstone simulation experiments (Liu et al., 2016a). Wang et al. (2019b) used an organic crosslinking agent, *N,N*-methylene-bis-acrylamide (MBA), and a metal crosslinking agent, zirconium acetate (Zr), as a dual crosslinking system, with ammonium persulfate (KPS) as the initiator. Using reverse emulsion copolymerization, they prepared

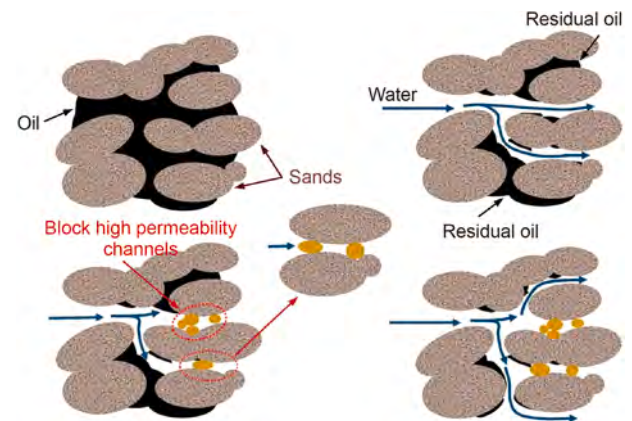


Fig. 27. Profile control mechanism and microstructure of DPGs. Adapted with permission from Liu et al. (2016a).

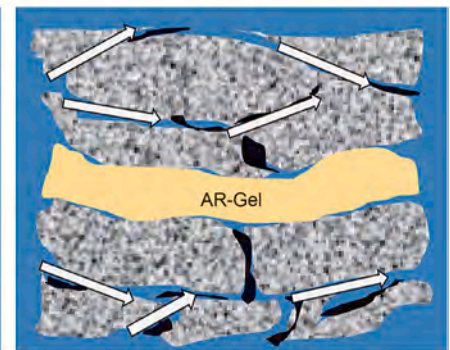
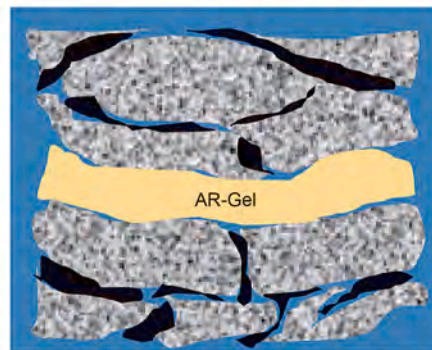
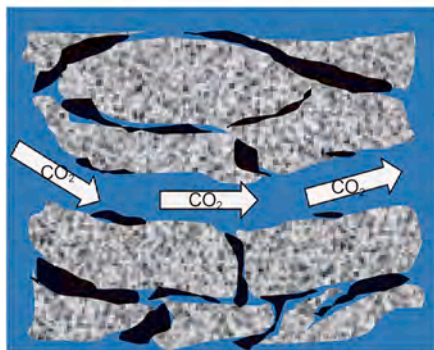
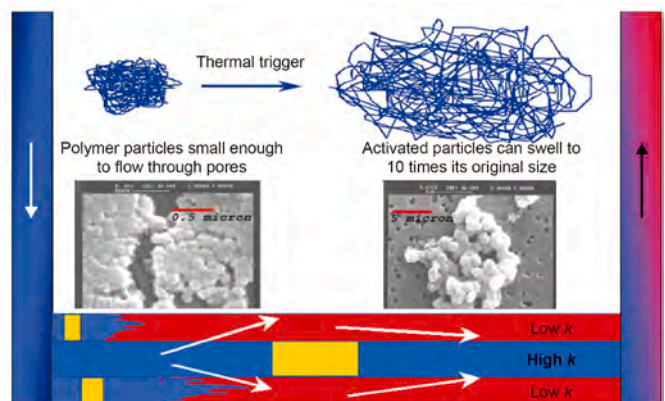
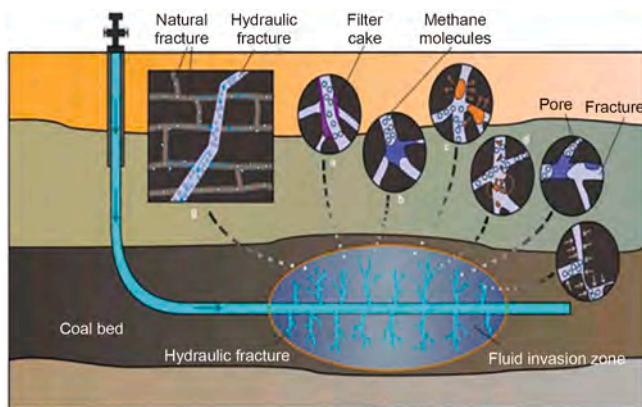


