

Review Paper

Advanced fluid-loss control in drilling fluids: A review on rationally designed temperature- and salt-tolerant synthetic polymers

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ABSTRACT

To meet the ever-increasing energy demands, oil and gas exploration is progressively extending into deep formations with high temperatures and high salinity, presenting new challenges for the performance improvement of fluid-loss additives in drilling fluids. From the perspective of controllable polymer structure design, this review systematically elucidates the intrinsic relationship and development trends between polymer molecular structures and their fluid-loss control. First, the adverse effects of high temperature and high salinity environments on bentonite and polymers are elucidated, revealing the fundamental causes of uncontrolled filtrate loss under extreme conditions. Subsequently, focusing on four major research trends—optimization of polymerization methods, design of polymer monomers, construction of ultra-stable structures, and controlled incorporation of inorganic materials—the fundamental principles for precise molecular construction and performance enhancement are thoroughly discussed. In addition, the environmental and economic impacts of these fluid-loss additives are discussed in detail, including monomer selection, synthesis methods, and subsequent treatment processes. Finally, this review summarizes the key challenges associated with high-temperature and high-salinity conditions and outlines specific future research directions for developing highly efficient fluid-loss reducers. In summary, this review provides a comprehensive overview of recent advances in synthetic polymer-based fluid-loss additives and offers guidance for developing multidimensional, highly efficient fluid-loss additives.

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1. Introduction

After centuries of extensive extraction, the easily exploitable shallow oil and gas resources are becoming increasingly depleted. To meet the continuously growing demand for hydrocarbons driven by global economic development, exploration and production activities are progressively shifting toward deeper geological formations characterized by more complex conditions (Lei et al., 2025; Sun et al., 2024). In drilling operations, drilling fluid is regarded as the “blood of drilling”, performing critical

functions including suspending and transporting cuttings, cleaning the borehole, cooling and lubricating the drill bit and tools, controlling wellbore pressure to prevent any intrusion of formation fluids into the wellbore, maintaining borehole stability, and transmitting geological information to assist drilling decisions. These functions ensure the safety and efficiency of drilling operations (Li et al., 2025c; Meng et al., 2025; Zuo et al., 2025). At present, the extreme conditions of high temperature, high pressure, and high salinity encountered in complex deep formations impose increasingly severe technical challenges on drilling fluid additives.

Fluid-loss reducers are among the most important fundamental additives in drilling fluids. By optimizing their interactions with clay particles, fluid-loss reducers lower filter-cake permeability and promote the formation of thin and dense filter cakes during drilling, thereby significantly reducing fluid loss.

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Nomenclature			
A-151	Triethoxyvinylsilane	M_n	Number-average molecular weight
AA	Acrylic acid	MPC	2-Methylpropenoyethyl phosphocholine
AAD	Amphoteric polymer (AM/AMPS/DMDAAC)	M_w	Weight-average molecular weight
ACMO	<i>N</i> -Acryloylmorpholine	Na-BT	Sodium bentonite
AD	Anionic polymer (AM/AMPS)	NIPAM	<i>N</i> -Isopropylacrylamide
AFM	Atomic force microscopy	NVCL	<i>N</i> -Vinylcaprolactam
AI	Artificial intelligence	NVP	<i>N</i> -Vinylpyrrolidone
AM	Acrylamide	OP-10	Octylphenol polyoxyethylene ether-10
AMPS	2-Acrylamido-2-methyl-propanesulfonic acid	OSMP	Sulfomethylated phenolic resin
APE	Pentaerythritol triallyl ether	PAAN-SiO ₂	Acrylamide/AMPS/NVP copolymer grafted on silica
APEG	Allyl polyoxyethylene ether	PDASN	DMAM/AMPS/NVCL/SVM copolymer
API	American Petroleum Institute	POSS	Polyhedral oligomeric silsesquioxane
APTES	3-Aminopropyltriethoxysilane	RAFT	Reversible addition-fragmentation chain transfer polymerization
AV	Apparent viscosity	R_g	Radius of gyration
CBMA	Carboxyl betaine methacrylate	R_h	Hydrodynamic radius
CSMP	Commercial sulfomethylated phenolic resin	SAS	Sodium allylsulfonate
DAC	Diallyl dimethyl ammonium chloride	SBAA	Thiamine acrylamide
DFT	Density functional theory	SBMA	Sulfobetaine methacrylate
DMAA	<i>N,N</i> -Dimethylacrylamide	SBVI	Sulfobetaine vinyl imidazole
DMC	Methacryloyloxyethyl trimethyl ammonium chloride	SDS	Sodium dodecyl sulfate
DMDAAC	Dimethyldiallyl ammonium chloride	SI-ATRP	Surface-initiated atom transfer radical polymerization
DVB	Divinylbenzene	SSS	Sodium <i>p</i> -styrene sulfonate
ESP	Electrostatic potential	ST	Styrene
FL _{API}	API fluid loss	SVM	Sodium (4-vinyl phenyl) methanesulfonate
FL _{HTHP}	High-temperature, high-pressure fluid loss	SVS	Sodium vinyl sulfonate
GO	Graphene oxide	TAC	Trimethylallyl ammonium chloride
HTHP	High temperature, high pressure	TEM	Transmission electron microscopy
IA	Itaconic acid	TiO ₂	Titanium dioxide
KH570	Methacryloxy propyl trimethoxyl silane	TEG	Isopentenyl polyoxyethylene ether
KMB703	3-Chloropropyltriethoxysilane	TPHs	Total petroleum hydrocarbons
LAP	Laponite	VBIPS	3-(1-(4-vinylbenzyl)-1H-imidazole-3-ium-3-yl) propane-1-sulfonate
LDH	Layered double hydroxide	VeiBr	Vinyl ethyl imidazolium bromide
LMA	Lauryl methacrylate	VTEO	Vinyltriethoxysilane
MAH	Maleic anhydride	WBDFs	Water-based drilling fluids
MBA	<i>N,N</i> -Methylene diacrylamide	XPS	X-ray photoelectron spectroscopy

Environmentally friendly, bio-based materials such as xanthan gum, starch, and cellulose have been found to be useable as effective fluid-loss reducers (Guo et al., 2024b; Noor et al., 2025; Saadi et al., 2025). Long et al. (2022) modified plant press residue with sodium hydroxide and chloroacetic acid to produce an eco-friendly fluid-loss reducer, which exhibited an American Petroleum Institute (API) fluid loss of only 5 mL after hot-rolling in a saturated salt-based slurry at 120 °C. Zhong et al. (2021) synthesized starch nanospheres via emulsion polymerization, which exhibited superior filtrate control performance compared with commercial starches after thermal rolling at 150 °C. However, the application of bio-based materials is still constrained by their susceptibility to enzymatic hydrolysis under high-temperature conditions and their relatively poor salt resistance.

Synthetic polymers enable targeted molecular structure design through the regulation of monomer types and proportions, thereby satisfying the stringent requirements for fluid-loss control under high-temperature and high-salinity conditions. At present, common strategies for improving the thermal resistance and salt tolerance of such polymer fluid-loss reducers include introducing strongly hydrated groups such as sulfonic acid groups to enhance salt resistance, incorporating ring-shaped rigid structural units such as benzene rings to improve thermal stability (Yang et al.,

2024d), doping with nanoparticles to reinforce high-temperature performance (Alkalbani and Chala, 2024; Tian et al., 2025), and exploiting mechanisms such as hydrophobic association, cross-linking stabilization, and anti-polyelectrolyte effects to enhance the overall tolerance of the polymer under adverse conditions. Yang et al. (2024c) prepared zwitterionic brush-like polymer/layered double hydroxide (LDH) composites that fully exploit the advantages of zwitterions, inorganic materials, and comb-like structures. At 240 °C and 15 wt% NaCl, the base slurry containing the synthetic polymer exhibited an API fluid loss (FL_{API}) of only 6.3 mL. Compared with other fluid-loss reducers, synthetic polymers exhibit superior filtrate control performance owing to their highly tunable molecular structures and excellent tolerance to harsh environments.

Overall, synthetic polymers have become a major research focus for drilling fluid additives used under extreme conditions because of their highly tunable molecular structures. In recent years, several reviews have summarized recent advances in synthetic polymers, including their preparation, classification, and applications in drilling fluids (Davoodi et al., 2023, 2024a; Gautam et al., 2022). Dedicated reviews have also focused on synthetic polymer-based fluid-loss reducers. For example, Balaga and Kulkarni (2022) summarized the fluid-loss reduction

performance of synthetic polymers at high-temperatures. Li et al. (2024a) reviewed research progress on natural and synthetic polymers as fluid-loss reducers. However, these reviews primarily focus on the performance advantages imparted by synthetic polymers, while offering limited in-depth analysis of the recent advances in the fine structure design of synthetic polymer-based fluid-loss additives. Consequently, they fail to provide systematic guidance for the molecular design of synthetic polymers. The unique contribution of this review lies in systematically establishing the relationship between the tailored structural design of synthetic polymers and their enhanced thermal resistance and salt tolerance. By integrating recent advances in synthesis, molecular design, structural stabilization, and composite modification, this review analyzes the intrinsic relationship between optimization strategies and performance enhancement across the full design pathway from preparation strategies and monomer selection to structural reinforcement for high-performance synthetic polymer-based fluid-loss reducers.

This review systematically summarizes recent advances in synthetic polymers for filtrate reducer from the perspective of “controllable structure–enhanced performance”. First, the effects of high-temperature and high-salt environments on bentonite and polymers are analyzed to clarify the primary causes of increased filtrate loss. Subsequently, recent progress in synthetic polymer-based filtrate loss control agents is summarized into the following four core directions: optimization of the synthesis methods and experimental procedures to explore the performance potential of different monomer combinations, independent design and synthesis of high-performance monomers to expand the range of the polymerization units, enhancement of polymer structural stability to improve the overall structural tolerance, and construction of inorganic material–polymer composite materials to improve performance through multicomponent synergistic effects (Fig. 1). This framework systematically elucidates how precisely engineered polymer structures enhance filtrate control performance under extreme conditions. In addition, environmental and economic issues associated with synthetic polymer-based filtrate control agents were explored. Finally, considering the current

trend of oil and gas exploration toward deep and complex formations, this review identifies the key challenges facing fluid-loss reducers and the outlines future research directions. This review is expected to provide effective guidance for the design and synthesis of high-performance fluid-loss reducers with high-temperature resistance and salt tolerance.

2. Effects of harsh conditions on filtrate loss

As oil and gas exploration continues to extend into deep and ultra-deep formations, drilling environments are increasingly characterized by high temperature and high salinity, which imposes more stringent requirements on the development of high-performance fluid-loss reducers. Clarifying the intrinsic mechanisms underlying the aggravation of fluid loss under harsh environments is essential for further improving fluid-loss control. Therefore, this section systematically elucidates the adverse effects of high-temperature and high-salinity conditions on polymers and bentonite.

Elevated temperature generally increases drilling fluid loss, primarily by adversely affecting the physicochemical properties of clay minerals and polymers, as well as their interactions. As temperature increases, the thermal motion of bentonite particles and water molecules becomes intensified, disrupting the hydration layer on the bentonite surface and causing the aggregation of clay particles. High temperatures also reduce the surface activity of clay minerals and weaken the strength of the clay network structure, leading to degraded filter cake quality and increased fluid loss. Meanwhile, elevated temperatures intensify the thermal motion of polymer molecular chains, inducing main chain breakage and functional group detachment, thereby significantly degrading polymer performance. Furthermore, high temperatures will also enhance the desorption tendency of polymers and weaken the electrostatic adsorption and hydrogen bond interaction between polymers and bentonite particles, resulting in a decrease in the adsorption capacity of polymers on the clay surface and fundamentally reducing their fluid-loss control.

The influence of salt contamination on filtrate loss can be analyzed from the perspectives of bentonite and polymers. In freshwater environments, bentonite rapidly undergoes hydration through crystalline swelling and osmotic swelling mechanisms (Aghdam et al., 2020), leading to a much larger specific surface area and greater dispersion than in the dry state (Fig. 2(a)). The plate-like structure of sodium bentonite (Na-BT) forms a basal surface with permanent negative charge (yellow region) and an edge surface with variable positive charge (blue region) (Fig. 2(b)). Bentonite nanoparticles can exhibit exfoliated dispersion forms or engage in interactions such as face-to-face, edge-to-edge, and edge-to-face associations (Fig. 2(b)). In freshwater environments, bentonite nanosheets tend to adopt a dispersed structure or form an open three-dimensional “house of cards” network through “edge-face” structure between positively charged edges and negatively charged surfaces, which fundamentally contributes to the high viscosity, high yield stress, and thixotropy of the base fluid. However, extraneous cationic contamination compresses the electrical double layer of bentonite particles. This promotes a shift in interparticle associations toward lower-energy “edge-face” structures and the lowest-energy “face-face” parallel stacking, resulting in a loose filter cake structure and substantially increased fluid loss of drilling fluid. Notably, although the mechanisms of action of polyvalent and monovalent salts on bentonite are similar, polyvalent cations induce more severe fluid loss because of their higher charge density and stronger affinity for clay crystal layers. Li et al. (2020a) investigated the effects of cations with different valence states on the dispersion state of base mud. The results

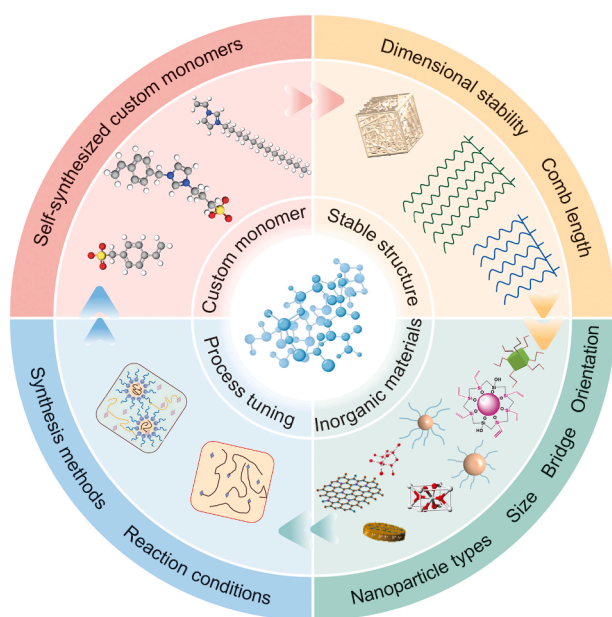


Fig. 1. The construction strategy of synthetic polymers as highly efficient fluid-loss reducers.

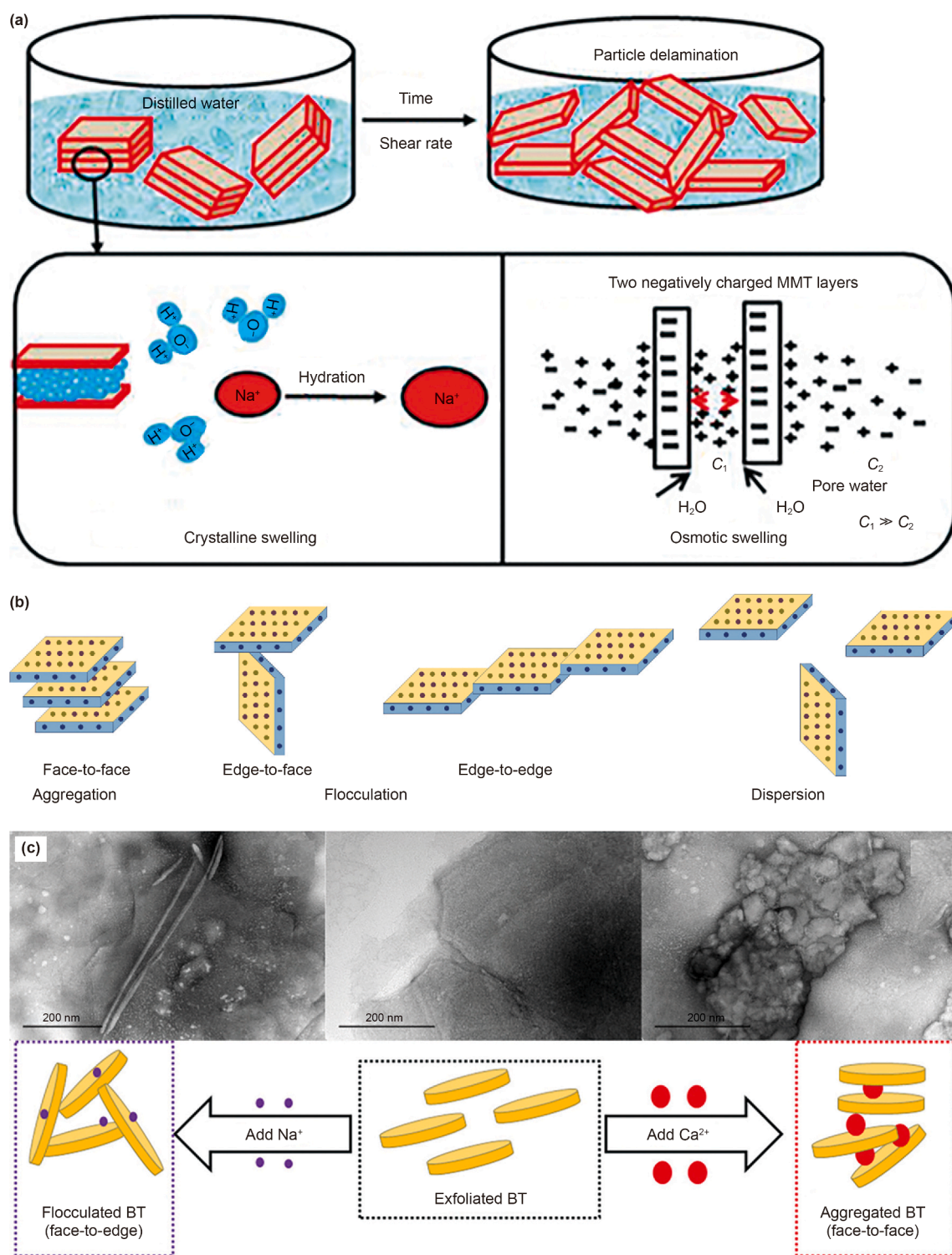


Fig. 2. (a) Hydration and swelling mechanism of bentonite. Adapted with permission from Aghdam et al. (2020). (b) Several states of bentonite nanoparticles. Adapted with permission from Li et al. (2021). (c) Transmission electron microscopy images and schematic diagrams of bentonite-based slurry under varying salinity conditions: freshwater (center), 4 wt% NaCl solution (left), and 4 wt% CaCl_2 solution (right). Adapted with permission from Li et al. (2020a).

indicate that bentonite particles exhibit a partial “edge-to-face” connection pattern at a NaCl addition of 4 wt%. Under the same CaCl_2 dosage conditions, bentonite particles further shifted toward a “face-to-face” linkage state, demonstrating pronounced flocculation and agglomeration phenomena (Fig. 2(c)). This phenomenon indicates that divalent salts exert a stronger influence on

bentonite dispersion than monovalent salts, thereby accelerating fluid loss during drilling operations. Therefore, how to effectively suppress the negative impact of high-valent salts on fluid-loss control remains an important challenge in drilling fluid treatment.

The addition of salt also affects the conformation of the polymer and its interaction with bentonite. The salting-out effect

competes with polymers for hydration water molecules, thereby reducing polymer hydration capacity and solubility. In addition, the electrostatic shielding effect induced by salt ions causes the polymer chains to change from an extended state to a coiled conformation (Fig. 3(a)), which substantially weakens the effectiveness of the functional groups in reducing filtrate loss. He et al. (2020) synthesized the anionic polymer AM₉₀-AMPS₁₀. In the presence of NaCl, the polymer chains tended to adopt a coiled conformation under the polyelectrolyte effect, leading to a gradual decrease in polymer solution viscosity with increasing Na⁺ concentration (Fig. 3(b)). However, they also discovered that the amphoteric ion polymer AM₉₀-AMPS₅-TAC₅, which contains equal amounts of cations and anions, could increase the viscosity of the polymer solution as salinity increased via the anti-polyelectrolyte effect (Fig. 3(c)). This finding provides a theoretical basis for the rational design of salt-resistant and even salt-responsive fluid-loss additives. Notably, divalent salts exert stronger salting-out and electrostatic shielding effects than monovalent salts owing to their higher ionic strength, leading to a more pronounced suppression of the fluid-loss control performance of synthetic polymers. Furthermore, salt addition also influences the adsorption behavior of synthetic polymers on clay particle

surfaces. Yang et al. (2023c) employed density functional theory (DFT) calculations to quantify the changes in the binding energy between polymers and bentonite under different valence salt contamination conditions. The addition of NaCl reduced the binding energy from 2.79 to 2.19 eV, while CaCl₂ further decreased it to 0.96 eV (Fig. 3(d)). These results theoretically confirm that salt addition markedly inhibits polymer–bentonite interactions, with divalent salts exhibiting a more pronounced effect. Inspired by this, they prepared an anti-calcium loss agent capable of interacting with Ca²⁺. As shown in the X-ray photoelectron spectroscopy (XPS) in Fig. 3(e), the Ca²⁺ peak exhibits a significant shift after addition of the fluid-loss-control agent, as discussed further in Section 3.

In conclusion, excluding the inherent adverse effects of harsh environments on bentonite, increased fluid loss under high-temperature and high-salinity conditions mainly originates from the reduced structural stability of polymers and the weakened interactions between polymers and bentonite. Therefore, effective fluid-loss control requires polymers to maintain stable molecular conformations and performance under extreme conditions, while forming sufficient stable and effective interactions with clay particles.

