

Unconventional Treatment Technologies to Control Lost Circulation in Fractured and Highly Permeable Formations; A Comprehensive Review

Abstract

The lost of drilling fluid is seen as a significant cause of non-productive time (NPT) during drilling operations. Lost circulation is a frequent problem during drilling, casing running, completing, or cementing oil and gas wells. This phenomenon occurs when drilling fluid flows in formations with high permeability, natural fractures, and also in case of cavernous formations. Although the drilling fluid lost is costly, it also generates consequences that are not only even more expensive but can lead to the overall failure of the drilling operation. Different conventional solutions have been used to overcome the lost circulation problem including conventional lost circulation materials (LCMs), chemical sealants, hydratable pills, rigid plugs, gel polymers, and cement. Today, many changes have been made to different materials and compounds to achieve better, more applicable, and more useful products to cure different types of mud losses. This paper intends to present unconventional plugging fluids and new technologies to control lost circulation in highly permeable formations and fractured zones.

Keywords: Lost Circulation, Unconventional Plugging Fluid, Fractured Zones, New Technology.

1. Introduction

Lost circulation as a high-priced phenomenon happens during drilling and completion operations (1). It usually occurs while drilling bit faces natural fractures or caverns (2). Lost circulation problem can begin in unconsolidated formations at shallow and extend into the hard formations that are fractured by the hydrostatic pressure of the drilling mud or naturally fractured formations. Lost circulation severity is often categorized as seepage (less than 25 bbl/hr), partial (25-100 bbl/hr), severe (greater than 100 bbl/hr) and total lost circulation. Millions of dollars are spent every year to control lost circulation which can cause problems such as improper removal of cuttings out of the wellbore, differential sticking, damage to bit, low rate of penetration, kick and even blow out. When lost circulation is started, a typical solution is to make a seal by injecting a particle-fluid mixture or a settable material into the formation that will plug fractures or pores of the thief zone. Formation properties such as its permeability, pores size or fractures affect the

treatment outcome. This leads undesirable performance of treatments in different formations and is one of the reasons why no universal solution for lost circulation control has been found yet (3, 4).

The severity of lost circulation is conventionally categorized into four main levels, primarily based on the rate of fluid loss, measured in barrels per hour (bbl/hr). Seepage Loss, the mildest form, involves a fluid loss rate of less than 10 bbl/hr (typically 1 to 5 bbl/hr). Operationally, this is manifested as a small decline in mud pit volume, which can usually be managed by adding minimal amounts of conventional Lost Circulation Material (LCM), often allowing drilling to continue uninterrupted. The next level is Partial Loss, characterized by rates between 10 and 100 bbl/hr. This results in a noticeable reduction in the drilling fluid return flow, demanding a temporary halt to drilling operations to initiate the pumping of conventional LCMs or primary chemical sealants for treatment. The third category, Severe/Heavy Loss, involves rates ranging from 100 to 500 bbl/hr. In this scenario, fluid return is highly intermittent or very low, posing serious operational risks such as wellbore instability or the potential for a blowout. Treating this often requires the application of more advanced treatment methods or unconventional materials. Finally, Total Loss represents the most critical severity, defined by rates exceeding 500 bbl/hr or complete absence of return flow (Zero Returns). This condition signifies that all pumped fluid is entering the formation, presenting a severe risk of Formation Fluid Influx and significant well damage, necessitating the use of strong, fast-setting plugging materials like cement or specialized polymeric gels for remediation.