Fig. 26. Schematic diagram of the working principle of in-situ crosslinked polymer gels. (a) Fracturing stimulation and fracturing fluid damage. Adapted from Han et al. (2022). (b) Water displacement mechanism of Brightwater. Adapted with permission from Roussennac and Toschi (2010). (c) Mechanisms of gas channeling control and enhanced oil recovery using AR-Gel. Adapted from Yang et al. (2025).

a special double-crosslinked structure with significantly improved thermal stability at 150 °C. Core flooding experiments showed that even after aging for 3 months at 150 °C, the nanopolymer gel particles could still effectively block the porous medium, increasing the oil recovery rate by 13%. This demonstrates the potential of the developed gel for long-term water control and oil production enhancement in high-temperature, high-salinity reservoirs.

4.2.2. Applications of non-crosslinked polymer gels in EOR

As oilfield development enters the high water-cut stage, characterized by exacerbated reservoir heterogeneity, enlarged seepage channels, and complex remaining oil distribution, conventional water flooding or polymer flooding methods struggle to achieve effective sweep efficiency. Chemically crosslinked polymer gels (such as phenolic gels and chromium ion crosslinked systems) are commonly used for water shut-off and profile control. However, these gels suffer from issues such as the high toxicity of crosslinkers, poor system controllability, and irreversibility (Afolabi et al., 2019). To address these limitations, researchers have proposed substituting traditional crosslinked systems with non-crosslinked or physically associated polymer gels. These materials form three-dimensional networks through hydrophobic associations, hydrogen bonding, or electrostatic interactions. Consequently, they exhibit viscoelasticity without the need for chemical crosslinkers, thereby enhancing the mobility ratio and oil displacement efficiency of the injected system. Conventional gels are prone to mechanical degradation within the formation, leading to a significant reduction in viscosity and resulting in poor plugging capability in high-permeability channels. Supramolecular gels based on non-covalent interactions demonstrate good application potential in profile control, owing to their unique

performance advantages (Yi et al., 2022). The network architecture of non-crosslinked polymer gels is primarily governed by inter-molecular physical associations. A representative class is hydrophobically associating polymers. By incorporating hydrophobic moieties onto the polymer backbone or side chains, these materials create transient association points, enabling the system to self-assemble into a three-dimensional network in solution. These association points can dissociate and reassociate under changes in external shear, temperature, or salinity, exhibiting excellent reversibility and self-healing properties. Abe et al. (2024) developed a weak gel system based on sulfonated polyacrylamide (SPAM) (Fig. 28). This system initially exists as a low-viscosity solution, facilitating injection into the reservoir. However, under high-temperature, high-salinity formation conditions, it gradually evolves into a reversible associated network. Experimental results demonstrate that this system achieves in-depth profile control and selective water plugging in sandstone cores, exhibiting excellent controllability and reproducibility.

5. Prospects of polymer gels in drilling and production

Polymer gels are essential functional materials in oil and gas drilling and production. Their future development will focus on meeting the extreme conditions encountered in complex deep geological environments. As the proportion of deep wells, ultra-deep wells, and high-temperature, high-salinity reservoirs continues to increase, gel systems face critical challenges such as insufficient temperature resistance, poor long-term stability, weak anti-pollution capabilities, and limited environmental adaptability. Crosslinked gels must evolve from “passive leak sealing” to “intelligent rheology-active pressure control” through the molecular design of crosslinking agents, optimization of network