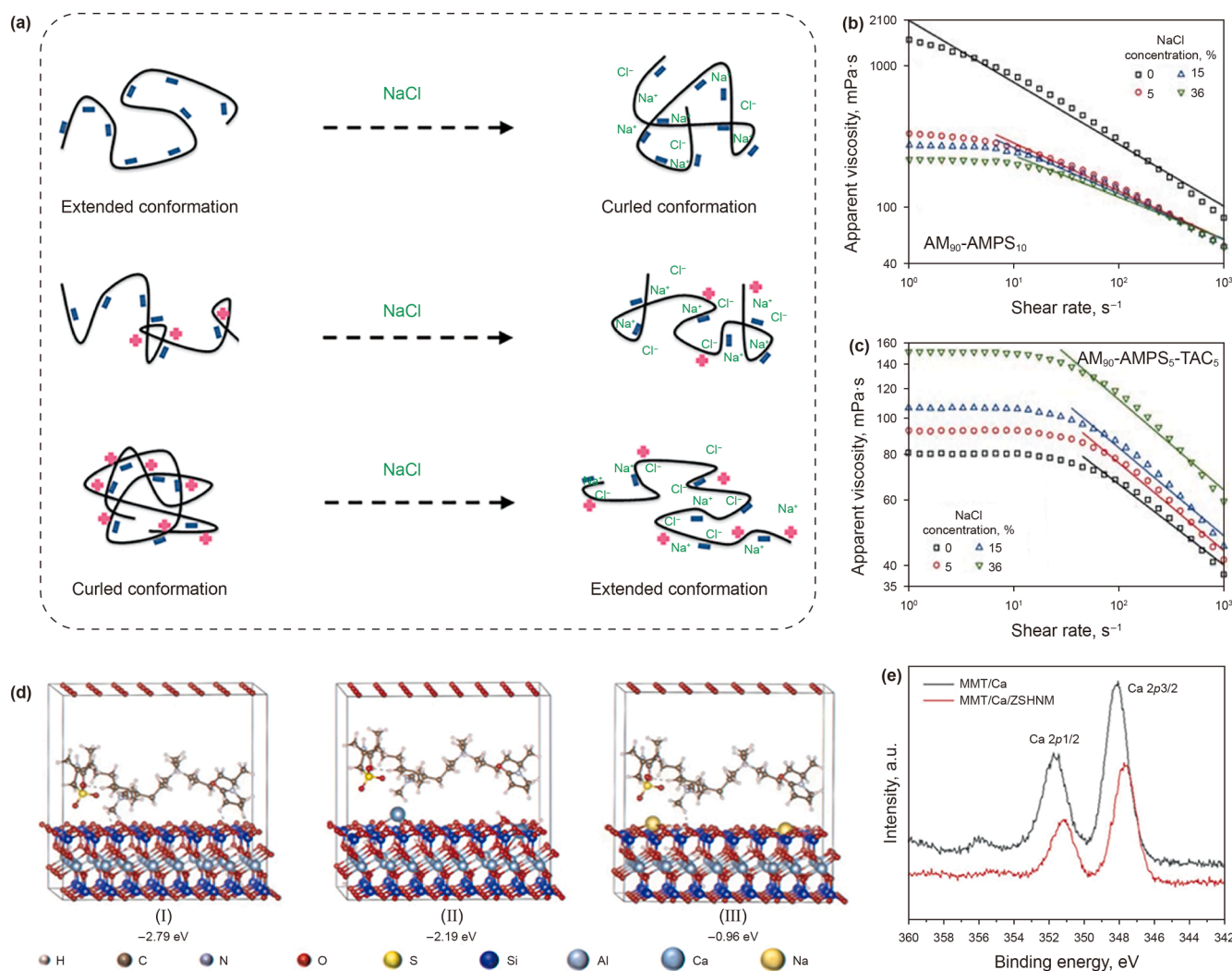


Fig. 3. (a) Conformational changes in different charged polymers under salt action; (b, c) the effects of NaCl concentration on the rheological properties of AM₉₀-AMPS₁₀ and AM₉₀-AMPS₅-TAC₅ polymer solutions. Adapted with permission from He et al. (2020). (d) Energy-optimized structures of polymers and bentonite under different conditions: (I) aqueous environment, (II) NaCl/H₂O solution system, and (III) CaCl₂/H₂O solution system; (e) the influence of the addition of polymers on the Ca²⁺ XPS spectrum. Adapted with permission from Yang et al. (2023c).

3. Current status of fluid-loss additives

Synthetic polymers for fluid-loss control have been rapidly developed for high-temperature and high-salinity applications owing to the high tunability of their molecular structures. Synthetic polymers are typically produced by low-molecular-weight monomers through polycondensation or addition polymerization, forming high-molecular-weight and long-chain polymers. Their fluid-loss control is affected by factors such as monomer type, molecular weight and distribution, and degree of branching. Among these factors, monomer type directly determines the performance to reduce fluid loss of the polymers because different monomers affect the rigidity and flexibility of the polymer main chain as well as the types of pendant functional groups. For example, amide and sulfonic acid groups play key roles in improving the anti-salt performance of this type of fluid-loss reducers. The molecular weight and distribution of polymers also have a significant impact on performance. An excessively high molecular weight may induce an abnormal viscosity increase in drilling fluid systems (Gautam et al., 2025), thereby impairing flowability, whereas an excessively low molecular weight may lead to poor temperature resistance and hinder effective bridging within filter cake pores. In addition, the degree of polymer branching also affects the performance. Although appropriate branching can enhance the anti-pollution ability of polymers, excessive crosslinking will disrupt damage the hydration layer and impair fluid-loss control.

To address the challenges posed by high-temperature and high-salinity drilling environments to synthetic polymer-based fluid-loss reducers, researchers have adopted various methods to improve fluid-loss control. These methods include introducing rigid groups or constructing comb-like or micro-crosslinked structures to enhance the overall stability of the polymer, utilizing anti-polyelectrolyte effects and hydrophobic association to mitigate the adverse effects of salt on the molecular chain, and combining with rigid inorganic nanomaterials to improve the polymer's tolerance under extreme conditions. More importantly, recent advances in synthetic polymer fluid-loss reducers have placed increasing emphasis on rational molecular design rather than empirical material fabrication.

This section systematically reviews recent advances in synthetic polymer-based fluid-loss reducers from four dimensions: optimization of synthesis methods, design of polymerizable monomers, stability of polymer segments, and incorporation of inorganic materials. Among these factors, the selection of an appropriate synthesis method and the optimization of reaction conditions constitute the foundation of polymer synthesis and should therefore be considered first. The design of polymer monomers enables the construction of high-performance polymer building blocks and provides the core support for further enhancing fluid-loss control. Furthermore, the construction of ultra-stable polymer frameworks and the introduction of composite materials offer reliable pathways to enhance the environmental tolerance of synthetic polymer-based fluid-loss additives. In summary, these four interconnected and progressive directions collectively elucidate how current synthetic polymer-based fluid-loss reducers improve fluid-loss control by constructing fine structures.

3.1. Optimization of synthesis methods

Methods for synthesizing polymers can be divided into addition polymerization and condensation polymerization. These two methods exhibit fundamental differences in the structural characteristics of the monomers involved and their reaction

mechanisms. Condensation reactions generally refer to the interaction of monomers containing two or more active functional groups, which releases small molecule by-products such as water and alcohols. This pathway is widely used for the synthesis of many commercially important polymers, such as polyesters, polyamides, and polycarbonates. Addition polymerization involves chain initiation, chain growth, and chain termination of monomer molecules under the action of initiators to form high-molecular-weight polymers. Generally, monomers containing carbon-carbon double bonds or triple bonds can be synthesized into polymers via this route. This paper focuses on the free radical addition polymerization reaction and its further development, which plays a significant role in the synthesis strategies for polymers as fluid-loss agents.

Free radical polymerization methods can be categorized into bulk polymerization, solution polymerization, suspension polymerization, and emulsion/inverse emulsion polymerization. Among these methods, bulk polymerization is conducted through the direct reaction of monomers without a solvent, but it is often limited by inefficient heat dissipation. Suspension polymerization enables the direct production of granular or powdered polymers and is widely applied in the synthesis of plugging agents used in drilling fluids. Solution polymerization and emulsion/inverse emulsion polymerization are commonly used to synthesize polymer-based fluid-loss reducers, with the specific route selected based on the characteristics of the monomers. For monomers with good dispersion in water, aqueous solution polymerization is generally selected, with polymerization initiated by potassium persulfate or ammonium persulfate. However, reverse emulsion polymerization is necessary when highly hydrophobic monomers are incorporated. This technique can ensure the uniform dispersion of the monomer in the solvent and its further polymerization with other monomers by adding an emulsifier. For example, Sun et al. (2022) employed sodium dodecyl sulfate (SDS) as an emulsifier for the incorporation of lauryl methacrylate (LMA), while Zhang et al. (2025a) used SDS to copolymerize styrene (ST) with specific vinyl monomer. In another study, Yang et al. (2023a) employed both SDS and octylphenol polyoxyethylene ether-10 (OP-10) as emulsifiers for the incorporation of styrene and butyl acrylate. However, the introduction of emulsifiers can cause severe foaming during drilling operations, thereby increasing hazards in the drilling process. Li et al. (2024b) independently synthesized hydrophobic monomers containing imidazole rings and long-chain alkanes. The incorporation of imidazole rings enhances the solubility of long-chain alkanes, thereby eliminating the need for emulsifiers during synthesis.

The choice of the polymerization method depends not only on the intrinsic reaction characteristics of the monomers but also has a profound influence on the performance of the final product. Different polymerization processes can lead to variations in polymer chain sequence, molecular weight distribution, and particle morphology, which ultimately govern the macroscopic performance of the material in practical applications. Ma et al. (2019) introduced acrylamide (AM), 2-acrylamido-2-methyl-propane-sulfonic acid (AMPS), and *N*-vinylpyrrolidone (NVP) onto silica via aqueous solution polymerization (PAAN-SiO₂), achieving only 2.0 wt% calcium resistance (Fig. 4(a) and (b)). Subsequently, they adopted reverse emulsion polymerization to graft the monomers onto silica, producing a silica-based polymer, EAANS. The resulting material maintained an API fluid loss below 9 mL even under 0–30 wt% CaCl₂ contamination (Fig. 4(c) and (d)) (Shan et al., 2022). More notably, within the above concentration range of divalent-salt contamination, a gradual decrease in API fluid loss was observed as the CaCl₂ concentration increased. However, the mechanistic basis for the performance enhancement induced by

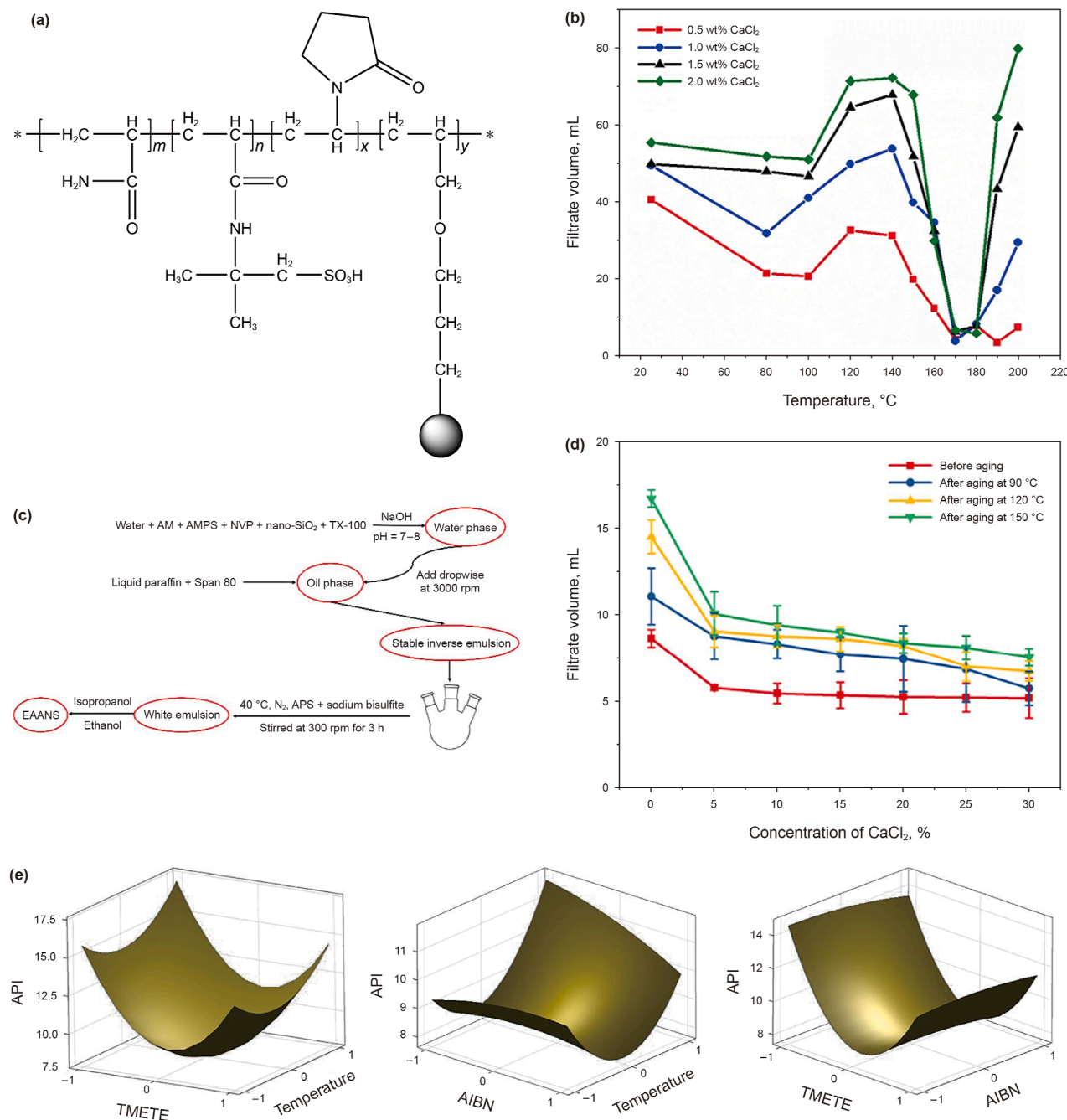


Fig. 4. Chemical structure (a) and fluid-loss reduction performance (b) of PAAN-SiO₂ synthesized via solution polymerization. Adapted with permission from [Ma et al. \(2019\)](#). Polymerization scheme (c) and fluid-loss reduction performance (d) of EAANS synthesized via reverse emulsion polymerization. Adapted with permission from [Shan et al. \(2022\)](#). (e) Response surface optimization results. Adapted with permission from [Yang et al. \(2024a\)](#).

optimizing the polymerization method was not further elucidated, and thus remains an important aspect for future investigation. Nevertheless, EAANS exhibited strong adsorption affinity toward bentonite, enabling bentonite particles to maintain a favorable particle size distribution under high-temperature and high-calcium conditions, thereby delivering excellent fluid-loss control.

The properties of synthetic polymers are influenced by various factors including reaction temperature, monomer concentration, initiator type and concentration, and solvent effects. For instance, the higher polymerization temperature increases the initial efficiency of initiators, accelerating the polymerization rate and resulting in polymers with lower molecular weights. Conversely,

the lower reaction temperature can also lead to lower molecular weights due to incomplete reactions. Bai et al. (2024) optimized the copolymerization conditions for AM, NVP, methacryloyloxethyl trimethyl ammonium chloride (DMC), and sodium p-styrene sulfonate (SSS) using orthogonal experiments, including reaction temperature, initiator concentration, monomer concentration, and reaction time. First, the optimal molar ratio of these four monomers was determined through orthogonal experiments, namely AM: NVP: DMC: SSS = 3.5: 2.0: 0.5: 0.5. Experimental results demonstrated that the relative proportions of the four monomers significantly affected the API fluid loss of the polymer-containing drilling fluid after hot rolling. Among these monomers,

excessive incorporation of the cationic monomer caused flocculation in the drilling fluid. NVP would enhance the temperature resistance of the polymer but would also have an adverse effect on the hydrolysis of the amide under high temperatures. SSS and NVP, owing to their pronounced steric hindrance, inhibited the polymerization reaction. On this basis, other reaction conditions were further optimized, and the optimal polymerization conditions were finally obtained. Yang et al. (2024a) conducted response surface optimization experiments on the reaction conditions for the polymerization of TMETE, AMPS, AM, and NVP, thereby selecting the optimal temperature, TMETE dosage, and initiator dosage. The results showed that, within this synthesis protocol, TMETE dosage exerted the greatest effect on API fluid loss, followed by reaction temperature and initiator dosage (Fig. 4(e)). Therefore, it is necessary to conduct orthogonal experiments or response surface analysis on the influencing factors to obtain the optimal synthesis conditions.

The preparation methods of synthetic polymers as filtrate reducers have gradually evolved toward more advanced controlled radical polymerization techniques and more industrially scalable synthesis processes. Controlled radical polymerization achieves precise control of the molecular weights of polymers by establishing a dynamic balance between free radical activation and reversibility, and enables the synthesis of polymers with complex architectures, such as block copolymers, star-shaped polymers, and hyperbranched polymers (Rong et al., 2023b). Currently, Rong et al. (2023a) synthesized block and random copolymers based on graphene oxide (GO) using the surface-initiated atom transfer radical polymerization (SI-ATRP) method (Fig. 5(a)), and further investigated their rheological regulation effects in water-based drilling fluids (WBDFs). Additionally, a novel star-shaped

polymer crosslinked with polyacrylic acid-block poly(-methacrylate) and methylene bisacrylamide was prepared via reversible addition-fragmentation chain transfer polymerization (RAFT) (Jian et al., 2023) (Fig. 5(b)), and its performance in regulating fluid loss of oil-based drilling fluids was evaluated. Although few studies have reported the application of controlled radical polymerization in water-based fluid-loss reducers, optimizing the performance of synthesized polymers through this strategy deserves further investigation. Furthermore, regarding the industrial synthesis prospects of synthetic polymers as fluid-loss agents, Liu et al. (2025) innovatively used sodium sulfate as a catalyst and sulfonating agent to synthesize an optimized sulfomethylated phenolic resin (OSMP) through a one-step process involving sulfomethylation and phenol-formaldehyde condensation (Fig. 5(c)). The addition of 4 wt% OSMP reduced the high-temperature high-pressure fluid loss (FL_{HTHP}) of the system by 90.4% (from 136 to 13 mL) after hot rolling at 150 °C, while increasing the apparent viscosity (AV) by 39.7% (from 29 to 40.5 mPa·s). Compared to commercial sulfomethylated phenolic resin (CSMP), OSMP exhibits multidimensional enhancements in thermal stability, high-temperature high-pressure (HTHP) filtration resistance, salt tolerance, and rheological properties with lower apparent viscosity (Fig. 5(d)). In summary, this preparation process simplifies the synthesis of sulfonated phenolic resins, reduces reaction time, and significantly enhances their industrial applicability.

In summary, the selection of synthetic methods for synthetic polymers as fluid-loss reducers should be guided by monomer compatibility, method optimization, and condition refinement. Researchers must first consider the compatibility between polymerization methods and monomer characteristics. For instance, common monomers such as acrylamide and styrene require

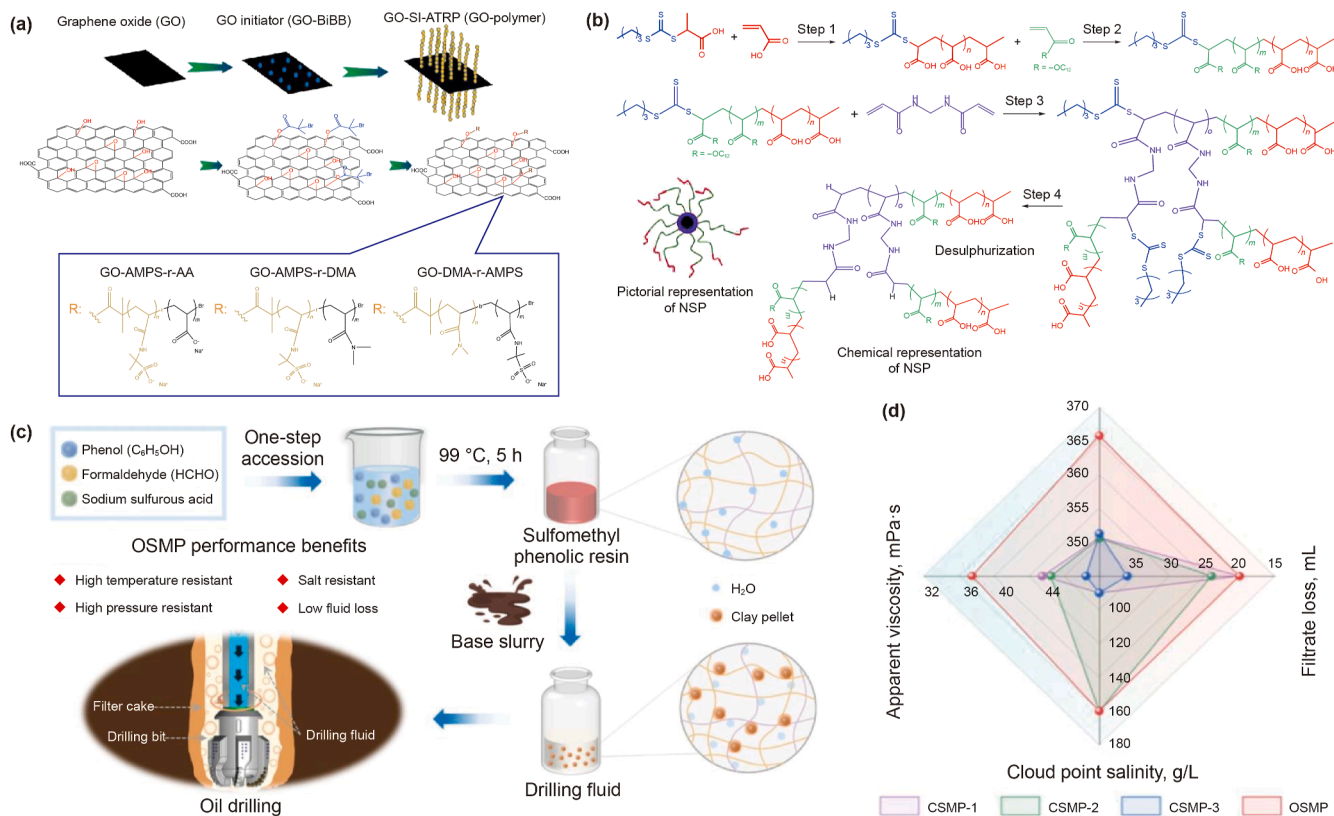


Fig. 5. (a) Schematic diagram of the steps for synthesizing graphene-based polymers by SI-ATRP. Adapted with permission from Rong et al. (2023a). (b) Schematic diagram of RAFT synthesis of polymers. Adapted with permission from Jian et al. (2023). (c) Schematic diagram of the synthesis of OSMP; (d) comparison of the properties of OSMP and CSMP. Adapted with permission from Liu et al. (2025).

different polymerization conditions. Attention should also be paid to the impact of different polymerization methods on polymer properties. Previous studies have demonstrated that aqueous solution polymerization and emulsion polymerization exert different effects on the fluid-loss control of polymers, requiring the polymerization method to be selected according to specific application requirements. On this basis, optimizing synthesis conditions is essential for enhancing the fluid-loss control of polymers. Orthogonal experiments and response surface methodology are effective approaches for evaluating the effects of key reaction parameters and determining favorable synthesis conditions. Notably, controlled radical polymerization has attracted increasing attention, offering new possibilities for constructing fluid-loss reducers with well-defined chain structures and narrow molecular-weight distributions. Meanwhile, simplifying synthesis procedures and reducing production costs remain key directions for promoting the transition of synthetic polymers from laboratory research to industrial application.

3.2. Designability of polymer monomers

At present, commonly used fluid-loss reducers are mainly prepared through free radical polymerization of various olefin-containing monomers. The superior fluid-loss control of synthetic polymer is rarely determined by a single monomer, but rather by the combined effects of multiple functional monomers such as adsorbent monomers, temperature-resistant monomers, hydrated monomers, and hydrophobic monomers. Currently, various functional monomers are gradually evolving from commercially available products towards custom-engineered monomers, which further improves the thermal stability and salt resistance of synthetic polymers. This section provides a detailed overview of the development of these functional monomers. Table 1 summarizes the properties of typical synthetic polymers for controlling fluid loss.

Adsorptive functional groups in polymers, such as hydroxyl, amide, and cationic groups, can adsorb onto bentonite surfaces through hydrogen bonding, coordination bonds, and electrostatic interactions. These interactions provide the basis for establishing the “bentonite–polymer–water molecule” association, thereby enhancing the zeta potential and increasing the thickness of the hydration layer. At present, adsorption monomers most commonly used in synthetic polymers are amide, for example, the classic AM and the more thermally stable *N,N*-dimethylacrylamide (DMAA). Most reported fluid-loss-control agents are prepared by copolymerizing these adsorption monomers with other functional monomers, as summarized in Table 1. Furthermore, strong chemical adsorption arising from Si–O–Si bonds formed between Si–OR groups in polymers and hydroxyl groups on bentonite surfaces has been shown to improve the fluid-loss control. Wang et al. (2025b) prepared a multi-site adsorption fluid-loss reducer using monomers DMAA, AMPS, dimethyldiallyl ammonium chloride (DMDAAC), NVP, and vinyltriethoxysilane (VTEO). The formation of covalent bonds, ionic bonds, and Si–O–Si chemical bonds between the polymer and bentonite enabled the polymer to maintain favorable fluid-loss control even under saturated-salt conditions at 220 °C. In addition, the multi-site adsorption structure endowed the polymer with excellent long-term thermal stability, as evidenced by an API fluid loss of only 9.7 mL for the freshwater-based slurry after long-term hot rolling at 240 °C for 72 h.

Anionic monomers can improve the dispersibility of clay particles and the colloidal stability of drilling fluids by introducing highly hydratable and negatively charged groups, such as carboxylic acids and sulfonic acids. Anionic monomers range from acrylic acid (AA) and itaconic acid (IA), which contain carboxylic

acid groups, to AMPS, sodium allylsulfonate (SAS), and sodium vinyl sulfonate (SVS), which contain highly hydrating sulfonic acid groups, as well as SSS, which offers relatively higher stability. Sulfonated modified phenolic resin is a commonly used anionic anti-salt fluid-loss reducer. Xu et al. (2021) investigated its performance and found that SMP-I could maintained effective fluid-loss control after hot rolling at 100 °C in a mixed salt environment containing 30 wt% NaCl, 6 wt% KCl, and 8 wt% HCOONa. Its API fluid loss was only 18 mL and significantly lower than that of cellulose-based CMC-Lv, which exhibited a fluid loss of 80 mL under the same testing conditions. Poly sodium styrenesulfonate (PSS) has also been successfully applied in the drilling process of a high-temperature deep well in Xinjiang, China, where the bottom temperature reaches 164.5 °C (Liu et al., 2020a). The PSS-containing drilling fluid system exhibited an HTHP filtrate volume of 6.2 mL, whereas the PSS-free system used in Well A recorded an HTHP filtrate volume of 9.8 mL under identical conditions. These results confirm the effectiveness of PSS in reducing fluid loss under elevated temperature conditions. Furthermore, researchers have successively synthesized AM-AMPS-NVP (Mao et al., 2021), AM-SSS-NVP (Bai et al., 2023), DMAA-AMPS-SSS-NVP (Wang et al., 2021), and DMAA-AMPS-ACMO-SSS (Li et al., 2023b) polymers as temperature-resistant and salt-resistant fluid-loss agents. The fluid-loss reducer DNAS synthesized by Wang et al. (2021) exhibited excellent high-temperature resistance and salt tolerance, reducing API fluid loss to 9.2 mL in a freshwater base slurry after hot rolling at 240 °C, while maintaining a low level of 13.4 mL even in a saturated saltwater base slurry. However, the addition of 2 wt% DNAS to the base mud resulted in an apparent viscosity exceeding 90 mPa·s before thermal rolling, which impaired the flowability of the system, although the viscosity decreased to 54 mPa·s after aging at 240 °C. The polymer has a weight-average molecular weight (M_w) of 8.28×10^5 g/mol and a number-average molecular weight (M_n) of 7.85×10^5 g/mol. The higher molecular weight leads to a significant increase in the viscosity of the system. In contrast, Dong et al. (2022a) synthesized a low-molecular-weight filtrate reducer LDMS using DMAA, SSS, and maleic anhydride (MAH) as monomers, with a weight-average molecular weight of only 1325 g/mol. After the addition of 2 wt% LDMS to the base slurry and hot rolling at 210 °C, the system exhibited an apparent viscosity of only 8.5 mPa·s and an API fluid loss of 8.0 mL. These results indicate that the low-molecular-weight polymer can provide excellent high-temperature fluid-loss control while avoiding a marked increase in the viscosity of the system.

The reduced fluid loss exhibited by anionic polymers typically stems from their strong adsorption of groups such as amide groups and their robust hydration of anionic groups such as sulfonic acid groups (Fig. 6(a)). These effects collectively ensure that bentonite maintains a stable dispersion under harsh conditions. Li et al. (2023b) evaluated the stability of bentonite-based muds with and without DAAS using multiple light scattering. As shown in Fig. 6(c), the saturated salt-containing mud exhibited rapid sedimentation after hot rolling at 200 °C, whereas the DAAS-containing sample demonstrated only minor changes with improved overall dispersion stability. This further confirms that anionic polymers enhance particle stability in the mud base, thereby improving fluid-loss control. Additionally, the fluid-loss control may also arise from the chelation between the oxygen atoms in sulfonamide groups and inorganic cations, thereby reducing salt erosion of bentonite (Fig. 6(a)). Li et al. (2020b) employed molecular simulations to investigate the structural changes of FT-1 (DMAA-AMPS-AA) without adjacent carboxyl groups and FT-2 (DMAA-AMPS-IA) with adjacent carboxyl groups in calcium-containing and calcium-free solutions (Fig. 6(b)).

Table 1
Performance summary of synthetic polymer loss control agents.

Polymer type	Polymer composition	Polymer properties (thermal stability ^a , molecular weight)	Optimal concentration	Temperature tolerance and salt tolerance	Optimal performance (after hot rolling)	Advantages/ finding	Limitations	References
Multi-target adsorption polymer	DMAA-AMP-DMDAAC-NVP-VTEO	318 °C, not mentioned	2 wt%	240 °C, base slurry	AV = 54 mPa·s, FL _{API} = 4.6 mL	Enhanced thermal stability	Restricted salt tolerance at elevated temperatures	Wang et al. (2025b)
			2 wt%	220 °C, 36 wt% NaCl	AV = 9.5 mPa·s, FL _{API} = 15.2 mL			
Anionic polymer	AM-AMPS-NVP	340 °C, $M_w = 5.332 \times 10^6$	1.5 wt%	180 °C, base slurry	FL _{API} = 5.6 mL	Reduced additive dosage Minimal impact on viscosity	Rheological property deficiency Limited temperature tolerance	Mao et al. (2021) Bai et al. (2023)
Anionic polymer	AM-SSS-NVP	215 °C, $M_w = 1007$	1.5 wt%	180 °C, 36 wt% NaCl	FL _{API} = 10.5 mL			
Anionic polymer	DMAA-AMPS-SSS-NVP	310 °C, $M_w = 8.28 \times 10^5$	2 wt%	160 °C, base slurry	AV = 20 mPa·s, FL _{API} = 8.25 mL	Viscosity less affected by salt after aging	High viscosity before aging	Wang et al. (2021)
			2 wt%	160 °C, 12 wt% NaCl	AV = 20 mPa·s, FL _{API} = 8.25 mL			
			2 wt%	160 °C, 3 wt% CaCl ₂	AV = 12 mPa·s, FL _{API} = 8.25 mL	Enhanced thermal stability	Restricted salt tolerance at elevated temperatures	Li et al. (2021)
			2 wt%	240 °C, base slurry	AV = 54 mPa·s, FL _{API} = 6.0 mL			
Anionic polymer	DMAA-SSS-IA	Not mentioned, $M_w = 42262$	2 wt%	240 °C, 20 wt% NaCl	AV = 58 mPa·s, FL _{API} = 9.4 mL	Minimal impact on viscosity	Restricted salt tolerance	Dong et al. (2022a)
			1.5 wt%	240 °C, base slurry	FL _{API} = 17.0 mL, FL _{HHTP} = 35.0 mL			
			2.0 wt%	180 °C, 34 wt% NaCl	FL _{API} = 12.0 mL, FL _{HHTP} = 60.0 mL			
Anionic polymer	DMAA-SSS-MAH	238 °C, $M_w = 1325$	2.0 wt%	180 °C, 1.5 wt% CaCl ₂	FL _{API} = 6.0 mL	Enhanced thermal stability	Restricted salt tolerance	Wang et al. (2024b)
Anionic polymer	DMAA-AMPS-NVCL-SVM	300 °C, $M_w = 995721$	2 wt%	210 °C, base slurry	AV = 13 mPa·s, FL _{API} = 8.0 mL, FL _{HHTP} = 41.0 mL			
Micro-crosslinked anionic polymer	DMAA-AMPS-NVCL-SVM-KMB703	294 °C, not mentioned	1 wt%	220 °C, base slurry	AV = 32 mPa·s, FL _{API} = 10.0 mL	Enhanced thermal stability	Restricted salt tolerance	Wang et al. (2024a)
			3 wt%	220 °C, 5 wt% NaCl	AV = 25 mPa·s, FL _{API} = 6.0 mL, FL _{HHTP} = 20.0 mL			
			3 wt%	240 °C, base slurry	AV = 34.5 mPa·s, FL _{API} = 6.0 mL, FL _{HHTP} = 24.4 mL	Divalent cation tolerance	Limited temperature tolerance	Liu et al. (2016)
			3 wt%	230 °C, 15 wt% NaCl	AV = 32 mPa·s, FL _{API} = 4.6 mL, FL _{HHTP} = 23.0 mL			
Zwitterionic copolymer	AM-AMPS-DMDAAC	300 °C, not mentioned	1.5 wt%	150 °C, base slurry	AV = 36 mPa·s, FL _{API} = 7.0 mL	Divalent cation tolerance Sodium chloride tolerance	Limited temperature tolerance Limited temperature tolerance	Yang et al. (2017) Bai et al. (2015)
Zwitterionic copolymer	AM-AMPS-VeiBr	301.3 °C, not mentioned	1.5 wt%	150 °C, 11.1 wt% CaCl ₂	FL _{API} = 9.6 mL			
Zwitterionic copolymer	AM-AMPS-DMDAAC-SSS	272.3 °C, not mentioned	4 wt%	180 °C, 11 wt% CaCl ₂	FL _{API} < 10.0 mL	Reduced additive dosage	Excessively low viscosity after aging	Tchameni et al. (2021)
Zwitterionic copolymer	DMAA-AMPS-DMDAAC-NVP	314 °C, $M_w = 11.91 \times 10^6$	1.2 wt%	180 °C, base slurry	AV = 19 mPa·s, FL _{API} = 9.6 mL, FL _{HHTP} = 19.8 mL			
			2.5 wt%	180 °C, 36 wt% NaCl	AV = 40.5 mPa·s, FL _{API} = 15.0 mL, FL _{HHTP} = 30.0 mL	Sodium chloride tolerance	No mention of divalent cation tolerance	Zhang et al. (2022b)
Zwitterionic copolymer	AM-SSS-DMDAAC-NVP	290 °C, not mentioned	1 wt%	230 °C, base slurry	AV = 7.5 mPa·s, FL _{API} = 8.9 mL, FL _{HHTP} = 35.2 mL			
			1 wt%	230 °C, 20 wt% NaCl	AV = 5 mPa·s, FL _{API} = 22.0 mL			
Zwitterionic copolymer	AM-SSS-DMDAAC-NVP	290 °C, not mentioned	1.5 wt%	210 °C, base slurry	AV = 30 mPa·s, FL _{API} = 12.6 mL			
			2.0 wt%	210 °C, 36 wt% NaCl				

Zwitterionic copolymer	DMAA-AMPS-DMDAAC-NVCL	298 °C, $M_w = 385149$	2 wt%	220 °C, base slurry	AV = 25 mPa·s, $FL_{API} = 18.0$ mL	Enhanced thermal stability	Restricted salt tolerance	Liu et al. (2022b)
			2 wt%	220 °C, 15 wt% NaCl	AV = 52 mPa·s, $FL_{API} = 6.5$ mL			
	AM-SBMA-NVCL	320 °C, not mentioned	2 wt%	150 °C, base slurry	AV = 22 mPa·s, $FL_{API} = 5.0$ mL, $FL_{HTHP} = 28.0$ mL	Salt response	Limited temperature tolerance	Sun et al. (2020)
			2 wt%	150 °C, 36 wt% NaCl	AV = 13 mPa·s, $FL_{API} = 28.0$ mL			
	AM-NIPAM-SBMA	203 °C, not mentioned	1 wt%	180 °C, base slurry	AV = 15 mPa·s, $FL_{API} = 30.0$ mL	Temperature response and salt response	Limited temperature tolerance	Lv et al. (2022)
			1 wt%	180 °C, 30 wt% NaCl	AV = 27 mPa·s, $FL_{API} = 10.0$ mL			
	DMAA-AMPS-SSS-SBMA	292 °C, not mentioned	2 wt%	200 °C, base slurry	AV = 38 mPa·s, $FL_{API} = 13.2$ mL	High viscosity before hot rolling	No mention of divalent cation tolerance	Li et al. (2025a)
			2 wt%	200 °C, 30 wt% NaCl	AV = 45 mPa·s, $FL_{API} = 6.4$ mL			
	AM-AMPS-DMDAAC-VPS	Not mentioned, $M_w = 582421$	1.25 wt%	200 °C, base slurry	AV = 18 mPa·s, $FL_{API} = 8.6$ mL	Enhanced thermal stability	Restricted salt tolerance at elevated temperatures	Ma et al. (2017)
			1.25 wt%	150 °C, 36 wt% NaCl	AV = 55 mPa·s, $FL_{API} = 19.2$ mL			
	DMAA-SBVI-[CEVIm]Cl	220 °C, not mentioned	2 wt%	200 °C, base slurry	AV = 35 mPa·s, $FL_{API} = 42.0$ mL	Salt response	No mention of divalent cation tolerance	Li et al. (2023c)
			2 wt%	200 °C, 36 wt% NaCl	AV = 20 mPa·s, $FL_{API} = 7.0$ mL			
	AM-AMPS-SSS-VBIPS	301 °C, not mentioned	2 wt%	240 °C, 30 wt% NaCl	AV = 18 mPa·s, $FL_{API} < 10.0$ mL	Strong resistance to divalent cations	Complex preparation process	Gao et al. (2025)
			2 wt%	200 °C, 25 wt% $CaCl_2$	AV = 12 mPa·s, $FL_{API} = 15.6$ mL			
					AV = 23 mPa·s, $FL_{API} < 15.0$ mL			

^a The temperature at which significant mass loss occurs.

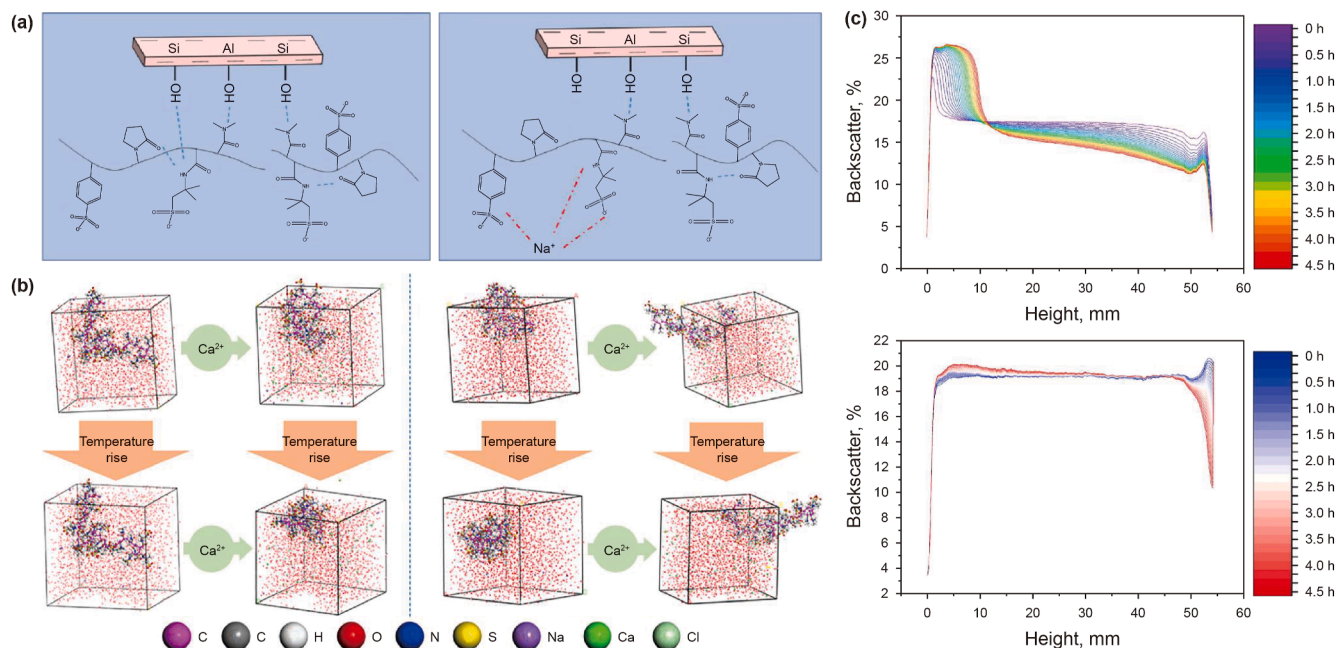


Fig. 6. (a) Schematic illustrations of fluid-loss control mechanism. Adapted with permission from Wang et al. (2021). (b) The structural changes of segments in the solution with and without Ca^{2+} at 303 and 363 K: FR-I (left) and FR-II (right). Adapted with permission from Li et al. (2020b). (c) Delta backscattering of saturated saline base slurry containing DAAS (bottom) and without it (top) after hot rolling at 200 °C. Adapted with permission from Li et al. (2023b).

Specifically, in the absence of Ca^{2+} , Na^{+} interacted with the charged monomers, causing FT-2 to adopt a coiled conformation while FT-1 remained in an extended state. In the presence of Ca^{2+} , enhanced electrostatic attraction and Ca^{2+} bridging effects caused FT-1 to transform from an extended state to a coiled conformation. In contrast, FT-2 maintained a locally rigid and extended conformation at low temperature because its adjacent hydroxyl groups could strongly chelate Ca^{2+} . On this basis, Li et al. (2021) synthesized a ternary polymer, DMAA-SSS-IA. The locally stretched structure between adjacent carboxyl groups and ionic groups endowed the polymer with a certain resistance to divalent salts. The addition of this filtrate reducer resulted in a FL_{HTHP} of 35.0 mL and a FL_{API} of 17.0 mL for fresh cement slurry after hot rolling at 240 °C for 16 h. Under saturated brine and 1.5 wt% CaCl_2 contamination, the API fluid losses were 12 and 6 mL, respectively. However, although adjacent carboxylic acid structures were present in the polymer, the expected improvement in calcium resistance arising from chelation was not significant. This may be attributed to the insufficient utilization of the chelation effect, or to the limited ability of this effect to effectively suppress calcium ion-induced bentonite aggregation.

Although polymers based on the aforementioned anionic monomers exhibit certain salt resistance and fluid-loss control capabilities—such as itaconic acid, whose adjacent carboxyl groups can chelate calcium, and SSS, which offers higher thermal stability than AMPS—the further development of novel anionic monomers remains an important trend for enhancing their performance. The electron-withdrawing effect of the sulfonic acid group on the benzene ring of SSS, arising from its conjugated structure, indicates that its stability under elevated temperatures remains an area for potential improvement. To address this issue, Wang et al. (2024b) synthesized sodium (4-vinyl phenyl) methanesulfonate (SVM) and subjected it to radical polymerization with DMAM, AMPS, and *N*-vinylcaprolactam (NVCL) in the aqueous solution (PDASN), as shown in Fig. 7(a) and (b). After hot rolling of a slurry containing 5 wt% NaCl at 220 °C, this polymer produced only 6 mL of FL_{API} and 20 mL of FL_{HTHP} (Fig. 7(d)),

demonstrating excellent fluid-loss control at high temperature. The corresponding mechanism is schematically illustrated in Fig. 7(c). Compared with SSS, SVM contains an additional methylene spacer between the benzene ring and the sulfonate group, which weakens the conjugation effect, thereby enhancing the thermal stability of the copolymer. Moreover, the methylene spacer adjacent to the sulfonate group provides pronounced steric hindrance, while the introduction of SVM into the polymer backbone increases polymer hydrophobicity. On this basis, this research group further incorporated 3-chloropropyltriethoxysilane (KMB703) into the above-mentioned polymer to prepare a novel micro-crosslinked anionic polymer with enhanced high-temperature and high-salt resistance (Wang et al., 2024a). The incorporation of KMB703 induced the formation of a “silane coupling layer” on the polymer surface, which promoted polymer crosslinking and aggregation and facilitated the formation of a dense and stable spatial network, thereby improving its fluid-loss control. Under conditions of 230 °C and 15 wt% NaCl, this polymer can achieve fluid losses as low as 4.6 mL under medium pressure and 23.0 mL under high temperature and high pressure, respectively.