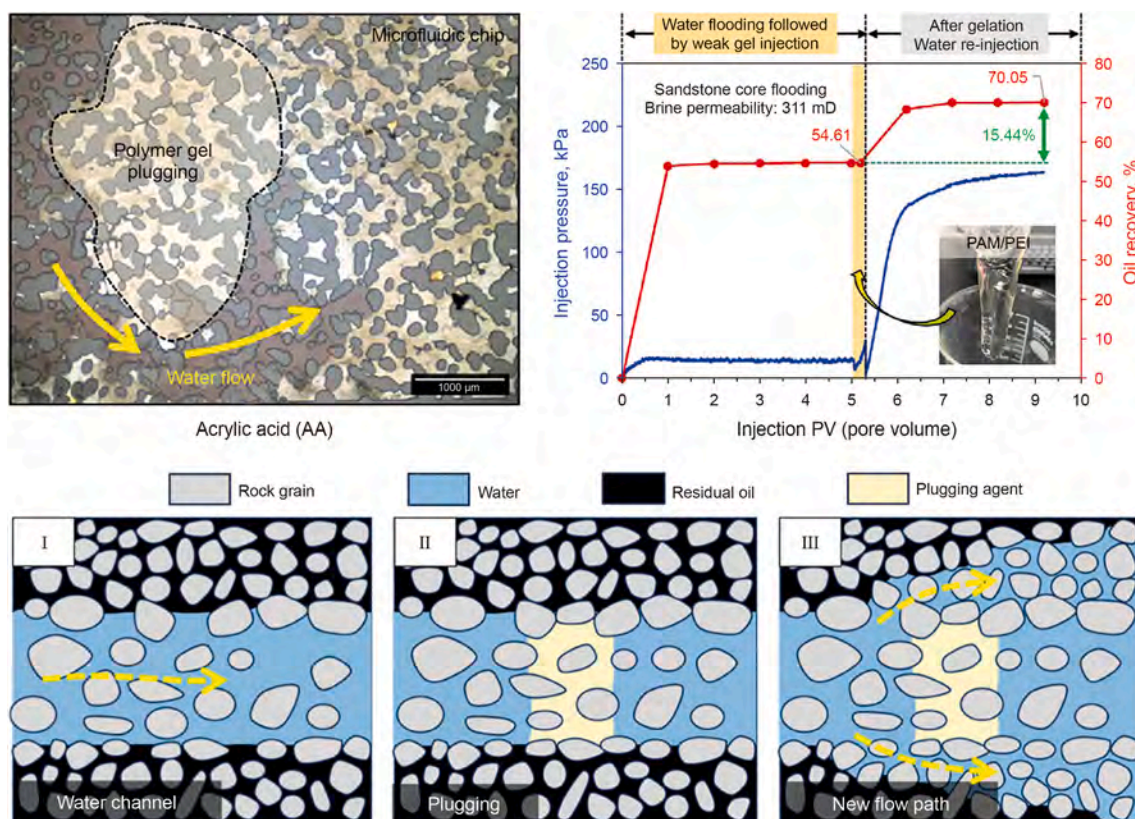


Fig. 28. Schematic of the weak gel system for in-depth profile control and selective water blocking in sandstone formations. Adapted from Abe et al. (2024).

topology, and multifunctional synergy. Non-cross-linked gels rely on the reversible characteristics of physical interactions, focusing on temperature-responsive regulation, strengthening anti-pollution mechanisms, and iterative molecular structure, to construct an “injected low viscosity–in-situ high viscosity” intelligent response system. This article systematically explores the future development directions of both crosslinked and non-crosslinked polymer gels in the two major fields of drilling fluids and enhanced oil recovery, providing forward-looking guidance for the next generation design of gel material design.

5.1. Prospects of polymer gels in drilling fluids

5.1.1. Prospects of crosslinked polymer gels in drilling fluids

Future advancements in crosslinked polymer gels will proceed along two primary trajectories. The first involves the molecular design of crosslinkers, incorporating thermally stable and salt-resistant backbones alongside hydrophobic micro-domains to reduce hydration sensitivity and enhance long-term plugging reliability under high-salinity, high-temperature conditions. The second entails the synergistic optimization of crosslinking networks and molecular weights to construct a gradient structure combining rigidity and flexibility. This approach realizes the unification of low-shear cuttings transport, high-shear drag reduction, and pressure-bearing plugging. By leveraging multifunctional crosslinking and the regulation of topological structures, gels will transition from traditional “passive plugging” to a new era of “intelligent rheology–active pressure control”, providing pivotal support for safe and efficient drilling in complex formations.

- (1) Design crosslinking agents to enhance temperature resistance, salt tolerance, and plugging performance

Polymer gels are widely used for plugging fractures, enhancing wellbore stability, and inhibiting water hydration. However, in practical applications, traditional polymer gels often encounter problems such as limited plugging durability and inadequate water hydration performance, which compromise their long-term stability and adaptability in complex environments. The design of the crosslinking structure is crucial for the plugging effectiveness of the gel. By increasing the crosslinking density or selecting crosslinking agents with higher crosslinking efficiency, the mechanical strength and three-dimensional network of the polymer gel can be enhanced. This improvement increases the stability of the gel in the pore space and prevents the rapid loss of its plugging capacity. In high-temperature, high-salinity environments, polymer gels often fail due to the degradation or dissolution of crosslinking agents. Therefore, selecting crosslinking agents that are resistant to high temperatures and high salinity is crucial for improving the sealing performance. Metal-organic mixed crosslinking agents, such as chromium lactate and phenolic resin, have excellent high-temperature resistance and can effectively improve the thermal stability and salt tolerance of the gel. Crosslinking agents containing functional groups, such as phenolic and aldehyde, can react with the polymer to form a strong three-dimensional crosslinking network, thereby enhancing the plugging effectiveness of the gel.

- (2) Optimize the crosslinking structure and molecular weight of polymer gels to enhance shear stability

The viscosity stability of polymer gels in drilling fluids is crucial for fluid flowability, wellbore stability, and the carrying capacity of suspended solids in the mud. Crosslinked polymer gels, as an important rheological control material, can significantly improve

their rheological properties by optimizing their structure and cross-linking methods, meeting the drilling requirements in extreme environments such as high temperature and high pressure. By adjusting the cross-linking density and selecting appropriate cross-linking agents, the three-dimensional network of the gel can be improved, thereby enhancing its viscosity and stability under different shear conditions. Changes in cross-linking density can significantly affect the rheological properties of the gel. In drilling fluids, a lower cross-linking density can increase the freedom of polymer molecules, thereby improving fluid flowability. However, an excessively low cross-linking density may result in insufficient gel strength and an inability to maintain the sealing effect. Therefore, when optimizing rheological properties, it is necessary to find the optimal cross-linking density that maintains appropriate fluid flowability without compromising sealing ability. By introducing structural units such as aromatic and alkyl groups, the rigidity and flexibility of the polymer can be controlled to regulate its fluidity. Modifying the polymer with acrylate or hydrophilic monomers can enhance its fluidity while maintaining stability under high-temperature and high-salinity conditions.

5.1.2. Prospects of non-crosslinked polymer gels in drilling fluids

Polymer gels are commonly used materials in oil and gas drilling and production engineering, and have extensive applications in the field of drilling fluids. With the development of deep and ultra-deep oil and gas reservoirs, the static temperature at the bottom of the well is rising, leading to increasingly stringent requirements for the temperature resistance of gel systems. Currently, the primary focus in the development and improvement of non-crosslinked polymer gels is on enhancing temperature resistance and improving anti-pollution capabilities.

- (1) Optimize the molecular structure design to improve temperature resistance

The thermal resistance of polymer gels is a fundamental and critical performance indicator. With the large-scale development of deep and ultra-deep wells the static temperature at the well bottom continues to rise, imposing increasingly stringent thermal resistance requirements on gel systems. The main solutions to this problem include three aspects. First, selecting thermally resistant monomers or incorporating rigid segments (such as aromatic rings or cyclic structures) into the main chain or side chain of the polymer to enhance the molecular thermal stability. Second, introducing temperature-responsive units (such as thermosensitive copolymer monomers or zwitterionic monomers) to induce structural reorganization of the gel at high temperatures, thereby strengthening the network. Third, enhancing the physical binding structure through nanomaterials, fillers or coordination-type cross-linking to resist thermal degradation. Therefore, future research should focus on the dual coupling of “thermal response + self-healing”, achieving adaptive repair in the wellbore through temperature-induced inter-chain reassembly, and strengthening the evaluation of long-term high-temperature aging and oxidation stability.

- (2) Optimize the iterative molecular structure triggering mechanism to enhance the anti-pollution ability

During the circulation process, drilling fluid continuously encounters various contaminants such as oil phases, organic acids, shale debris, and water with high mineral content. These invading substances can disrupt polymer associations through mechanisms such as hydrogen bond shielding, competitive

adsorption, charge neutralization, or physical occupation. This disruption leads to network collapse, a sudden drop in viscosity, sealing failure, and an increased risk of irreversible blockage of fine pores. Enhancing the gel's anti-pollution capability requires a coordinated approach at the molecular, mesoscopic, and engineering levels. At the molecular level, introducing amphoteric ions or hydrophobic-hydrophilic block structures, along with charge compensation and solvent shielding, can mitigate the effects of high concentration of salts and organic molecules, thereby reducing irreversible adsorption. At the mesoscopic level, precise control of particle size distribution and pore structure enables gel particles to “bridge, deform, and plug” at the pore throats rather than invading deeper, which reduces residual damage. In engineering applications, gel degradation or dissolution can be achieved through temperature, pH, or chelation triggers, allowing permeability recovery after the plugging task is completed, thus satisfying both environmental protection and production capacity requirements.