As the salt concentration increases, anionic polymers inevitably undergo chain coiling due to electrolyte effects, which weakens their adsorption onto clay particles and significantly reduces their fluid-loss control. By contrast, amphoteric polymers exhibit superior salt tolerance in terms of viscosity retention and fluid-loss control, mainly because of their anti-polyelectrolyte effect and strong charge-mediated adsorption onto clay particles. Amphoteric polymers are typically prepared through the copolymerization of anionic and cationic monomers. Commonly used cationic monomers include vinyl ethyl imidazolium bromide (VeiBr) (Yang et al., 2017), diallyl dimethyl ammonium chloride (DAC), DMC (Bai et al., 2024; Tan et al., 2021), trimethylallyl ammonium chloride (TAC) (He et al., 2020; Jiang et al., 2019), and DMDAAC, etc. Zwitterionic polymers with zero net charge exhibit a pronounced anti-polyelectrolyte effect, in which increasing salt concentration drives their molecular conformation from a coiled to an extended

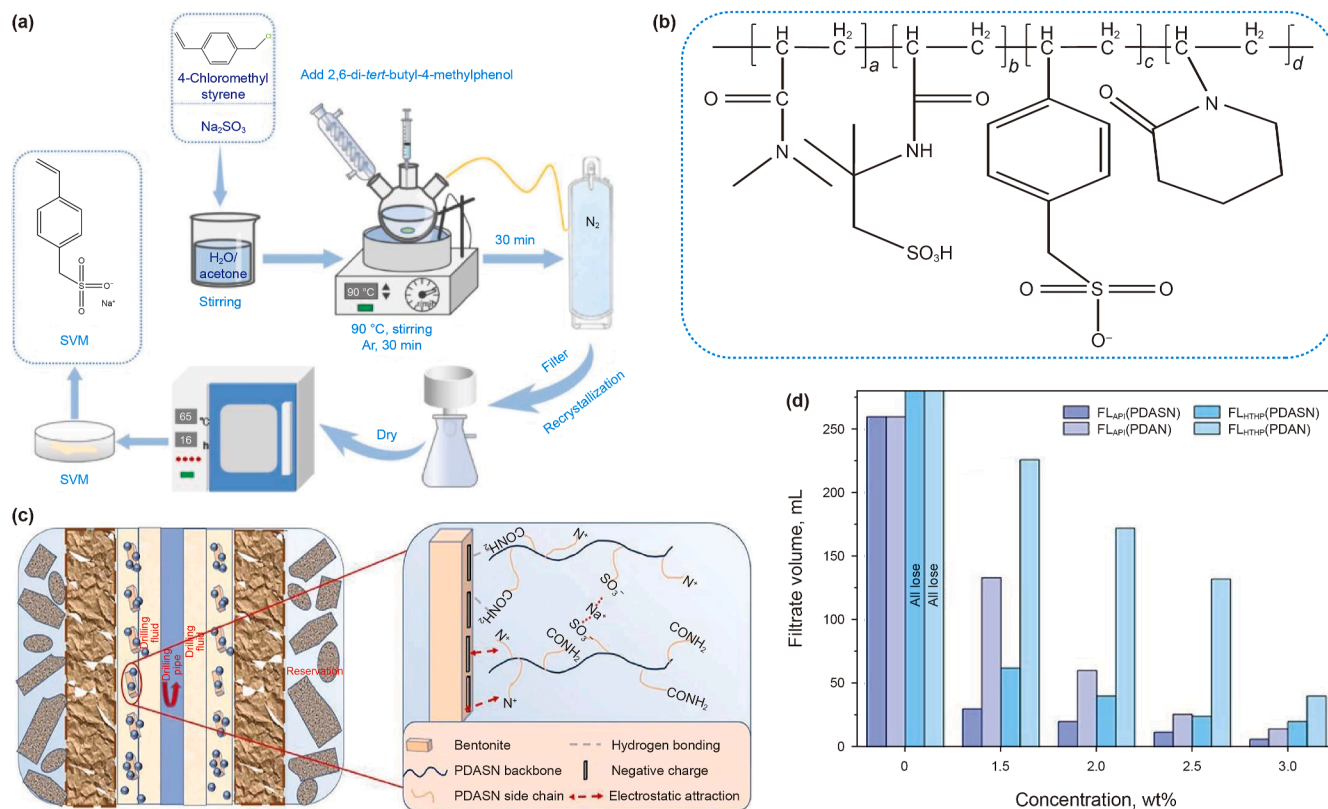


Fig. 7. (a) Preparation process of SVM; (b) structure of PDASN (polymer synthesized with DMAM, AMPS, SVM, and NVCL); (c) schematic diagram of the fluid-loss reduction mechanism; (d) filtrate loss of PDASN and PDAN (polymer synthesized with DMAM, AMPS, and NVCL) after hot rolling for 16 h (220 °C, 5 wt% NaCl) at different concentrations. Adapted with permission from Wang et al. (2024b).

state, thereby increasing fluid viscosity and reducing fluid loss. This behavior shifts their function from simple “salt resistance” to “salt responsiveness”. For instance, the AM/AMPS/TAC copolymer exhibited enhanced salt responsiveness when the cationic-to-anionic monomer ratio approached charge balance (He et al., 2020; Jiang et al., 2019). In aqueous solutions of AM₉₀AMP-S₅TAC₅, viscosity steadily increased with rising NaCl content (0–36 wt%), and the corresponding base mud maintained effective fluid-loss control even after thermal rolling in saturated brine at 150 °C. Notably, the anti-polyelectrolyte effect operates within specific boundary conditions, including temperature, salt concentration, and salt type. Once these conditions exceed the applicable range, the expected increase in viscosity and reduction in fluid loss may no longer occur. This limitation may explain why related studies have rarely been extended to higher-temperature conditions or divalent-salt systems.

When zwitterionic polymers possess a non-zero net charge, such as a weakly negative charge, the applicable range of the anti-polyelectrolyte effect becomes narrower. In this case, the polymer cannot maintain viscosity increase and reduced fluid loss across the entire 0–36 wt% salt range as the salt concentration increases. However, it still achieves superior salt resistance and fluid-loss control compared to anionic polymers through cation adsorption and certain counter-polyelectrolyte effects (Fig. 8(a)). Liu et al. (2016) synthesized an amphoteric polymer (AAD) composed of AM, AMPS, and DMAAC, and an anionic polymer (AD) composed of AM and AMPS, and then compared their temperature and salt resistance. Transmission electron microscopy (TEM) revealed that after exposure to 11.1 wt% CaCl_2 contamination and 150 °C thermal rolling, AAD formed a characteristic “star-net” structure with bentonite through strong cationic adsorption, which helped

maintain relatively stable dispersion in the system. In contrast, AD-treated bentonite exhibited significant agglomeration (Fig. 8(c)). Furthermore, at a shear rate of 1000 s^{-1} , the viscosity of the AAD-based slurry reached 25 mPa·s, which was significantly higher than that of the AD-based slurry, 15 mPa·s (Fig. 8(b)). Correspondingly, after thermal rolling under identical high-temperature and high- CaCl_2 conditions, the FL_{API} in the 1.5 wt% AAD-based slurry was only 9.6 mL, substantially lower than the 36 mL observed for the equivalent dose of AD (Fig. 8(d)). In addition, amphoteric polymers with a slightly overall negative charge can also exhibit certain resistance to salt-induced fluid loss through the anti-polyelectrolyte effect. After hot rolling at 220 °C, the API fluid loss of the DADN-containing base slurry decreased at 15 wt% NaCl because of the release of cation-adsorbing groups (Liu et al., 2022b), but increased at higher salinities due to bentonite aggregation (Fig. 8(e)). Liu et al. (2026) prepared an amphoteric fluid-loss reducer using SSS and AMPS as anionic monomers and DMAAC as a cationic monomer. The additive achieved an HTHP fluid loss of only 28.2 mL at 220 °C under saturated salt conditions. More importantly, the drilling fluid system formulated with this additive was successfully applied in the 7858–10910 m interval of the Shendi Take-1 Well, where the formation temperature ranged from 145 to 213 °C. The system maintained excellent performance throughout the interval, with HTHP fluid loss controlled within 7.6–14.0 mL. Building on this foundation, researchers have further improved the fluid-loss control of zwitterionic polymers through several approaches (Li et al., 2022b; Wang et al., 2022c). These methods included replacing AM with DMAA as the main-chain monomer (Tchameni et al., 2021; Wang et al., 2025a), introducing the heat-resistant anionic monomer SSS (Bai et al., 2015; Wang et al., 2022b; Yang et al., 2023d), incorporating the

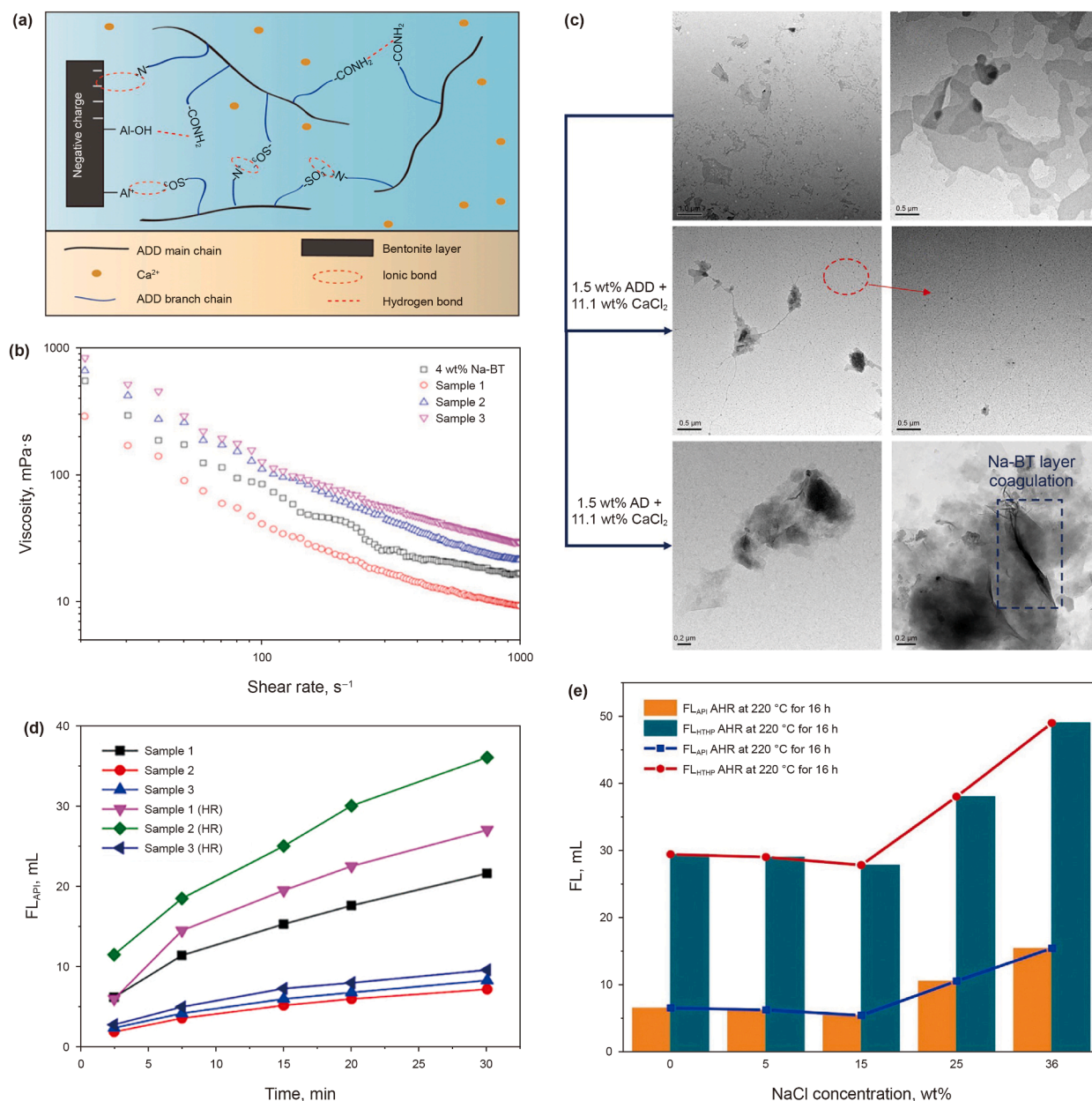


Fig. 8. (a) The interaction between AAD and bentonite; (b) rheological properties of Na-bentonite-based muds after hot rolling at 150 °C (Sample 1: 4 wt% based muds + 11.1 wt% CaCl_2 ; Sample 2: 4 wt% based muds + 1.5 wt% AD + 11.1 wt% CaCl_2 ; Sample 3: 4 wt% based muds + 1.5 wt% ADD + 11.1 wt% CaCl_2); (c) transmission electron microscopy of Na-BT-based slurry after 150 °C hot rolling; (d) medium-pressure fluid loss for different samples: Sample 1: 4 wt% based muds + 11.1 wt% CaCl_2 , Sample 2: 4 wt% based muds + 1.5 wt% AD + 11.1 wt% CaCl_2 , Sample 3: 4 wt% based muds + 1.5 wt% ADD + 11.1 wt% CaCl_2 , Sample HR denotes fluid loss after 16 h of thermal rolling at 150 °C. Adapted with permission from Liu et al. (2016). (e) Fluid loss of base slurry containing 2 wt% DADN at various salt concentrations before and after hot rolling at 220 °C for 16 h. Adapted with permission from Liu et al. (2022b).

heat-resistant cyclic monomer NVP (Qiao et al., 2021; Tchameni et al., 2021; Zhang et al., 2022b) or NVCL (Liu et al., 2022b), and adding isopentanol polyether with substantial steric hindrance (Liu et al., 2022a). Detailed information is presented in Table 1. Huang et al. (2023) prepared zwitterionic polymers DADN from DMAA, AMPS, DMDAAC, NVP, which can reduce the API fluid loss of saturated NaCl-based slurry after hot rolling at 200 °C to only 7.4 mL. It maintained excellent fluid-loss control performance even in drilling fluid systems containing 5 wt% potassium formate and 36 wt% sodium chloride. After hot rolling at 200 °C for 16 h, the FL_{API} was only 1.6 mL, and the FL_{HTHP} was 14.2 mL. Even after a further 72 h of prolonged hot rolling, the FL_{API} increased only slightly to 1.8 mL, and the FL_{HTHP} increased marginally to 19.6 mL.

Zhang et al. (2022b) synthesized PMSC from AM, SSS, DMDAAC, and NVP. After hot rolling at 200 °C in saturated brine, the PMSC-containing base slurry showed an API fluid loss of approximately 15 mL. Moreover, PMSC retained a certain fluid-loss control capability in a composite-salt system (4.5 wt% NaCl, 13 wt% MgCl_2 , 0.5 wt% CaCl_2), achieving an API fluid loss of approximately 25 mL. However, owing to the high concentration of divalent cations in the composite salt system, its fluid-loss control performance remained limited. Previous studies indicate that direct incorporation of temperature-resistant monomers into zwitterionic polymers can improve NaCl tolerance at elevated temperatures. However, limited progress has been made in improving resistance to divalent cations under high-temperature conditions. Further

investigation remains necessary for the future development of fluid-loss reducers that can resist polyvalent cations at high temperatures.

In addition to preparing zwitterionic polymers by copolymerizing anionic and cationic monomers, amphoteric monomers containing both anionic and cationic groups have also gradually attracted increasing attention. However, commercially available amphoteric monomers are scarce, mainly including carboxyl betaine methacrylate (CBMA), 2-methylpropenoethyl phosphocholine (MPC), thiamine acrylamide (SBAA), and sulfobetaine methacrylate (SBMA). Sun et al. (2020) used the polymer AM-SBMA-NVCL (PAMN) as a thickening agent and fluid-loss-control agent in saline drilling fluids (Fig. 9(a)). The zwitterionic polymer with a net charge of 0 swells upon with the addition of salt, exhibiting a curled-to-stretched conformation change as shown in Fig. 9(b) and (c). Furthermore, molecular simulations reveal that the radius of gyration (R_g) of PAMN in saline solution is 12.5 Å, compared to only 8.8 Å in water, theoretically substantiating the anti-polyelectrolyte effect (Fig. 9(d)). The research group further substituted NVCL monomers with *N*-isopropylacrylamide (NIPAM) to synthesize a salt-resistant and temperature-resistant polymer (Lv et al., 2022). The average hydrodynamic radius (R_h) of the polymer progressively increased with rising Na^+ concentration, exhibiting a pronounced anti-polyelectrolyte effect (Fig. 9(e) and (f)). By leveraging the anti-polyelectrolyte effect of zwitterionic

ions and the hydrophobic association effect of thermosensitive monomers, this polymer exhibits outstanding rheological properties and fluid-loss control ($\text{AV} = 34 \text{ mPa}\cdot\text{s}$, $\text{FL}_{\text{API}} < 10 \text{ mL}$) under harsh conditions of 180°C and 30 wt% NaCl. Subsequent studies further expanded the structural design of SBMA-based polymers by incorporating lignin nanoparticles (Sun et al., 2021) and the temperature-resistant anionic monomer SSS (Li et al., 2025a), both of which demonstrated excellent salt resistance.

However, the ester bonds within SBMA readily undergo hydrolysis at elevated temperatures, reducing the thermal stability of the polymer. Meanwhile, steric shielding of the cationic groups by multiple methylene groups limits their interactions with salt ions, thereby weakening the anti-polyelectrolyte effect. Recently, increasing attention has been paid to elucidating the molecular mechanisms underlying the anti-polyelectrolyte effect and refining related chemical structures to maximize salt resistance (Luo et al., 2022; Zheng et al., 2021, 2023) (Fig. 10(a)). Li et al. (2023c) synthesized 1-(2-carboxyethyl)-3-vinyl imidazolium chloride ([CEVIm]Cl) and sulfobetaine vinyl imidazole (SBVI), which were further polymerized with DMAA to produce a fluid-loss reducer resistant to saturated salts at 200°C . The viscosity of aqueous solutions containing this zwitterionic polymer gradually increases with NaCl concentration (0–36 wt%) due to the anti-polyelectrolyte effect (Fig. 10(b)). Furthermore, the polymer-containing base slurry displays a notable salt-responsive

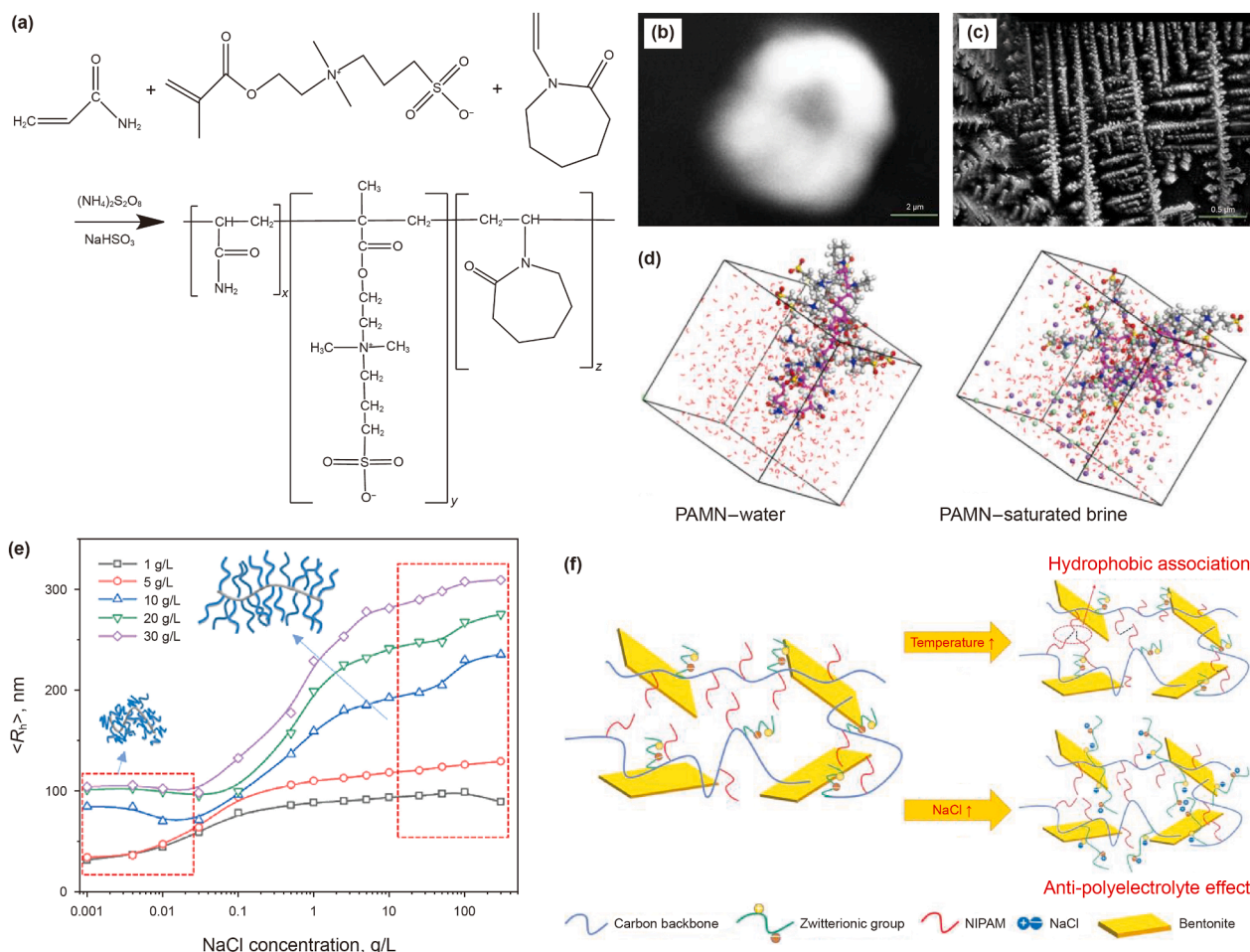


Fig. 9. (a) Polymer composition; (b, c) conformation of polymers in clear water (b) and saturated brine (c); (d) molecular simulation schematic diagram. Adapted with permission from Sun et al. (2020). (e) The radius of the polymer fluid varies with the concentration of NaCl; (f) the mechanism of action of polymers. Adapted with permission from Lv et al. (2022).

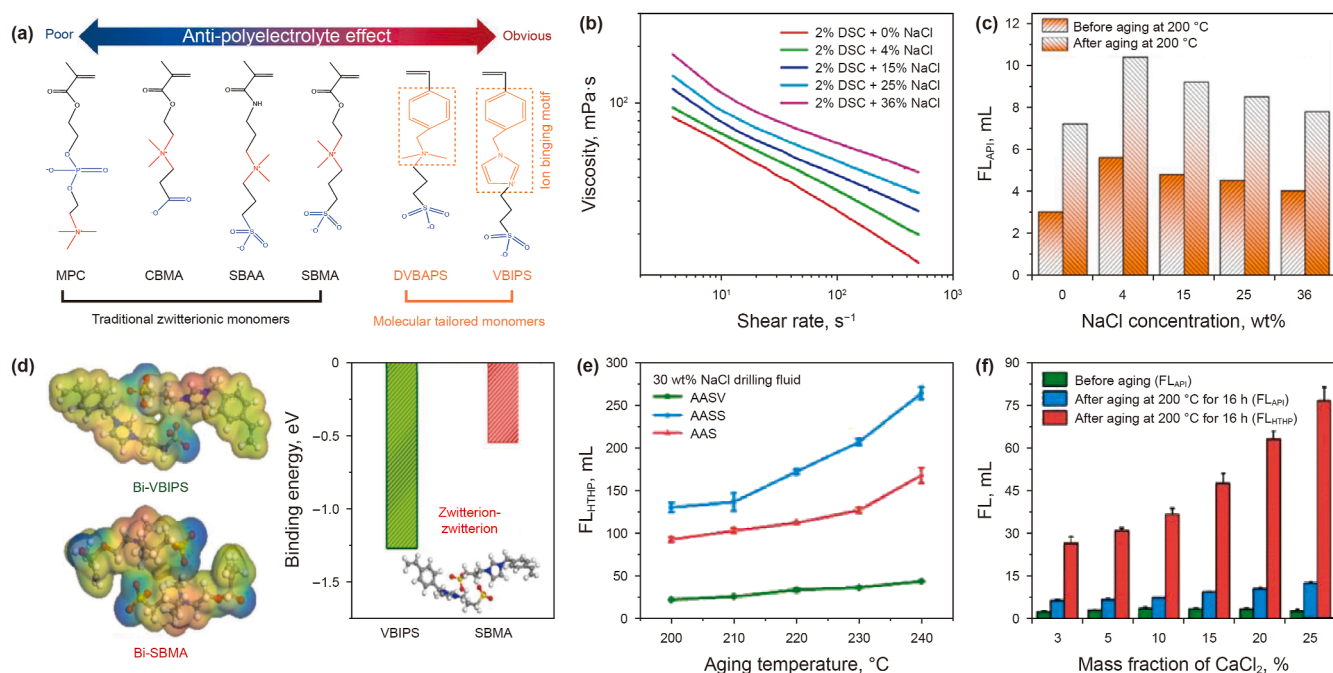


Fig. 10. (a) Self-made amphoteric ions for enhancing anti-polyelectrolytes. Adapted with permission from Zheng et al. (2023). (b) Viscosity curves of 2 wt% DCS aqueous solution at varying NaCl concentrations; (c) filtrate volume of base slurry containing 2 wt% DCS with respect to NaCl concentration before and after hot rolling at 200 °C for 16 h. Adapted with permission from Li et al. (2023c). (d) Electrostatic potential (ESP) values and binding energies of VBIPS and SBMA calculated using DFT; (e) HTHP filtrate volume of base slurry containing 2 wt% AAS, AASS, or AASV (30 wt% NaCl) after hot rolling at various temperatures; (f) filtrate volume of base slurry containing 2 wt% AASV at varying CaCl_2 concentrations (hot rolling conditions: 200 °C for 16 h). Adapted with permission from Gao et al. (2025).

behavior after thermal rolling at 200 °C. Specifically, as the salt concentration increased from 4 to 36 wt%, the apparent viscosity increased, whereas the API fluid loss decreased and remained below 10 mL under saturated-salt conditions (Fig. 10(c)). The temperature boundary of the anti-polyelectrolyte effect extends to 200 °C, owing to the rigid cationic imidazole ring in the synthesized zwitterionic monomer, which enhanced the temperature tolerance of the polymer. Gao et al. (2025) synthesized 3-(1-(4-vinylbenzyl)-1H-imidazole-3-ium-3-yl) propane-1-sulfonate (VBIPS) and theoretically demonstrated its superior anti-polyelectrolyte effect compared with SBMA. Specifically, DFT calculations demonstrated that the introduction of phenyl-methylene-imidazole units in VBIPS increased its intermolecular bonding energy compared to SBMA (Fig. 10(d)), thereby enhancing hydrophilicity in the presence of Cl^- and strengthening the anti-polyelectrolyte effect. Based on this, several polymers were further synthesized, including AAS without zwitterionic groups, AASS containing SBMA monomers, and AASV containing VBIPS monomers, and their fluid-loss control was compared. Under 30 wt% NaCl contamination, AASV exhibited a pronounced anti-polyelectrolyte effect. After hot rolling at elevated temperatures ranging from 200 to 240 °C, its FL_{HTHP} remained significantly lower than those of AAS and AASS. For instance, after hot rolling at 220 °C, the FL_{HTHP} of AASV system was only 22.2 mL, whereas those of AAS and AASS exceeded 80 mL (Fig. 10(e)). Moreover, after hot rolling at 200 °C in a base slurry contaminated with 25 wt% CaCl_2 , this fluid-loss-control agent exhibited FL_{API} and FL_{HTHP} values of only 12.3 and 76.5 mL (Fig. 10(f)), respectively, demonstrating outstanding resistance to divalent cations, which is difficult to achieve using conventional cationic or anionic agents.

Hydrophobic association polymers are a type of polymer containing hydrophobic side chains. Upon reaching a certain concentration in aqueous solution, the hydrophobic chains form an intermolecular crosslinked network, which increases solution

viscosity through hydrophobic association (Zhang et al., 2026a). Hydrophobic monomers are commonly selected from compounds containing long alkyl chains or cyclic compounds, such as dodecyl methacrylate (Sun et al., 2022), styrene (Davoodi et al., 2019; Shen et al., 2020), etc. (Fig. 11(a)). Notably, highly hydrophobic monomers typically require surfactants, such as SDS, during polymerization to achieve a uniform reaction phase with hydrophilic monomers. However, surfactant addition inevitably causes severe foaming during drilling operations, compromising operational safety and well-completion efficiency. To address this challenge, Gao et al. (2024) incorporated *N,N*-methylbisacrylamide as a crosslinking agent during the introduction of lauryl methacrylate to alleviate foaming. Li et al. (2024b) synthesized a novel monomer bearing both an imidazole ring and a hydrophobic chain through the reaction of 1-vinylimidazole with 1-chlorododecane. This monomer was subsequently copolymerized with DMAA, DMDAAC, AMPS, and APE to yield DADC (Fig. 11(b)). The incorporation of the imidazole ring enhanced the solubility of the hydrophobic chain, eliminating the need for surfactants during polymerization. In aqueous solution, DADC exhibited a distinct three-dimensional network through the synergistic effects of hydrophobic association, cross-linking, and zwitterionic interactions (Fig. 11(c)). The aqueous solution viscosity increased with salinity, driven by the anti-polyelectrolyte effect and salt-enhanced hydrophobic association (Fig. 11(d)). This rational molecular design eliminated the need for surfactants while imparting excellent salt resistance to the resulting polymer. After hot rolling at 200 °C, the salt-saturated base slurry containing this polymer exhibited an FL_{HTHP} value of only 12 mL, providing new insights into the molecular design of highly efficient fluid-loss-control reducers.

In conclusion, the new challenges posed by high-temperature and high-salinity drilling environments have shifted research on fluid-loss reducers beyond the direct use of commercially available monomers toward the molecular-level design of high-

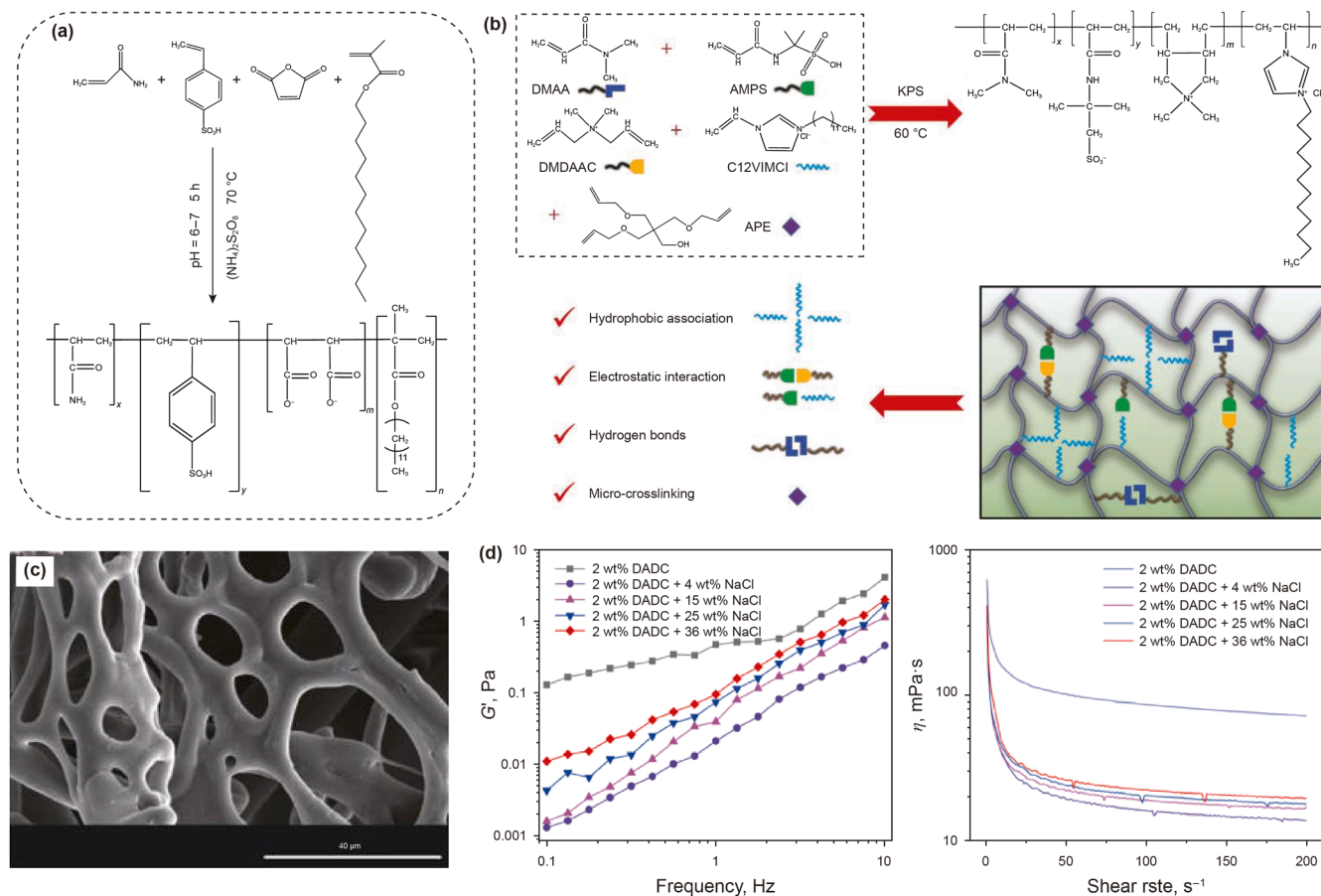


Fig. 11. (a) The synthesis procedure and structural formula of ASML. Adapted with permission from Sun et al. (2022). (b) Synthesis and schematic diagram of micro-crosslinked amphoteric hydrophobic association copolymers; (c) microstructure of DADC copolymer; (d) viscoelastic properties and viscosity variation curves of the 2 wt% DADC aqueous solution at different sodium chloride concentrations. Adapted with permission from Li et al. (2024b).

performance functional monomers. Representative examples of such custom-designed monomers include the highly stable anionic monomer SVM without conjugated structures, VBIPS with a strong anti-polyelectrolyte effect, and the hydrophobic monomer C12VMCl containing an imidazole ring. Employing these independently designed and synthesized monomers enables the regulation and optimization of fluid-loss control at the level of the polymer primary structure. On this basis, further design and regulation of higher-order structures, such as secondary structures, is emerging as a significant future development direction in this field.

3.3. Superstability of polymer structures

The previous section discussed the structural design of constituent monomers for linear polymers to enhance the temperature and salt resistance of fluid-loss reducers. In addition, improving the stability of the overall polymer structure is also an effective approach. The main methods to enhance the stability of polymer structures include constructing comb-shaped polymers by introducing long-chain side groups and adding crosslinking agents to form micro-crosslinked structures. In summary, the core concept of the above-mentioned method is to introduce monomers with stronger steric hindrance or to establish stronger interactions within polymer structures, thereby improving structural stability under harsh conditions and enhancing temperature and salt resistance. The following section provides a

detailed overview of the recent progress achieved through these methods.

Comb polymers refer to polymers in which one type of monomer unit possesses a significantly longer chain than the others, resulting in a structure resembling a comb (Abbasi et al., 2019; Liu et al., 2020b). Compared with linear polymers, the increased steric hindrance provided by the long-chain side groups enhances the polymer's rigidity, thereby improving structural stability and resistance to contamination. Polyoxyethylene chains are commonly used as long side groups for preparing comb polymers, including allyl polyoxyethylene ether (APEG) (Huang et al., 2025; Liu et al., 2018a, 2018b) and isopentenyl polyoxyethylene ether (TPEG) (Yang et al., 2024b). Liu et al. (2018a) prepared comb-shaped loss reducers using AM, AMPS, NVP, and APEG (Fig. 12(a)). These reducers decreased the medium pressure fluid loss of the base slurry to less than 10 mL after hot rolling at 180 °C, without causing significant viscosity increase.

Notably, despite its relatively high molecular weight ($M_w = 439427$), the polymer maintained apparent viscosities below 15 mPa·s at a dosage of 2 wt% both before and after hot rolling, avoiding the significant viscosity increase observed in commercial linear polymers such as JT888 and SY-3. This comb polymer forms a three-dimensional network via self-assembly of amide/sulfonic groups with ether oxygen atoms (Fig. 12(b)) and interacts with bentonite through anchoring groups, with its polyethylene glycol chains inserting into the interlayer spaces of bentonite (Fig. 12(c)). This promotes clay hydration and dispersion,

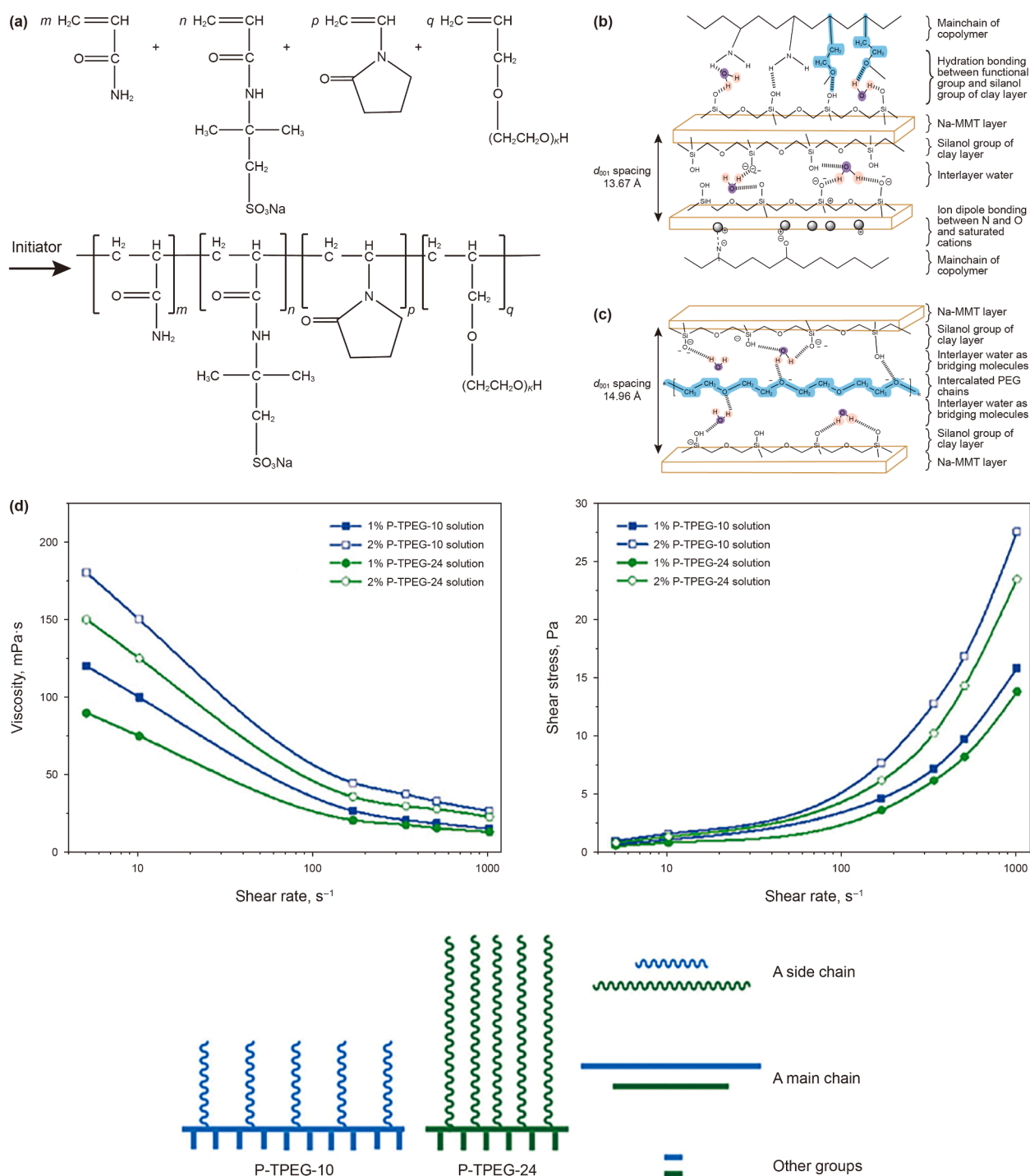


Fig. 12. (a) Schematic diagram of comb polymer synthesis; (b) schematic illustration of APEG side chains intercalating between bentonite layers; (c) interactions between comb polymers and clay. Adapted with permission from [Liu et al. \(2018a\)](#). (d) Rheological properties of comb polymers with varying side chain lengths. Adapted with permission from [Yang et al. \(2024b\)](#).

thereby enhancing fluid-loss control performance beyond simple viscosity enhancement. The research group further synthesized a novel high-temperature-resistant comb-shaped fluid-loss additive using AMPS, NVP, SSS, and APEG (Liu et al., 2018b). After hot rolling at 200 °C, the base slurry containing this additive maintained API fluid loss below 10 mL, markedly outperforming the linear polymer NS-1 ($FL_{API} = 19.2$ mL). Crucially, unlike linear PAC polymers, this additive does not increase the viscosity of the base slurry due to steric hindrance and electrostatic repulsion. In addition, the

influence of side-chain length on the performance of comb polymers has also been further explored. Yang et al. (2024b) prepared comb-shaped polymers with different side chain lengths using TPEG-1000 and TPEG-2400 to withstand with high temperatures of 220 °C and contamination with 15 wt% NaCl or 0.5 wt% CaCl₂. The results showed that TPEG-1000, with shorter side chains, exhibited higher viscosity (Fig. 12(d)). This can be attributed to its shorter comb-like structure, which tends to adopt a worm-like conformation and is therefore more prone to chain

entanglement, leading to higher solution viscosity than the long-comb polymer with a star-like conformation. However, comb polymers with longer side chain lengths exhibited lower fluid loss, probably because the longer side chains provided stronger structural stability.

Introducing crosslinking agents to construct a spatial network among traditional linear polymer chains is another effective strategy for enhancing polymer structural stability. Crosslinked polymers reduce the mobility of polymer chains to a certain extent, thereby improving the thermal resistance and contamination resistance of polymers (Ma et al., 2016; Yang et al., 2024a). Commonly used crosslinking agents include divinylbenzene (DVB), *N,N*-methylene diacrylamide (MBA) (Gao et al., 2024; Tchameni et al., 2025), triallylamine (Dong et al., 2024; Li et al., 2022b), pentaerythritol triallyl ether (APE) crosslinker (Li et al., 2024b; Wang and Ding, 2021; Wang et al., 2022a). Based on this strategy, researchers incorporated crosslinking agents into linear polymers, zwitterionic polymers, and hydrophobic association polymers to develop high-performance fluid-loss additives with enhanced temperature and salt resistance. For instance, a base slurry treated with a zwitterionic-triallylamine copolymer exhibited an apparent viscosity of 41 mPa·s and an API fluid loss of only 8 mL after hot rolling in saturated saline at 200 °C (Li et al., 2022b). Similarly, treatment with an LMA-triallylamine polymer resulted in an apparent viscosity of 24.5 mPa·s and an API fluid loss of 9.2 mL (Dong et al., 2024).

Furthermore, researchers enhanced the performance of the fluid-loss-control agent by optimizing the type of crosslinking agent and introducing multidimensional crosslinking methods. Gao et al. (2024) prepared a fluid-loss reducer with a dual chemical-physical crosslinking, utilizing LMA as the hydrophobic group and MBA as the crosslinking agent. The fluorescence spectroscopy analysis revealed that polymers with additional crosslinking agents had lower I_1/I_3 values compared to those containing only hydrophobic groups, indicating that chemical crosslinking enhances hydrophobic association between polymer chains (Fig. 13(b) and (c)). Owing to the dual effects of micro-crosslinking and hydrophobic association (Fig. 13(a)), the freshwater base slurry containing 2 wt% polymer showed a gradual increase in FL_{HTHP} as the hot rolling temperature increased from 180 to 220 °C, reaching 37.8 mL at 220 °C. In contrast, the base slurry treated with the polymer without a crosslinker exhibited a sharp increase in FL_{HTHP} to 60 mL above 200 °C, highlighting the critical role of crosslinking in inhibiting polymer degradation and enhancing thermal stability. Guo et al. (2024a) incorporated divinylbenzene and triethoxyvinylsilane (A-151) as crosslinkers into zwitterionic polymers, constructing planar (AASDD-2) and three-dimensional (AASDD) networks by regulating the hydrolysis and condensation of silane in A-151 (Fig. 13(d)). The steric hindrance provided by AASDD is stronger than that of the two-dimensional network, resulting in a higher zeta potential for the AASDD-containing base fluid after thermal rolling at 210 °C than that of AASDD-2

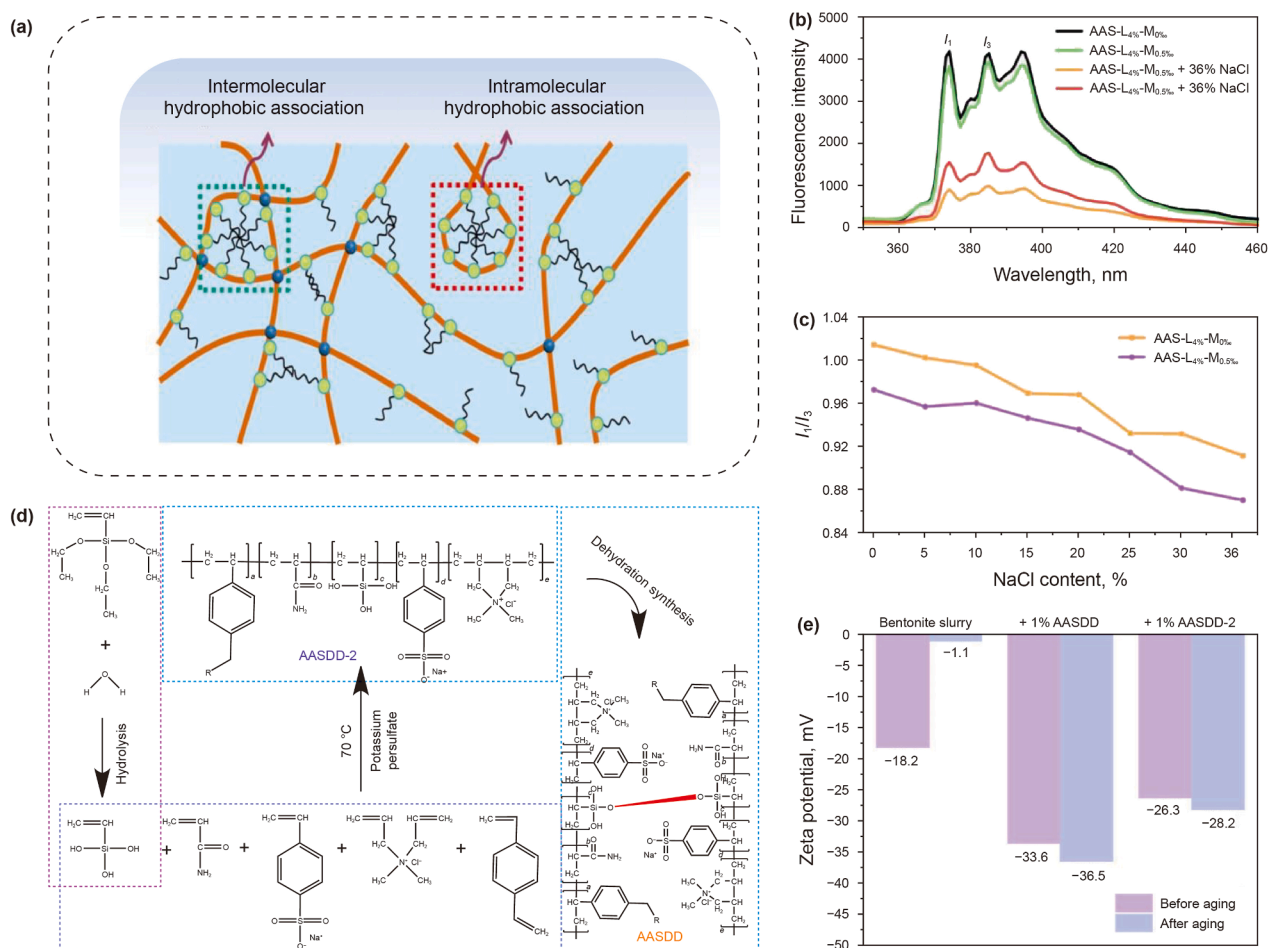


Fig. 13. (a) Schematic diagram of hydrophobic crosslinking and physical crosslinking; (b) fluorescence spectra of the copolymers; (c) I_1/I_3 ratio for different polymers at varying NaCl concentrations. Adapted with permission from Gao et al. (2024). (d) Synthesis diagram of two-dimensional AASDD-2 and three-dimensional AASDD fluid-loss-control agents; (e) zeta potential results for bentonite slurry before and after adding fluid-loss-control agents. Adapted with permission from Guo et al. (2024a).