5.2. Prospects of polymer gels in EOR

5.2.1. Prospects of crosslinked polymer gels in EOR

At present, improving the technology for enhancing oil recovery has become a key factor for the sustainable development of the petroleum industry. Among various EOR technologies, crosslinked polymer gels have attracted much attention due to their ability to effectively regulate reservoir permeability, control water flow direction, and enhance sweep efficiency. Especially in harsh oil reservoirs with severe heterogeneity and high temperature and high salinity, the design and application of high-performance gel systems have become a research hotspot.

- (1) Optimize the design of crosslinking monomers and molecules to enhance stability in high-temperature and high-salinity conditions

Traditional polymer gels often encounter problems such as unstable structure and rapid degradation, resulting in poor plugging effectiveness and subsequently affecting the recovery efficiency. To improve the long-term stability and adaptability of polymer gels, optimization must be carried out in the selection of materials and cross-linking design. The combination of phenol/formaldehyde with appropriate polymers can enhance the heat resistance of the gel system. By introducing resorcinol and formaldehyde into the polymer gel system, phenolic resin can be formed, which also improves the temperature resistance of the gel system. The influence of high-salinity conditions on the performance of polymer gels mainly manifests in the gel structure. Resorcinol, HMTA, and oxalic acid can be used as modifiers to improve the salt resistance of polymer gels. Although metal ion-crosslinked gels are prone to shrinkage and dehydration due to high-temperature hydrolysis and exhibit low stability compared to organic systems, pre-inserting metal ions into the polymer chain can significantly enhance the salt resistance of the organic cross-linked network.

- (2) Develop environmentally friendly polymer gels using preferred bio-based degradable materials

Traditional polymer gels tend to remain in the underground for a long time and are difficult to degrade, posing potential threats to groundwater safety and the ecological environment. Therefore, it is imperative to promote the green transformation of oilfield operations. Natural biobased polymers possess the characteristics of being renewable, low toxic, and degradable,

making them the core candidates for environmentally friendly gels. Molecular chains of chitosan, alginate, gelatin, and cellulose contain a large number of the hydroxyl, carboxyl, or amino groups, which can form physical cross-links under reservoir conditions. With appropriate chemical modification (quaternization, carboxymethylation, or esterification), their thermal and salt resistance can be significantly improved, and they can remain stable in acidic and alkaline environments. The corresponding degradable cross-linking agents are equally crucial. Esters, aldehydes, or natural polysaccharide-derived cross-linking agents can be hydrolyzed or enzymatically degraded into non-toxic small molecules after use. Plant-derived polyphenols/acids such as resorcinol and oxalic acid can undergo Schiff base or esterification reactions with the polymer to form a moderately strong network. Once the plugging is completed, they can rapidly degrade, effectively avoiding the persistent pollution caused by traditional organic chromium or phenolic cross-linking agents.

5.2.2. Prospects of non-crosslinked polymer gels in EOR

As the recovery rate of conventional oil reservoirs approaches its limit, enhancing recovery has become a critical focus in oil and gas development. Although traditional crosslinked polymer gels have been widely used to seal high-permeability channels and improve fluid distribution, they often suffer from chain degradation, precipitation, and structural collapse in high-temperature, high-salinity, and highly mineralized water environments. These issues affect their injectability and sealing efficiency. In recent years, non-crosslinked polymer gels have shown potential in maintaining injectability while improving thermal and salt stability. Based on this, the potential applications of non-crosslinked polymer gels are envisioned in terms of improving the performance of the gel materials and enhancing their adaptability to reservoir environments.