(−36.5 eV vs. −28.2 eV) (Fig. 13(e)). AASDD's superior base slurry stabilization capability enhances its fluid-loss control. After hot rolling at 210 °C for 16 h, the AASDD-containing slurry maintained an FL_{HTHP} of 24 mL, compared to 31 mL for AASDD-2 under identical conditions. Furthermore, after three days of hot rolling, the viscosity of the AASDD-treated slurry remained approximately 24 mPa·s with FL_{API} below 10 mL, whereas AASDD-2 showed significant performance degradation, with viscosity dropping to 8.5 mPa·s and FL_{API} increasing to 32 mL. In summary, AASDD exhibited long-lasting thermal stability and this polymer also resists contamination from saturated brine or 6 wt% $CaCl_2$ solutions.

In summary, the introduction of comb-like side chains or crosslinking agents can mitigate the influence of external environments on polymer conformation, thereby maintaining a highly stable polymer structure and enhancing temperature and salt resistance. Moreover, researchers are increasingly focused on the precise construction of polymer superstable structures. Progress has evolved from the simple addition of comb-like side chains to systematic investigations of how side-chain length influences polymer properties, and from the construction of planar cross-linked structures to the development of three-dimensional crosslinked networks. This strategy for improving polymer structural stability also broadens the optimization scope for the controllable structural design of highly efficient fluid-loss reducers.

3.4. Controllable incorporation of inorganic materials

Combining the rigidity, dimensional stability, and thermal stability of inorganic nanomaterials with the toughness and processability of polymers has emerged as a research focus for improving drilling-fluid-loss control in recent years. Nanomaterials refer to ultrafine materials with particle sizes ranging from 1 to 100 nm. Common examples include silica (SiO_2) (Cheng et al., 2025; Shi et al., 2025; Sun et al., 2026), titanium dioxide (TiO_2), graphene oxide (Li et al., 2026), and laponite (LAP), etc. (Cao et al., 2025; Fu et al., 2025; Li et al., 2025f). With the rapid advancement of nanotechnology, the use of micro- and nanomaterials to formulate high-performance drilling fluids has become increasingly feasible. Researchers have developed various nanomaterial-based loss-control agents that demonstrate outstanding performance. Recently, the integration of nanomaterials and polymers has gradually evolved from a simple combination of two components to the design of more refined composite materials. Representative strategies include integrating inorganic materials of differing geometries, incorporating inorganic materials with varied particle sizes, optimizing bridging agents between inorganic and organic components, and controlling the orientation of polymer grafting onto inorganic materials. This section first discusses recent developments in common silicon-based composite fluid-loss reducers, followed by a brief overview of advances in other inorganic materials. Table 2 lists the fluid-loss reduction properties of typical organic/polymer composites.

Silicon dioxide is a common nanomaterial with abundant surface hydroxyl groups, which provide active sites for chemical modification. However, owing to the large specific surface area of silica nanomaterials and the mutual attraction between surface hydroxyl groups, silica nanoparticles are prone to agglomeration, preventing full utilization of their nanoscale advantages. Silane coupling agents can react with surface hydroxyl groups and simultaneously introduce carbon–carbon double bonds that participate in free-radical polymerization. This not only improves the dispersibility of nanomaterials but also enables further controllable modification of inorganic materials. Ma et al. (2019)

pioneered the use of vinyltrimethoxysilane as a coupling agent between silica nanomaterial and organic compounds. They synthesized the composite loss control agent PAAN- SiO_2 by polymerizing AM, AMPS, and NVP on the silica surface. After hot rolling at 200 °C, the PAAN- SiO_2 -treated base slurry maintained an FL_{API} below 10 mL. In contrast, for the PAAN system without inorganic material modification, the FL_{API} increased significantly after hot rolling at temperatures exceeding 150 °C, reaching 29.6 mL at 200 °C. This demonstrates the advantage of introducing inorganic nanomaterials in enhancing fluid-loss control. On this basis, researchers further replaced AM with the more thermally stable monomer DMAA or incorporated the high-temperature-resistant group NVCL to enhance the fluid-loss reduction performance of the filtrate reducer. Representative systems include DMAM-AMPS (Liu et al., 2021) and AM-AMPS-NVCL (Li et al., 2023a). Furthermore, copolymerizing silica with zwitterionic monomers effectively enhances salt resistance (Wang et al., 2023), as demonstrated in systems such as AM-AMPS-DMDAAC-NIPAM (Li et al., 2022a) and DMAA-AMPS-SSS-DMDAAC (Xiong et al., 2024). Ao et al. (2021) combined spherical silica with AMPS, DMDAAC, and NVP to prepare a fluid-loss reducer that could resist 240 °C saturated salt solution or 11 wt% $CaCl_2$ solution (Fig. 14(a)). The modified silica showed improved dispersibility in water and could refine the particle-size distribution of bentonite. Through multipoint adsorption and its nanoscale structure, it filled pores within the filter cake, thereby promoting the formation of a denser and more compact filter cake. These properties enable the base mud containing 2 wt% of this fluid-loss reducer to achieve an FL_{API} of merely 10 mL after undergoing thermal rolling at 240 °C under saturated NaCl contamination. Furthermore, ZSHNM effectively mitigates the calcium-promoted aggregation of bentonite (Fig. 14(b)), thereby maintaining the FL_{API} of the base slurry below 15 mL under harsh conditions of 240 °C and 11 wt% $CaCl_2$ solution with only 2 wt% polymer concentration (Fig. 14(d)). Notably, after exposure to 11 wt% $CaCl_2$ contamination and hot rolling at 240 °C, the apparent viscosity of the base slurry containing this filtrate reducer was 11.5 mPa·s, lower than that of the untreated base slurry (14.5 mPa·s) (Fig. 14(c)). This indicates that the fluid-loss reducer does not achieve its fluid-loss control properties through viscosity enhancement, but rather by improving the density of the filter cake. This finding has important implications for simultaneously optimizing rheological behavior and fluid-loss control during drilling operations.

The preceding section demonstrated the advantages of combining polymers with inorganic silica nanomaterials. Recently, researchers have advanced further by constructing more sophisticated hybrid materials, such as selecting appropriate bridging agents, optimizing the size of inorganic materials and controlling the orientation relationship between inorganic materials and polymers. The selection of suitable bridging agents between nanomaterials and polymers is critical, with methacryloxy propyl trimethoxyl silane (KH570) and vinyl trimethoxysilane commonly used for this purpose. A novel modification method has recently been explored. Specifically, Wandji Djouonkep et al. (2024) modified silica by sequentially applying 3-aminopropyltriethoxysilane (APTES) and VTEO (Fig. 15(a)). Compared with KH570-modified SiO_2 , this approach avoids the introduction of ester bonds into the interfacial linkages, thereby improving the thermal stability of the composite. And it triples the surface area of the silica nanomaterials, endowing the nanomaterial with additional active sites that facilitate subsequent polymer grafting. Furthermore, modified silica was polymerized with DMAA, AMPS, DAC, and NVP to produce a composite filtrate reducer (Nano-DAVD), which demonstrated superior fluid-loss reduction compared to pure polymer DAVD. After contamination with

Table 2

Performance summary of inorganic material/polymer composite fluid-loss reducers.

Types of inorganic materials	Composition of organic polymers	Polymer properties (thermal stability ^a , molecular weight)	Optimal concentration	Temperature tolerance and salt tolerance	Optimal performance (after hot rolling)	Advantages/finding	Limitations	References
SiO ₂	AM-AMPS-St-MA	290 °C, $M_w = 7.36895 \times 10^5$	1.0 wt%	220 °C, base slurry	AV = 42 mPa·s, FL _{API} = 5.4 mL, FL _{HTHP} = 16.0 mL	Enhanced thermal stability	Restricted salt tolerance at elevated temperatures	Mao et al. (2015)
			0.8 wt%	230 °C, 36 wt% NaCl	AV = 26 mPa·s, FL _{API} = 8.2 mL, FL _{HTHP} = 22.0 mL			
SiO ₂	AM-AMPS	293 °C, not mentioned	2 wt%	180 °C, base slurry	FL _{API} = 5.6 mL, FL _{HTHP} = 14.6 mL	Minimal impact on mud cake permeability	No mention of salt (NaCl/CaCl ₂) tolerance	Liu et al. (2021)
SiO ₂	AM-AMPS-NVP	312.6 °C, not mentioned	2 wt%	200 °C, base slurry	FL _{API} = 8.0 mL			
			2 wt%	180 °C, 2 wt% CaCl ₂	FL _{API} = 6.0 mL	Divalent cation tolerance	Restricted calcium tolerance at temperatures except 170–180 °C	Ma et al. (2019)
SiO ₂	AM-AMPS-NVCL	300 °C, not mentioned	1.5 wt%	220 °C, base slurry	FL _{API} = 13.25 mL	Enhanced thermal stability	Restricted salt tolerance at elevated temperatures	Li et al. (2023a)
			2.0 wt%	180 °C, 30 wt% NaCl	FL _{API} = 52.0 mL			
			2.0 wt%	180 °C, 2 wt% CaCl ₂	FL _{API} = 52.0 mL	Sodium chloride tolerance	Higher cost due to expensive monomers (NIPAM)	Li et al. (2022a)
SiO ₂	AM-AMPS-DMDAAC-NIPAM	280 °C, not mentioned	2 wt%	200 °C, base slurry	AV = 20 mPa·s, FL _{API} = 8.0 mL			
			2 wt%	200 °C, 36 wt% NaCl	AV = 26 mPa·s, FL _{API} = 12.0 mL	Enhanced thermal stability	No mention of divalent cation tolerance	Xiong et al. (2024)
SiO ₂	DMAA-AMPS-SSS-DMDAAC	323.4 °C, $M_w = 111137$	1 wt%	260 °C, base slurry	FL _{API} = 8.8 mL, FL _{HTHP} = 34.0 mL			
			3 wt%	220 °C, 15 wt% NaCl	AV = 26 mPa·s, FL _{API} = 8.0 mL, FL _{HTHP} = 46.0 mL	Enhanced thermal stability	No mention of long-term stability under cyclic temperature	Ao et al. (2021)
SiO ₂	AMPS-DMDAAC-NVP	308.0 °C, not mentioned	2 wt%	240 °C, base slurry	AV = 11.5 mPa·s, FL _{API} = 10.2 mL			
			2 wt%	240 °C, 11 wt% CaCl ₂	FL _{API} = 12.8 mL	Superior divalent cation tolerance	High rejection to polyamine shale inhibitors	Yang et al. (2023c)
SiO ₂	AMPS-DMDAAC-NVP	294.6 °C, not mentioned	2 wt%	240 °C, 36 wt% NaCl	FL _{API} = 10.0 mL			
			2 wt%	250 °C, base slurry	AV = 10.5 mPa·s, FL _{API} = 10.2 mL	Enhanced thermal stability	No mention of divalent cation (Ca ²⁺) tolerance	Wandji Djouonkep et al. (2024)
			2 wt%	250 °C, 11 wt% CaCl ₂	FL _{API} = 13.8 mL			
SiO ₂	DMAA-AMPS-DAC-NVP	319 °C, not mentioned	2.5 wt%	250 °C, 36 wt% NaCl	AV = 10.5 mPa·s, FL _{API} = 3.6 mL, FL _{HTHP} = 30.0 mL	Enhanced thermal stability	No mention of divalent cation (Ca ²⁺) tolerance	He et al. (2024)
OV-POSS	AM-AMPS-DMDAAC	304.2 °C, not mentioned	2 wt%	240 °C, 15 wt% NaCl	AV = 12.5 mPa·s, FL _{API} = 35.8 mL	Enhanced thermal stability	No mention of divalent cation (Ca ²⁺) tolerance	Lin and Luo (2024)
						Superior sodium chloride tolerance		
SiO ₂ and Iaponite	DMAA-AMPS-DMDAAC-NVP	220 °C, $M_n = 227271$	3.5 wt%	230 °C, 15 wt% NaCl	FL _{API} = 4.2 mL, FL _{HTHP} = 22.0 mL	Enhanced thermal stability	No mention of divalent cation (Ca ²⁺) tolerance	Lin and Luo (2024)
CaCO ₃ (15 nm)	AM-AMPS-MA-St	300 °C, $M_w = 6.98 \times 10^5$	1.5 wt%	200 °C, base slurry	AV = 37.5 mPa·s, FL _{API} = 4.0 mL, FL _{HTHP} = 14.4 mL	Excellent colloidal stability at high temperature	No mention of salt (NaCl/CaCl ₂) tolerance	Tang et al. (2022)
CaCO ₃ (96.6 nm)	AM-AMPS-AA-MBA	301 °C, not mentioned	1 wt%	220 °C, base slurry	FL _{API} = 10.0 mL, FL _{HTHP} = 60.0 mL	Enhanced thermal stability	Restricted salt tolerance at elevated temperatures	Zhong et al. (2023)
			1 wt%	200 °C, 30 wt% NaCl	FL _{API} = 40.0 mL	Excellent plugging performance for micro/nano-pores	No mention of salt (NaCl/CaCl ₂) tolerance	Li et al. (2025d)
			1 wt%	200 °C, 0.5 wt% CaCl ₂	FL _{API} = 25.0 mL			
TiO ₂ (20–25 nm)	AMPS-DMDAAC-ACMO	282 °C, not mentioned	2.5 wt%	180 °C, base slurry	AV = 13.5 mPa·s, FL _{API} = 6.4 mL, FL _{HTHP} = 16.4 mL			

(continued on next page)

Table 2 (continued)

Types of inorganic materials	Composition of organic polymers	Polymer properties (thermal stability ^a , molecular weight)	Optimal concentration	Temperature tolerance and salt tolerance	Optimal performance (after hot rolling)	Advantages/finding	Limitations	References
TiO ₂	DMAA-AMPS-DMDAAC-NVP	292.3 °C, not mentioned	2 wt%	260 °C, base slurry	AV = 27.5 mPa·s, FL _{API} = 10.2 mL, FL _{HTHP} = 25.0 mL	Excellent sodium chloride and calcium chloride tolerance	Long-term stability beyond 72 h not verified	Zhang et al. (2025b)
			2 wt%	260 °C, 40 wt% NaCl	AV = 30 mPa·s, FL _{API} = 6.1 mL, FL _{HTHP} = 70.0 mL			
			2 wt%	260 °C, 5 wt% CaCl ₂	AV = 12 mPa·s, FL _{API} = 9.2 mL, FL _{HTHP} = 78.0 mL			
Go	AM-AMPS-NVP	Not mentioned	2 wt%	240 °C, base slurry	FL _{API} = 12.5 mL	Excellent sodium chloride and calcium chloride tolerance	Higher cost due to expensive monomers (Go)	Ma et al. (2021)
			2 wt%	150 °C, 25 wt% NaCl	AV = 25 mPa·s, FL _{API} = 9.0 mL			
Go	DMAA-AMPS-ACMO	264 °C, not mentioned	2 wt%	150 °C, 25 wt% CaCl ₂	AV = 22.5 mPa·s, FL _{API} = 15.2 mL	Strong adsorption on bentonite surface, reducing particle agglomeration	No mention of divalent cation (Ca ²⁺) tolerance	Li et al. (2025e)
			3 wt%	220 °C, 15 wt% NaCl	AV = 18 mPa·s, FL _{API} = 13.6 mL, FL _{HTHP} = 27.4 mL			
LAP (20 nm)	AM-AMPS-DMDAAC	306 °C, not mentioned	2 wt%	200 °C, base slurry	AV = 20 mPa·s, FL _{API} = 10.4 mL, FL _{HTHP} = 72.0 mL	Excellent saturated salt tolerance, thickens clay hydration layer	No mention of divalent cation (Ca ²⁺) tolerance	Dong et al. (2022b)
			2 wt%	150 °C, 35 wt% NaCl	AV = 23.5 mPa·s, FL _{API} = 6.4 mL			
LAP	DMAA-AMPS-DMDAAC-NVP-PEG-1000	305.3 °C, M _n = 1062538	2 wt%	240 °C, 15 wt% NaCl	AV = 25.5 mPa·s, FL _{API} = 9.0 mL, FL _{HTHP} = 41.6 mL	Forms reversible “dual” spatial network, superior shear thinning behavior	No mention of divalent cation (Ca ²⁺) tolerance	Yang et al. (2023b)
LAP	AM-AMPS-DMDAAC-ACMO	306.5 °C, not mentioned	2 wt%	180 °C, 15 wt% NaCl	AV = 28.5 mPa·s, FL _{API} = 7.1 mL, FL _{HTHP} = 29.2 mL	Strengthens clay hydration layer, seals formation pores/cracks	No mention of divalent cation (Ca ²⁺) tolerance	Yang et al. (2022)
LAP	AM-AMPS-DMDAAC-NVP	321 °C, not mentioned	1.0 wt%	240 °C, base slurry	AV = 20 mPa·s, FL _{API} = 9.0 mL, FL _{HTHP} = 39.2 mL	Outperforms commercial filtrate reducers, forms dense smooth filter cake	No mention of salt (NaCl/CaCl ₂) tolerance	Lin et al. (2024a)
			1.5 wt%	240 °C, base slurry	AV = 40 mPa·s, FL _{HTHP} = 29.0 mL			
LAP	DMAA-AMPS-DMDAAC-ACMO	Not mentioned	3 wt%	220 °C, 20 wt% NaCl	AV = 20 mPa·s, FL _{API} = 7.0 mL, FL _{HTHP} = 28.6 mL	Enhanced thermal stability	No mention of divalent cation (Ca ²⁺) tolerance	Luo et al. (2024)
Polyoxyalkylsilane	DMAA-AMPS-DMDAAC-NVP	282.8 °C, not mentioned	2 wt%	240 °C, base slurry	FL _{API} = 9.2 mL	Enhanced tolerance to divalent cations	Higher cost due to expensive monomers	Yang et al. (2026)
			2 wt%	240 °C, 36 wt% NaCl	FL _{API} = 14.2 mL			
			2 wt%	220 °C, 74 wt% CaCl ₂	FL _{API} = 13.8 mL			

^a The temperature at which significant mass loss occurs.

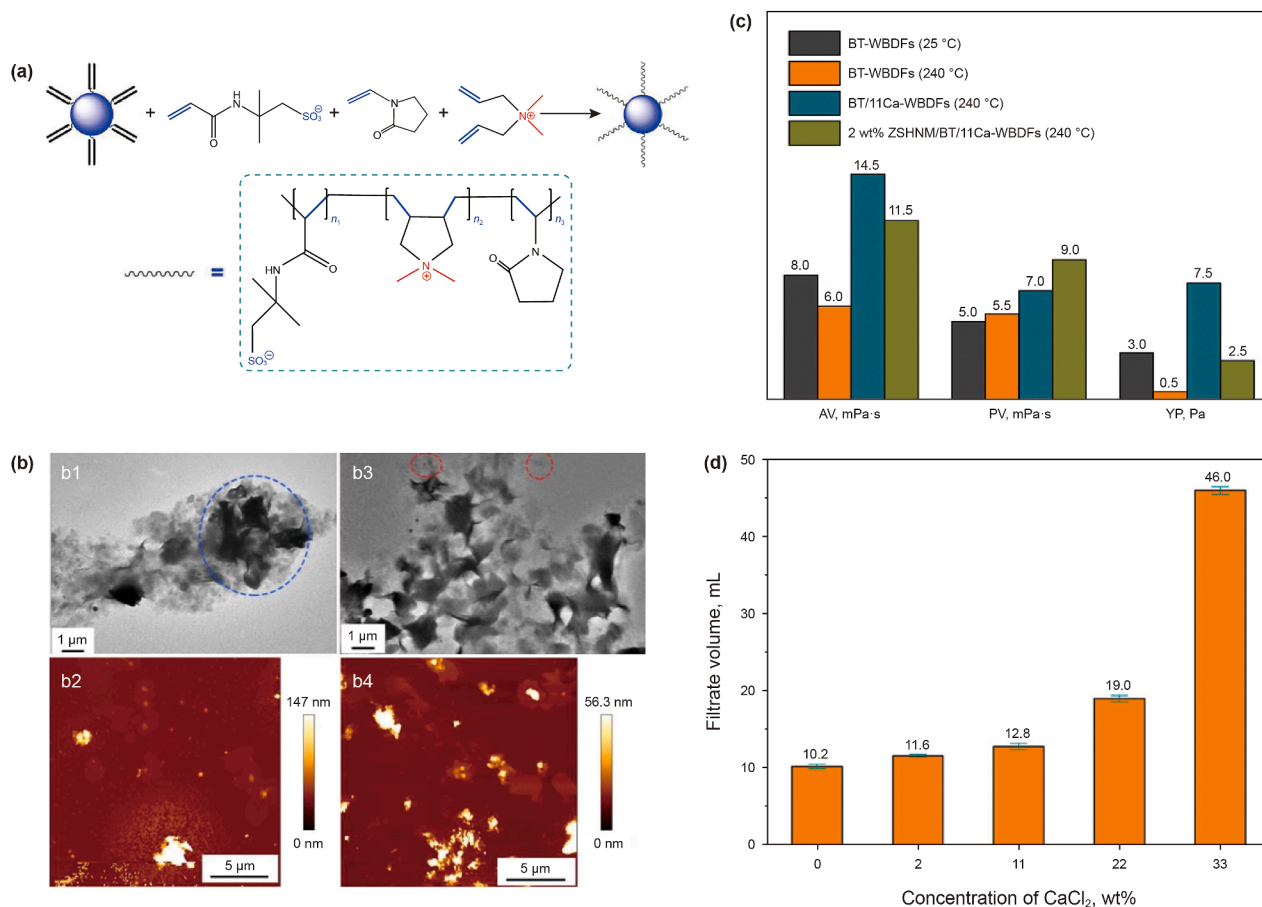


Fig. 14. (a) Schematic diagram of ZSHNM synthesis; (b) transmission electron microscopy and atomic force microscopy (AFM) images: (b1, b2) microstructure of bentonite after adding only 2 wt% CaCl_2 ; (b3, b4) microstructure of bentonite after simultaneously adding 2 wt% ZSHNM and 2 wt% CaCl_2 ; (c) rheological properties of 0–2.0 wt% ZSHNM/BT-WBDFs at 25 and 240 °C; (d) filtrate volume after 16 h hot rolling at 240 °C with 2 wt% ZSHNM under different calcium contamination levels. Adapted with permission from Ao et al. (2021).

15 wt% NaCl at 240 °C, the base slurry with 2.5 wt% Nano-DAVD exhibited an FL_{API} of only 3.6 mL and an FL_{HTHP} of 30 mL, whereas the DAVD system showed 8.0 and 55.5 mL, respectively (Fig. 15(c)). The enhanced performance of Nano-DAVD is attributed to its ability to maintain a finer and more favorable particle size distribution of bentonite after hot rolling, as demonstrated in Fig. 15(b). The properties of composite materials can also be enhanced by optimizing the nanoscale dimensions of inorganic materials, Yang et al. (2023c) synthesized two composite materials with silica cores of 20 nm (ZSHNM-1) and 200 nm (ZSHNM-2), and found that larger core size improved fluid-loss control. At 240 °C with 11 wt% CaCl_2 contamination, the base slurry containing 2 wt% ZSHNM-1 exhibited an FL_{API} of approximately 13 mL, whereas ZSHNM-2 reduced the FL_{API} to about 5 mL. The superior salt resistance of ZSHNM-2 is attributed to longer polymer chains and more hydrophilic and ionic groups resulting from the reduced number of inorganic nuclei. After high-temperature hot rolling and CaCl_2 contamination, the ZSHNM-2 system maintained a broader particle size distribution with increased fine particles (Fig. 15(d)) while exhibited significantly enhanced colloidal stability (zeta potential: -10.2 mV vs. -8.8 mV, Fig. 15(e)), synergistically promoting the formation of a denser filter cake and effectively reduced fluid loss. Moreover, the arrangement of nanomaterials within polymer matrices has gradually evolved from random dispersion toward controllable spatial organization, as exemplified by cage-like polyhedral oligomeric silsesquioxane (POSS), which enables the introduction of organic groups at

defined positions (Bai et al., 2020). He et al. (2024) used octa-vinyl polysiloxane, a POSS-based inorganic nanomaterial bearing terminal carbon–carbon double bonds, and copolymerized it with AM, AMPS, and DMAAC to prepare a fluid-loss reducer capable of withstanding 220 °C and 20 wt% NaCl (Fig. 15(f)).