- (1) Optimize material properties to enhance the reversibility of the gel network

Replacing traditional chemical cross-linking with reversible physical networks is the core design concept of the new generation of deep stimulation gels. By precisely incorporating hydrophobic associations, hydrogen bond donors/receptors, or ionic coordination groups into the main chain, trigger signals such as formation temperature, mineralization degree, or shear force can be utilized to achieve reversible phase transformations—from low viscosity during injection to high viscosity during in-situ formation. The association units dissociate under low shear, resulting in low system viscosity, which ensures deep migration. After entering the high-permeability zone, the shielding of salt ions or an increase in the concentration of hydrophobic microregions prompts reversible inter-chain cross-linking, instantly forming a high-viscosity elastic network that effectively blocks water flow channels and enhances the pressure gradient, forcing subsequent fluids to divert to the unaffected areas. Based on copolymerization modification with hydrophobic amines and sulfonic acid groups, nano-SiO₂ or laponite is further introduced. Through the dual mechanisms of “physical hooking” and “interfacial adsorption”, the thermal motion of chain segments is inhibited, increasing the heat resistance of the network and extending the plugging effectiveness period. By integrating methods such as the synergy of hydrophobic clusters and hydrophilic chain segments, along with nano-composites, non-crosslinked physical gels can achieve deep injection, stable plugging, and long-lasting stimulation under varying permeability, temperature, and water quality conditions. This provides a reliable and environmentally friendly material solution for further

enhancing recovery rates during the high water cut stage of mature oil fields.

- (2) Introduce special functional groups to enhance the adaptability of the gel

At present, the weakly crosslinked gel systems remain dominant at high temperatures ($>180\text{ }^{\circ}\text{C}$). However, once non-crosslinked networks overcome temperature imitation, they hold significant potential for applications in deep wells, hot dry rocks, and ultra-deep oil and gas reservoirs. In complex reservoir environments, for non-crosslinked polymer gels to effectively increase on-site production, they must simultaneously possess environmental adaptability and a sustainable lifecycle. High temperature and high salt resistance remain the key technical bottlenecks. Incorporating sulfonic acid groups, cyclic structures, or rigid aromatic heterocycles into the polymer backbone can inhibit the thermal motion of chain segments and reduce ionic shielding effects. Coupled with physical barriers of nano oxides or clays, the thermal decomposition temperature and salt tolerance range can be further enhanced.

6. Conclusions

Crosslinked polymer gels, characterized by their designable three-dimensional network and controllable performance, have become essential materials for plugging and profile control in oil and gas fields. Alongside non-crosslinked systems, which rely on chain entanglement and reversible physical associations, they form functional materials that achieve “strong near-well plugging and deep flowability”. Crosslinked polymer gels form irreversible frameworks at $200\text{ }^{\circ}\text{C}$ and in saturated saltwater through organic-metallic complex crosslinkers such as chromium lactate, phenolic resin, and resorcinol-formaldehyde. The addition of SiO_2 nanoparticles, graphene oxide, or smart responsive monomers synergistically enhances their thermal stability, self-healing ability, and mechanical strength. Conversely, non-crosslinked polymer gels maintain low viscosity and ease of injection under low shear but instantly increase viscosity under high shear or high-salinity conditions, meeting the needs of deep fluid flow diversion. These two types of materials complement each other functionally, providing an integrated “plugging, profile control, and displacement” solution for fractured, high-permeability, and heterogeneous reservoirs. Facing deep and ultra-deep wells and unconventional oil and gas development, crosslinked gels will evolve along the paths of intelligence, greenness, and high performance. By introducing multiple environmental response units—such as temperature, pH, and ionic strength—self-adaptive reversible networks can be constructed to achieve in-situ dynamic regulation of plugging strength and rheological behavior. The synergy of nano-hybridization and molecular self-assembly significantly enhances interfacial stability and resistance to shear fatigue, reducing performance degradation under cyclic loading. Meanwhile, using natural polymers such as chitosan, cellulose, and alginate as frameworks, combined with degradable ester groups, Schiff bases, or dynamic covalent crosslinks, allows gels to be triggered to degrade by weak acids, enzymes, or microorganisms after completing their functions. This restores permeability and meets the needs of green drilling and carbon emission reduction. In summary, future polymer gels will integrate the threefold characteristics of high-strength networks, intelligent responsiveness, and green biodegradability. This integration will establish an environmentally friendly, adaptive and recyclable gel technology system, providing robust material and engineering

support for the efficient, low-carbon, and sustainable development of oil and gas resources.

CRedit authorship contribution statement

Jing-Bin Yang: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ying-Rui Bai:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jin-Sheng Sun:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Bauyrzhan Sarsenbekuly:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kai-He Lv:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jia-Kai Chen:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation. **Qing-Yang Feng:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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