In addition to the composite fluid-loss reducer based on silica nanomaterials, other composite materials have also gradually developed (Ahmed et al., 2025), such as TiO_2 (Sadeghalvaad and Sabbaghi, 2015; Tang et al., 2025), CaCO_3 , LAP, GO (Movahedi et al., 2021), polysiloxane (Lin et al., 2024b), etc. Various nanomaterials have different characteristics. For instance, commonly used SiO_2 exhibits excellent chemical stability, and its surface hydroxyl groups facilitate further modification. However, its inherent brittleness limits the formation of a robust structure under harsh conditions (Li et al., 2025d). Calcium carbonate is inexpensive and can be generated in situ directly, enabling monomers to polymerize on its surface through favorable interfacial compatibility (Tang et al., 2022; Zhong et al., 2023). On this basis, a fluid-loss-control agent resistant to 200 °C and 30 wt% NaCl has been prepared (Zhong et al., 2023). However, the poor structural integrity of sodium carbonate at elevated temperatures continues to restrict its application under higher temperatures (Li et al., 2025d). Compared to silica nanomaterials, TiO_2 demonstrates superior thermal and mechanical stability (Li et al., 2025d; Sadeghalvaad and Sabbaghi, 2015; Sarokolai and Shiri, 2025; Tang et al., 2025). TiO_2 has been hybridized with polymers such as AM, AA-AMPS-LAM, AMPS-DMAAC-ACMO, and DMAA-AMPS-

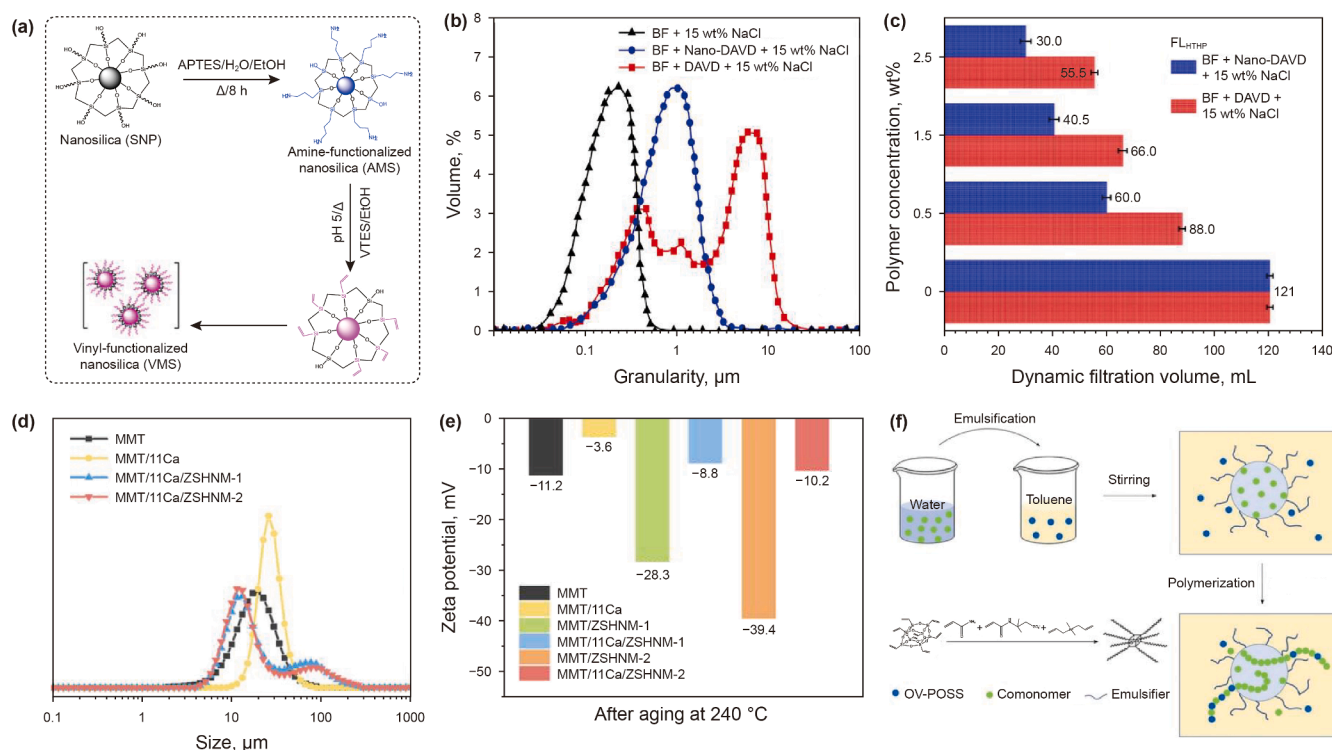


Fig. 15. (a) Surface functionalization process of silica nanoparticles; (b) particle size distribution curves; (c) HTHP properties of different dispersion systems under conditions of 240 °C and 15 wt% NaCl. Adapted with permission from Wandji Djouonkep et al. (2024). (d) Particle size distribution curves; (e) zeta potential values of different dispersion systems after 16 h of hot rolling at 240 °C. Adapted with permission from Yang et al. (2023c). (f) Schematic diagram of POSS-polymer synthesis. Adapted with permission from He et al. (2024).

DMDAAC-NVP, successfully overcoming the limitations associated with 260 °C and saturated salt environments (Li et al., 2025d; Zhang et al., 2025b). Furthermore, flake-structured Go (Abdullah et al., 2024; Movahedi et al., 2021), and LAP (Lin et al., 2024a; Luo et al., 2024; Yang et al., 2022, 2023b) have also demonstrated progress in enhancing resistance to temperature and salt in composite fluid-loss control. Aramendiz and Imqam (2019) found that graphene flakes exhibit superior fluid-loss control compared to silica nanomaterials. Li et al. (2025e) polymerized graphene oxide with DMAA, AMPS, and *N*-acryloylmorpholine (ACMO) to prepare a composite fluid-loss reducer capable of withstand 220 °C and 15 wt% NaCl contamination (Fig. 16(a)), yet its high cost remains a primary challenge. Furthermore, researchers have also explored the enhancement of fluid-loss control by integrating two types of inorganic materials (Ahmed et al., 2024), such as combining multiwalled carbon nanotubes with TiO₂ (Khan et al., 2024), or incorporating silica with LAP (Khan et al., 2024). Additionally, the selection of inorganic materials is not always rigid. Recently, researchers have also investigated the fluid-loss reduction performance of polyoxysilanes as flexible nanomaterials into polymers systems (Li et al., 2025b; Lin et al., 2024b; Ni et al., 2026; Yang et al., 2026). Fig. 16(b) shows the synthesis flowchart of the modified siloxane monomer, which was copolymerized with AM, AMPS, and NVCL to prepare a novel modified polysiloxane fluid-loss additive (Lin et al., 2024b). With 1 wt% of this additive, the base slurry exhibited an API fluid loss of only 8.8 mL after hot rolling at 220 °C for 16 h. Yang et al. (2026) introduced polyoxysilane into a zwitterionic polymer to develop a highly effective fluid-loss-control agent resistant to divalent cations. Benefiting from the flexibility of the silane segments, the composite could more effectively penetrate and plug pores within the filter cake, thereby enhancing its compactness. This innovation overcomes

limitations associated with divalent-cation resistance, achieving an API fluid loss of only 4.3 mL under saturated CaCl₂ contamination at 220 °C (Fig. 16(c)) and only 14.2 mL under 30 wt% CaCl₂ contamination at 240 °C. In a field application in Xinjiang block, the material withstood high temperature of 150 °C and multivalent cation contamination, maintaining an HTHP fluid loss below 12 mL. This achievement not only validates the reliability of the material but also points to a new direction for the molecular design of filtrate reducers resistant to high-valent cations.

Generally speaking, the incorporation of nanomaterials can enhance the thermal resistance of polymers. However, under severe conditions, the bridging structures between the two components or the polymer itself may become unstable and undergo partial degradation. Degradation is not entirely detrimental, the released nanoparticles may even further increase the density of the filter cake, thereby controlling filtrate loss. Lin and Luo (2024) prepared nanocomposites with nano-silica/nano-laponite as the core, KH570 as the bridge, and DMAA, AMPS, DMDAAC, and NVP as the shell layer. At 220 °C in an aqueous environment, the nanomaterials escape from the polymer network, yet the nanoparticles remain connected to a small amount of polymer, forming shorter molecular chains (Fig. 16(d)). The escaped nanoparticles can still physically block nanopores within the filter cake, while the short polymer chains attached to them enhance their adhesion within the cake. Consequently, filtrate loss remains effectively controlled under conditions of 230 °C and 15 wt% NaCl (FL_{API} = 4.2 mL, FL_{HTHP} = 22 mL). Luo et al. (2023) also found that the filtrate loss at 240 °C was comparable to that at 220 °C because of the release of nano-styrene. However, although nanoparticles released from polymers at high temperatures can contribute to fluid-loss reduction to some extent, the effective range of this effect remains limited. Enhancing the thermal and salt-resistance stability

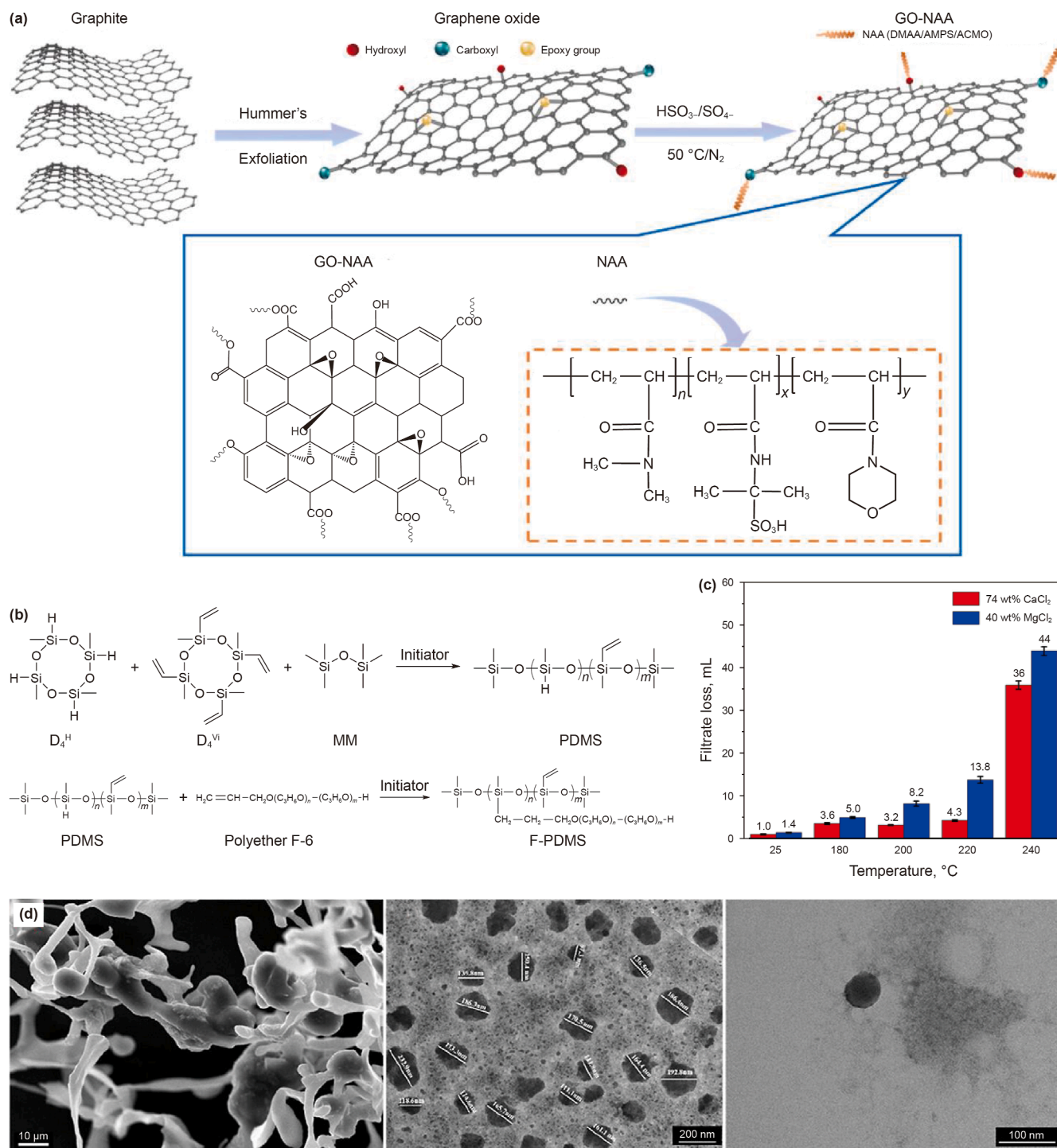


Fig. 16. (a) Preparation process of graphene oxide/polymer composites. Adapted with permission from Li et al. (2025e). (b) Synthesis of modified siloxane monomers. Adapted with permission from Lin et al. (2024b). (c) API fluid losses of 2 wt% flexible composite base slurry contaminated by 74 wt% CaCl₂ or 40 wt% MgCl₂ after hot rolling at different temperatures for 16 h. Adapted with permission from Yang et al. (2026). (d) The microscopic morphology of NP-3 after thermal degradation at 230 °C. Adapted with permission from Lin and Luo. (2024).

of composite materials remains a primary focus for future research.

In summary, the incorporation of inorganic nanomaterials into polymer matrices has significantly improved the thermal and salt resistance of fluid-loss reducers. This improvement is achieved by combining the excellent thermal stability and mechanical strength of inorganic materials with the structural tunability of flexible

polymer shells. Researchers have progressively shifted from simple material combinations toward rationally engineered composite structures. This improvement encompasses various aspects, including more efficient bridging mechanisms, optimized nano-scale dimensions, enhanced control over the orientation of inorganic–organic interfaces, and the selection of optimal nanomaterial types. Future efforts will likely focus on strengthening the

synergistic interactions between these components and harnessing their combined advantages to develop composite fluid-loss-control agents capable of withstanding elevated temperatures, high-salinity environments, and divalent salts.

In conclusion, this section systematically reviews recent progress in advanced synthetic fluid-loss reducers from four perspectives: preparation methods, monomer development, structural stability, and synergistic integration with inorganic materials. The foregoing analysis indicates that considerable progress has been made in improving resistance to high temperatures and monovalent salts. With respect to preparation methods, selecting an appropriate polymerization process and systematically optimizing the polymerization conditions are essential for fully exploiting the potential of monomer combinations and optimizing polymer performance. In terms of monomer development, anionic polymers with abundant cyclic structures have enabled freshwater-based slurries to maintain effective fluid-loss control at temperatures up to 200 °C, and in some cases even 220 °C. However, these anionic polymers are prone to chain coiling in salt solutions, resulting in poor salt resistance. Although increasing molecular weight has been explored as a strategy to improve salt tolerance, this approach often compromises the overall rheology of freshwater-based systems and still suffers from significant viscosity reduction in salt-containing environments. The emergence of zwitterionic polymers has helped overcome this limitation, exhibiting excellent performance in monovalent salt systems and even achieving a “salt-responsive” fluid-loss-control effect. On this basis, researchers have further developed novel zwitterionic monomers, thereby expanding the applicable boundaries of anti-polyelectrolyte effects. In addition, the incorporation of hydrophobic monomers enables drilling fluid system to retain viscosity through hydrophobic association upon salt intrusion, thereby improving fluid-loss control. From the perspective of structural stability, introducing comb-shaped or crosslinking monomers into the polymer structure significantly enhances its structural stability under harsh conditions such as saturated brine at 200 °C and enables effective fluid-loss control. Notably, compared with linear polymers, the introduction of comb-shaped monomers does not markedly increase system viscosity, which is particularly advantageous for maintaining drilling fluid rheology. Furthermore, the incorporation of inorganic nanomaterials can synergistically improve thermal resistance and fluid-loss control by leveraging their physical plugging effect while suppressing excessive viscosity increase. As a result, effective fluid-loss control can be achieved in base slurries contaminated with saturated brine even at 240 °C.

However, progress in improving the tolerance of fluid-loss additives to divalent cations has been relatively slow and fragmented. The initial design strategy based on anionic- Ca^{2+} chelation quickly revealed its limitations. Specifically, polymers composed solely of anionic monomers generally exhibit CaCl_2 tolerance below 3 wt%. This limitation may arise either from the insufficient utilization of the chelation effect or from the inherent inability of this mechanism to counteract multivalent-cation-induced bentonite aggregation. The introduction of strongly adsorptive cationic groups, such as DMDAAC, enables polymers to form a “star-network” structure with bentonite, thereby effectively controlling fluid loss. However, relying solely on cationic incorporation remains limited in enhancing tolerance to high-valent cations, with existing studies reporting effective control only at 150 °C and 11 wt% CaCl_2 . Subsequently, composite formation through the incorporation of common inorganic materials, such as SiO_2 , GO, and LAP, increased the temperature tolerance to 240 °C, but still failed to overcome the 11 wt% CaCl_2 threshold. Encouragingly, several recent breakthrough studies have achieved substantial improvements in CaCl_2 tolerance. For instance, by moving

beyond the conventional anti-polyelectrolyte framework of commercially available ionic monomers, researchers have designed amphoteric monomers with strong anti-polyelectrolyte effects and high thermal resistance. Polymers constructed from these monomers can withstand harsh conditions of 200 °C and 25 wt% CaCl_2 , which is difficult to achieve using traditional commercial zwitterionic monomers. Another breakthrough addressed the inherent rigidity of common nanomaterials by introducing flexible nanomaterials into polymer composites, enabling effective fluid-loss control under extreme conditions of saturated CaCl_2 at 220 °C. In summary, major advances in high-valence-cation tolerance require both fundamental innovation in monomer design and the active integration of advanced insights from other fields.

4. Environmental and economic impacts

4.1. Relevant environmental impacts

As an indispensable working medium in oil and gas exploration and development, the environmental impact of various components in drilling fluids should be given full attention to promote the green and sustainable development of the drilling cycle. Compared with oil-based or synthetic-based drilling fluids, water-based drilling fluids are generally considered to pose relatively lower environmental risks. Currently, increasingly stringent environmental regulations have imposed explicit restrictions on the use of oil-based drilling fluids, objectively driving the research, development, and application of water-based drilling fluid systems. To systematically assess and effectively mitigate environmental impacts, high priority should be given to the molecular structural design, synthesis process, and post-use treatment of synthetic polymer fluid-loss reducers. This systematic consideration of the additive's entire life cycle aligns with the core objectives of Sustainable Development Goal (SDG) 12, and is expected to meet the requirements for environmentally friendly management and significant waste reduction throughout the entire chemical product lifecycle.

The selection of monomers and synthesis methods for synthetic polymers form the basis for assessing their environmental impact. During the molecular structure design process of synthetic polymers, both functionality and environmental compatibility should be considered when selecting monomers. Table 3 lists the hazard levels of commonly used monomers, providing a basis for comprehensively assessing their impact on the environment, humans, and animals. Although most monomers possess a certain degree of toxicity, the use of monomers with higher hazard levels and greater toxicity should be avoided or minimized. Acrylamide, a commonly used adsorption monomer, has been reported to exhibit neurotoxicity, reproductive toxicity, and carcinogenicity, and its neurotoxicity in humans has been confirmed. Nevertheless, it should be noted that although acrylamide possesses certain toxicity, the toxicity of polyacrylamide is lower than that of acrylamide. On this basis, ensuring the stability of polyacrylamide under harsh conditions through molecular modification may be a feasible strategy to improve its environmental friendliness. However, the toxicity of the adsorbent monomer hydroxyethyl methacrylate is greater than that of acrylamide and *N,N*-dimethylacrylamide, and its dosage should therefore be reduced during synthesis. For anionic monomers, AMPS exhibits a lower hazard level, indicating better environmental safety than SSS and AA. Furthermore, the incorporation of degradable precursors, such as itaconic acid, lignin derivatives, and other bio-based monomers, also represents an effective pathway for improving green sustainability. However, biodegradable green precursors generally

Table 3
Summary of hazard levels for common monomers.

No.	Name	Classification	Hazard description	Hazard class
1	AM	Adsorbed monomer	Neurotoxicity and reproductive toxicity concerns	II
2	DMAA	Adsorbed monomer	Acute toxicity	II
3	HEMA	Adsorbed monomer	Skin/eye irritation	IV
4	AN	Adsorbed monomer	Acute toxicity, serious systemic toxicity	III
5	AA	Anionic monomer	Respiratory irritation, aquatic toxicity, carcinogenicity	II
6	SSS	Anionic monomer	Skin/eye irritation	III
7	AMPS	Anionic monomer	Serious eye damage, respiratory irritation	I
8	IA	Anionic monomer	Low systemic toxicity, Skin/eye/respiratory irritation	I
9	FA	Anionic monomer	Low toxicity, eye irritation	I
10	DMDAAC	Cationic monomer	Skin/eye irritation	III
11	VP	Cationic monomer	Irritation, chronic organ toxicity/hearing damage	III
12	ST	Thermally resistant monomer	Irritation, suspected reproductive toxicity	III
13	NVP	Thermally resistant monomer	Serious eye irritation, carcinogenic evidence not definitive	IV
14	VA	Hydrophobic monomer	Harmful if inhaled, respiratory irritation	II
15	BA	Hydrophobic monomer	Skin/eye irritation, skin sensitizer, aquatic hazard	III

exhibit lower thermal stability than conventional chemical monomers. Consequently, heat-resistant monomers must often be introduced to improve their fluid-loss control under high-temperature conditions, but these anti-temperature monomers such as NVP and ST may increase the overall hazard level during polymer synthesis. Therefore, achieving a balance between performance and sustainability requires careful control over the type and dosage of monomer precursors, thereby meeting the environmental requirements for highly effective filtrate reducers.

When selecting a synthesis strategy for synthetic polymers, the environmental impacts associated with the chemicals used during synthesis and the subsequent separation processes should be fully considered. The commonly used methods of free radical polymerization include aqueous solution polymerization, emulsion polymerization, suspension polymerization, and solvent-free polymerization, etc. Solvent-free polymerization completely eliminates the use of solvents and is therefore advantageous for reducing solvent-related environmental impacts. However, the polymerization process is difficult to control in solvent-free systems, which may lead to premature polymerization and localized overheating. These issues can result in an uneven molecular weight distribution of the polymer and ultimately reduce the performance of the product. Suspension polymerization solves the heat dissipation problem of bulk polymerization and can directly produce powder or granular products. However, the introduction of dispersants may also cause certain environmental impacts. Emulsion polymerization requires surfactants or emulsifiers to form a stable emulsion system during synthesis. The introduction of organic solvents and the subsequent demulsification process may further raise new environmental concerns related to ecotoxicity and solid waste disposal. Aqueous solution polymerization uses water as the reaction medium, ensuring a mild reaction process while avoiding the environmental hazards associated with organic solvents. As one of the most environmentally benign

solvents, water also aligns with green chemistry's demand for "safer solvents and additives". However, hydrophobic monomers are generally difficult to polymerize through aqueous solution polymerization because of their poor dispersibility in water. To address this issue, Li et al. (2024b) synthesized novel hydrophobic monomers by introducing imidazole groups, which improved the aqueous solubility of long-chain alkyl groups. This strategy avoided the use of organic solvents while enhancing the thermal resistance of the fluid-loss reducers. Overall, when selecting polymerization methods for synthesizing filtrate reducers, priority should be given to the more environmentally friendly aqueous solution polymerization technique, which generally involves lower environmental pollution and separation costs than methods such as emulsion polymerization.

In addition, developing efficient and reliable technologies for the harmless treatment of drilling fluid waste is an effective strategy for meeting environmental protection requirements. Spent drilling fluid, one of the main solid wastes generated during oil and gas exploration and development, is a complex colloidal suspension system consisting of clay, weighting agents, various chemical additives, wastewater, waste oil, and drill cuttings. If not properly treated, it may pose potential pollution risks to water bodies, soil, and ecosystems. At present, the main treatment methods include secure landfill disposal, physicochemical separation, electrochemical treatment, pyrolysis/incineration, supercritical fluid technology, and bioremediation, as well as other physical, chemical, and biological approaches (Pereira et al., 2022) (Fig. 17(a)). Jing et al. (2022) employed $K_2S_2O_8$ to treat drilling fluid waste under subcritical conditions, achieving organic matter degradation and heavy metal immobilization (Fig. 17(b)). Adhami et al. (2021) utilized a combined electro-Fenton process to treat water-based drilling fluid waste, achieving a total petroleum hydrocarbons (TPHs) removal rate of up to 77% (Fig. 17(c)). It should be noted that, during the treatment process, a systematic assessment of the toxicity, bioaccumulation potential, and biodegradability of the synthetic polymers contained within the waste drilling fluid is essential for guiding process optimization and improving treatment efficiency. In summary, the most suitable combination of treatment technologies should be selected according to the specific compositional characteristics of the waste drilling fluid and local environmental emission standards, thereby minimizing its negative impact on the environment.

4.2. Relevant economic impacts

The development and application of synthetic polymers should take cost factors into account from multiple perspectives, including synthesis methods, industrial production, and monomer costs, to ensure economic feasibility in practical applications. First, selecting an appropriate production method from bulk polymerization, solution polymerization, suspension polymerization, and emulsion polymerization is critical for the synthesis of polymer treatment agents, because the production route directly affects production cost and energy consumption. In addition, the recycling of solvents and unreacted monomers during polymerization can further reduce production costs. Secondly, effective validation and coordination should be conducted at each stage, from laboratory-scale experiments to pilot production and ultimately field application, to avoid repeated investment and resource waste caused by scale-up problems. For example, the adverse effects of using impure industrial products in field applications must be fully considered. At the same time, greater emphasis should be placed on developing highly efficient fluid-loss-control agents. Although their initial research and development costs may be relatively high, these dosage forms offer better performance per unit mass,

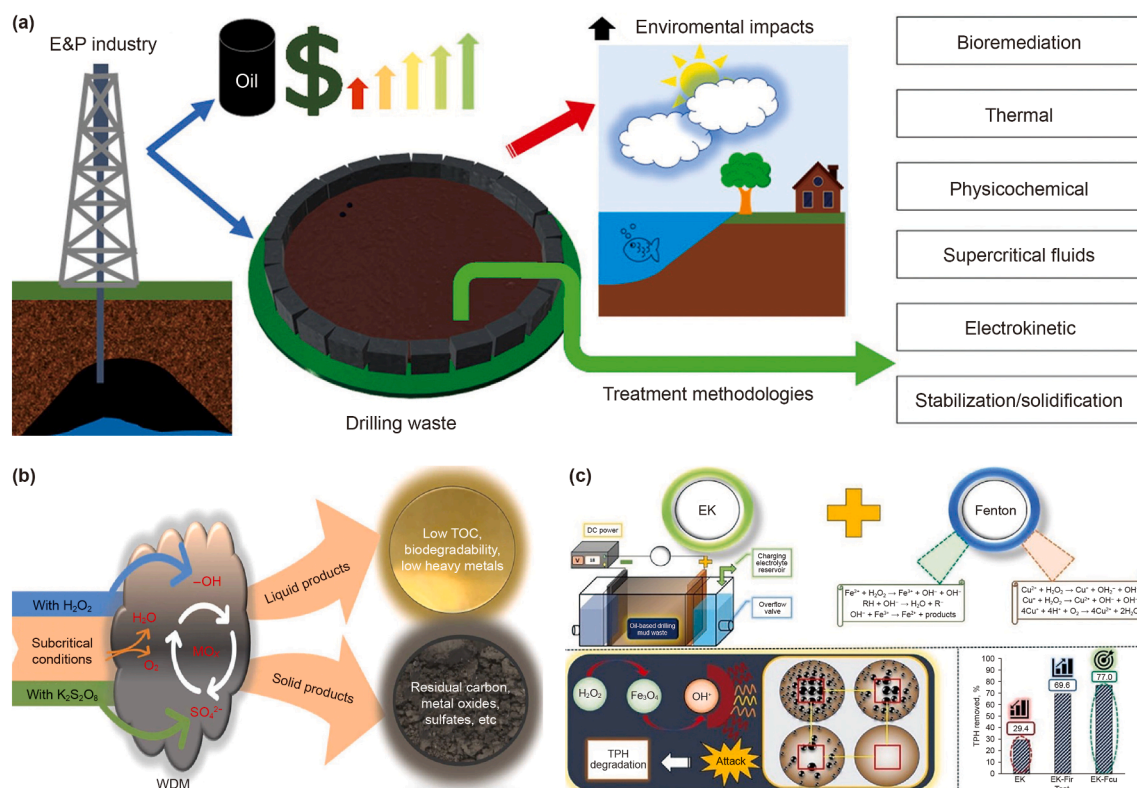


Fig. 17. (a) Treatment methods for waste drilling fluid. Adapted with permission from Pereira et al. (2022). (b) The mechanism of treating waste drilling fluid under subcritical conditions. Adapted with permission from Jing et al. (2022). (c) The mechanism of treating waste drilling fluid by electric-Fenton composite technology. Adapted with permission from Adhami et al. (2021).

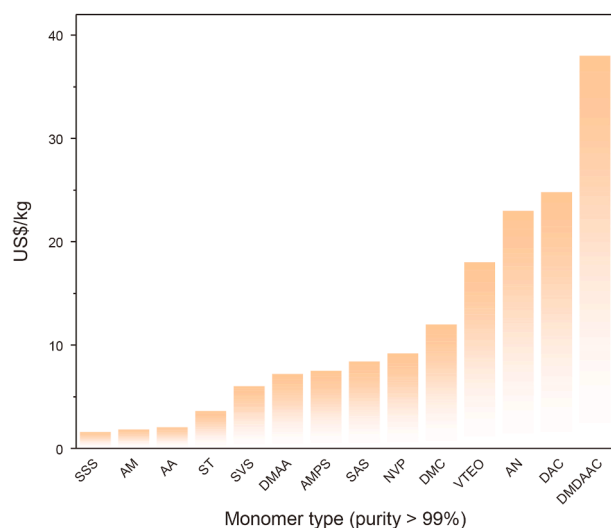


Fig. 18. Costs of key monomers for synthesizing polymers as fluid-loss-control agents (Davoodi et al., 2023, 2024a, 2024b).

which directly reduces usage costs due to lower dosage requirements while meeting equivalent performance standards.

The price of synthetic monomers should be fully considered, as it is a key factor affecting the overall cost of synthetic polymers. During the molecular design stage, the cost of raw material monomers should be evaluated as early as possible to avoid excessive use of expensive or price-volatile monomers, thereby achieving a balance between economic feasibility and performance improvement. Fig. 18 summarizes the costs of the

commonly used monomers for synthesizing polymer-based fluid-loss-control agents. Adsorption monomers such as AM and anionic monomers such as AMPS, SSS, and AA are relatively inexpensive, with prices below \$10 per kilogram. By contrast, cationic monomers and nanomaterials are generally more expensive, especially DMDAAC, which cost over \$30 per kilogram. Furthermore, from an economic perspective, conventional nanomaterials such as silica and calcium carbonate are generally associated with relatively low costs, whereas the high production cost of nanomaterials such as graphene oxide remains a key constraint on their large-scale manufacturing and field-scale application. Therefore, during the molecular design stage of polymer synthesis, it is advisable to minimize the usage of expensive cationic monomers and nanomaterials to reduce overall costs. At present, partially hydrolyzed poly-acrylamide and AMPS-copolymers have become common commercial fluid-loss-control agents benefiting from mature industrial chains, lower unit costs, and stable performance, with their costs all being lower than \$4 per kilogram. In addition, Huo et al. (2018) synthesized a fluid-loss reducer with industrial-scale potential using relatively inexpensive monomers, including AMPS, AM, and SSS, achieving a cost of approximately \$4.5 per kilogram. In conclusion, the full-cycle cost-effectiveness of synthetic polymer research and development, pilot testing, scale-up production, and field application should be comprehensively considered to accelerate the application of synthetic polymers as fluid-loss-control agents in field drilling.

5. Challenges and strategies

Although significant progress has been made in improving the high-temperature and salt resistance of synthetic polymers used

as filtrate reducer through controlled structural design, increasingly harsh downhole conditions resulting from the expansion of oil and gas exploration into deeper formations pose new challenges for the development of high-performance fluid-loss-control additives. This section outlines the challenges and future research directions for synthetic polymers as filtrate reducers.

5.1. Current challenges

(1) The insufficient resistance to high-valent cations

Existing filtrate reducers have shown a certain ability to withstand high-temperature conditions and monovalent-salt contamination. However, compared with monovalent ions, divalent cations (such as Ca^{2+} and Mg^{2+}) exhibit stronger electrostatic shielding effects, more markedly compress the electrical double layer of clay particles, and more severely inhibit the adsorption between polymers and bentonite. These adverse effects of divalent cations limit the development of fluid-loss-control agents with strong resistance to multivalent cations. Therefore, future research should accelerate the development of highly efficient fluid-loss-control agents with combined high temperature and multivalent-cation resistance.

(2) The unclear synergistic mechanism of functional groups

At present, researchers have improved the fluid-loss control by introducing various functional groups, such as sulfonic acid groups, amide groups, hydroxyl groups, pyridine groups, etc. However, although the incorporation of multiple functional groups can improve the overall performance of fluid-loss reducers, a clear additive or synergistic enhancement is not always achieved. This indicates that the synergistic effects among different functional groups remain insufficiently utilized. In particular, the synergistic action pathways, interaction intensities, and optimal ratios of these groups under high-temperature and high-salinity conditions remain unclear. The potential mechanism by which different functional groups synergistically regulate molecular adsorption behavior, colloidal stability, and filter cake structural compactness therefore requires further elucidation.

(3) The mutual constraint between rheology and fluid-loss control

The fluid-loss reducer can adsorb onto bentonite surfaces through hydrogen bonding and electrostatic interactions, thereby improving the particle size distribution of bentonite under harsh conditions, making the filter cake denser and reducing the fluid loss. However, although synthetic polymer-based additives provide effective fluid-loss control, they are often accompanied by increased viscosity, which may affect the safety and efficiency of drilling operations. Therefore, a key challenge is to optimize the molecular structure of synthetic polymers to achieve both favorable rheological properties and excellent filtrate control.

(4) The gap between laboratory and field applications

Although fluid-loss reducers demonstrate outstanding performance in laboratory evaluations, they still face numerous challenges in actual field applications. These challenges include interactions among different treatment agents, the limited ability of the commonly used 16 h hot-rolling test to accurately simulate downhole operating conditions, the potential impact of fluid-loss reducers on drill-cuttings dispersion, the structural stability of these agents under high shear rates. Overall, a significant gap

remains between simplified laboratory evaluations and the complex requirements of field operations. Therefore, translating laboratory results into reliable field performance remains a major challenge.

5.2. Future research directions

(1) Accelerating the development of high-performance monomers

Currently, synthetic polymer monomers have gradually shifted from commercial procurement to self-synthesis. Self-synthesized monomers can overcome the inherent limitations of commercial monomers and enable polymer properties to better meet targeted requirements, such as high thermal stability and a strong anti-polyelectrolyte effect. Synthetic polymers based on custom monomers have demonstrated promising fluid-loss control, but related studies remain relatively limited. In addition, the efficient synthesis of custom monomers requires a solid foundation in disciplines such as polymer chemistry. Therefore, future research should draw on advances in polymer development from related fields and strengthen the development of fundamental monomers, thereby providing more diverse and high-performance polymerizable units for the efficient synthesis of polymer-based filtrate reducers.

(2) Exploring the synergistic mechanism of functional groups

The excellent performance of fluid-loss reducers does not arise from a single functional group, but rather depends on the synergistic interactions among multiple functional groups along the polymer molecular chain. However, the microscopic mechanisms underlying these synergistic effects remain unclear, which limits the rational screening of efficient functional group combinations. Future research should further investigate the synergistic mechanisms among different functional groups, with particular emphasis on clarifying how functional-group type, ratio, and arrangement affect the strength of synergistic interactions. Such efforts will help establish the relationship between molecular structure and macroscopic performance, thereby providing guidance for the optimized design of functional group combinations in high-performance fluid-loss-control agents.

(3) Overcoming the technical bottlenecks in high temperature and multivalent cation tolerance

Research on high-temperature and salt-resistant fluid-loss reducers has achieved considerable progress, with current formulations capable of withstanding temperatures up to 200 °C and saturated salt environments. However, owing to the stronger electrostatic shielding and bridging effects of high-valence cations, existing formulations still show clear limitations in simultaneously tolerating high-temperatures and high-valence cation contamination, and there is an urgent need to overcome this technical bottleneck. Future research should draw on advances from related fields to deepen the understanding of existing mechanisms, while moving beyond conventional design strategies by introducing new monomers or inorganic materials to explore alternative mechanisms. For example, inspired by progress in hydrogel research, novel monomers with strong anti-polyelectrolyte effects could be designed to extend the stability boundary of existing polymers under high-temperature and high-valence-cation environments. Meanwhile, strategies for introducing strongly adsorptive monomers beyond conventional cationic monomers should be further explored, so as to fully exploit strong interactions such as ionic and chemical bonding

and mitigate the adverse effects of harsh conditions on polymer-bentonite adsorption. In addition, novel inorganic materials with different morphologies, such as nanoflakes and nanospheres, as well as varying degrees of flexibility, can be incorporated to enhance tolerance to high-valence cations through multiple nano-effects. These strategies may provide an innovative approach to overcome the bottleneck of high-valence ion tolerance in fluid-loss reducer.

(4) Balancing rheological properties and fluid-loss control

In practical applications, the use of fluid-loss reducers often increases drilling fluid viscosity, which adversely affects the safety and efficiency of drilling operations. Future research should focus on the collaborative optimization of rheological properties and fluid-loss control to overcome the limitations imposed by viscosity enhancement associated with fluid-loss control. During polymer molecular design and structure-property relationship analysis, attention should be paid not only to the effects of polymer structure, such as functional group type, molecular weight, and cross-linking degree, on fluid-loss control, but also to its influence on rheological behavior. In addition, during formulation optimization, low viscosity and good flowability should be maintained while ensuring efficient fluid-loss control. Overall, through molecular design and formulation optimization, it is expected that fluid-loss-control systems with a favorable balance between rheological properties and fluid loss reduction efficiency can be established.

(5) Deepening mechanism research through characterization-theoretical modeling

Current research on the thermal and salt-resistance mechanisms of fluid-loss reducers mainly relies on experimental characterization techniques to elucidate polymer structural evolution and mechanisms of action, including X-ray diffraction, zeta potential analysis, transmission electron microscopy, scanning electron microscopy, and particle size analysis. Although experimental characterization is essential, further theoretical calculations remain indispensable, because they can provide deeper and more explicit mechanistic insights. However, there are still relatively few systematic studies that use theoretical calculations (such as molecular simulations) to elucidate the structure-function relationship of polymerized filtrate reducers. It is recommended that future work focus on establishing a comprehensive characterization approach that combines experimental characterization with theoretical modeling, such as molecular dynamics simulations, thereby providing a deeper understanding of the action mechanism of fluid-loss reducers.

(6) Employing artificial intelligence (AI) to support research.

Currently, the synthesis and design of fluid-loss reducers rely heavily on experience rather than AI. By drawing on the application of AI in the field of materials science (Dananjaya et al., 2024; Long et al., 2025; Tran et al., 2024), the research and development process of polymer-based filtrate reducers can be accelerated. First, machine learning can be used to optimize the polymer synthesis processes. For instance, Zhang et al. (2022a) utilized machine learning to optimize parameters such as synthesis temperature, reaction time, and solvent type, significantly reducing the experimental workload. Furthermore, by reviewing the literature on filtrate reducers and constructing machine-learning datasets, correlations between input descriptors, such as polymer structure and environmental conditions, and output properties, such as fluid-loss control, can be established using methods such as neural networks (Han et al., 2025). Zhang et al. (2026b)

recently pioneered the development of an artificial neural network for predicting the properties of fluid-loss reducers. They established a nonlinear relationship between input parameters—including polymer concentration, NaCl concentration, and hot rolling temperature—and output data represented by apparent viscosity, enabling accurate prediction of system viscosity under varying environmental conditions. In addition, reversing the modeling direction can provide a new approach for performance-oriented structural optimization. For instance, the work of Webb et al. (2020), in which targeted polymer sequence design was achieved by integrating coarse-grained modeling with machine learning, provides useful inspiration for optimizing the molecular structure of synthetic polymers. In conclusion, establishing a data-driven research paradigm by integrating AI into the synthesis optimization, performance prediction, and reverse design of synthetic polymer-based fluid-loss reducers will significantly accelerate the development of highly efficient fluid-loss-control agents.

(7) Accelerating the transition from laboratory research to field application

To accelerate the transition of high-efficiency fluid-loss reducers from laboratory evaluation to practical applications, future efforts should focus on the following key directions. In the synthesis of synthetic polymers, production costs should be minimized by optimizing the types of functional monomers and the synthesis process, thereby reducing the economic burden of large-scale production. In laboratory performance evaluation, a combination of short-term and long-term thermal cycling methods should be established to assess the thermal stability of synthetic polymer filtrate reducers. In addition, it is necessary to consider the synergistic or antagonistic effects between the filtrate reducers and other treatment agents, as well as the performance stability of the fluid-loss reducers under high shear conditions. In conclusion, future research should focus on simulating realistic underground conditions in laboratory evaluations, in order to cope with the field complexities and accelerate the translation of fluid-loss-control agents from research to practical application.

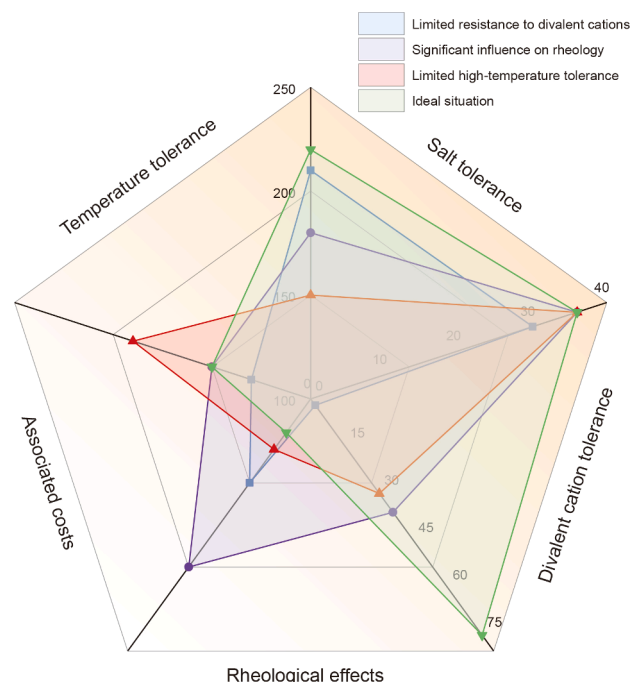


Fig. 19. Ideal multifunctional radar chart for fluid-loss reducers.

In summary, a key direction for future research is to integrate AI tools throughout the entire process of polymer design, synthesis optimization, performance prediction, and mechanism elucidation. This integration can help clarify the relationship between polymer structure and fluid-loss control and promote the transition of synthetic polymer fluid-loss reducers from “experiment-based trial-and-error” approaches toward “mechanism-guided quantitative design” approaches. Ultimately, a highly efficient multidimensional fluid-loss reducer is expected to be constructed that can meet high-temperature and cation-resistance requirements while balancing rheological properties and fluid-loss control (Fig. 19).

6. Conclusions

This review provides a comprehensive overview of recent advances in the development of synthetic polymers as fluid-loss reducers, with particular emphasis on the relationship between controllable structural design and enhanced temperature and salt tolerance. First, the mechanism by which high-temperature and high-salinity environments in drilling operations affect key drilling fluid components including bentonite and polymers, are systematically elucidated, revealing the intrinsic causes of increased drilling fluid loss. Subsequently, the improvement in fluid-loss control achieved through precise structural design of synthetic polymers is discussed in detail, with a focus on optimizing synthesis methods, monomer design, polymer structural stability, and the controllable incorporation of inorganic materials. The performance optimization of synthetic fluid-loss additives is fundamentally governed by the suitability of the synthesis method and the optimization of synthesis conditions. Polymerization monomers are progressively shifting from commercially available sources towards custom-synthesized monomers tailored to specific requirements, thereby enhancing the temperature and salt tolerance of the polymer's fundamental structural units. The stability of polymer structures is evolving from conventional comb-like and cross-linked configurations towards more suitable comb-like monomer chain lengths and more stable multidimensional cross-linking arrangements. In addition, the connection between inorganic materials and polymers is progressively evolving from random connection toward more suitable material types, superior nanoparticle sizes, more stable connecting “bridges”, and more controllable bonding orientations. Furthermore, economic and environmental considerations related to synthetic polymers are discussed to promote their large-scale production and sustainable development. Finally, the current challenges and future research directions for highly efficient filtrate reducers are presented. Future research should shift from “empirical trial-and-error” based on extensive experimentation to AI-driven “mechanism-guided quantitative design,” thereby enabling the development of highly efficient synthetic polymers with multidimensional performance. In conclusion, this paper systematically reviews the research progress on the structure–performance relationship of synthetic polymer-based fluid-loss reducers from the perspective of polymer molecular structure, providing guidance for the future development of more efficient fluid-loss reducers.

CRediT authorship contribution statement

Xin-Yan Li: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Guan-Cheng Jiang:** Supervision, Resources, Methodology, Formal analysis. **Jun Liu:** Writing – original draft, Investigation, Data curation. **Li-Li Yang:** Validation, Supervision, Formal analysis. **Wei Zhang:**

Validation, Conceptualization. **Hao-Zhe Chen:** Investigation, Conceptualization. **Yin-Bo He:** Resources, Methodology. **Teng-Fei Dong:** Visualization, Supervision.

Data availability

No data was used for the research described in the article.

Conflict of 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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