This comprehensive review paper addresses the challenges of lost circulation in drilling operations and presents unconventional plugging fluids and new technologies to control lost circulation in highly permeable formations and fractured zones. The document emphasizes the significant impact of lost circulation on non-productive time (NPT) and the overall failure of drilling operations, attributing this to the costly consequences such as improper removal of cuttings, differential sticking, damage to the bit, low rate of penetration, and the risk of kicks and blowouts. It outlines the conventional solutions that have been used to overcome lost circulation problems, including lost circulation materials, chemical sealants, hydratable pills, rigid plugs, gel polymers, and cement. The paper categorizes the severity of lost circulation as seepage, partial, severe, and total, highlighting the need for effective treatment based on the formation properties,

which significantly influence the performance of treatments and the selection of LCMs. The review also delves into the fundamental aspects of lost circulation control, emphasizing the need for suitable understandings about sealing mechanisms and parameters affecting their performances. It introduces a comprehensive four-tiered approach to lost circulation management, involving diligent pre-drill simulations, accurate calculations about mud density, wellbore strengthening materials, and the utilization of lost circulation materials to address ongoing issues. The document further discusses the classification of LCMs based on physical and chemical properties, emphasizing the importance of selecting LCMs with desired properties to ensure successful lost circulation control.

It concludes with an overview of various unconventional lost circulation treatments such as wedge foam, smart LCMs, self-healing hydrogels, viscoelastic surfactants, oil swellable glass, and nanotechnology, highlighting their potential to efficiently prevent or mitigate lost circulation and reduce non-productive time and drilling problems. The study also presents experimental investigations of the performance and application of these unconventional materials for lost circulation control, offering insights into their potential benefits and limitations. Overall, the paper provides a comprehensive overview of the challenges associated with lost circulation in drilling operations and presents a range of unconventional plugging fluids and technologies as potential solutions to control lost circulation in highly permeable formations and fractured zones.

2. Fundamentals of Lost Circulation Control

There are a noticeable number of studies on understanding loss circulation control mechanics. It is necessary to have suitable understandings about sealing mechanisms and the all parameters effective on their performances(5), so lost circulation control is not just a LCM selection but it is a fully engineered approach. Some of the approaches are based on analyzing borehole stability, leak-off flow-path geometry essentials, modelling of Equivalent Circulating Density (ECD), minimizing ECD effects considering drilling fluid and LCM selection, on-site Annular Pressure While Drilling (APWD) evaluation and on-time LCM utilizing and treatment (6).

Controlling severe to total lost circulation in challenging naturally fractured and vugular carbonate formations, particularly in the Middle East, remains a significant operational challenge. In these environments, conventional particulate Lost Circulation Materials are rarely effective due

to the inherent uncertainty regarding the size and geometry of the formation openings where losses occur.

One case study reports the successful laboratory evaluation and field application of an advanced, dual-component treatment. This approach utilizes a High Fluid Loss Squeeze (HFLS) in combination with a Reticulated Foam LCM (RFLCM). The combined technology was rigorously designed and qualified through laboratory tests to effectively seal simulated slots up to 40,000 microns, providing the necessary confidence for tackling uncertain downhole fracture and vug sizes (7).

Field validation of the dual HFLS/RFLCM approach was successfully demonstrated across two distinct Middle Eastern environments: Oman and the United Arab Emirates (UAE). In the Oman operation, wells drilled in vugular formations with water-based fluid experienced static losses up to 125 bbl/hr and dynamic losses reaching 280 bbl/hr (at 550 gpm), often resulting in "No returns." Following the application of the HFLS and RFLCM treatment (mixed in water) via a circulating sub using a hesitation squeeze technique, both static and dynamic loss rates were successfully reduced to zero.

For the UAE applications, wells drilled with non-aqueous fluid in naturally fractured formations encountered static losses between 85 and 200 bbl/hr and dynamic losses escalating up to complete loss (at 990–1250 gpm). After the squeeze application using the components mixed in base oil, static losses were dramatically curtailed to a minimal 2-15 bbl/hr, and dynamic losses were reduced to a maximum of 25 bbl/hr (dropping to 5 bbl/hr while drilling), which allowed operations to resume (7).

The laboratory qualification, coupled with these successful field applications which effectively cured severe to total losses, validates the superior performance and versatility of the HFLS/RFLCM dual approach compared to traditional methods. The most notable advantage of this improved LCM technology is the substantial reduction in well construction costs by decreasing the non-productive rig time associated with controlling severe lost circulation events (7).

3. Lost Circulation Management

Lost circulation is commonly managed through a comprehensive four-tiered approach. The initial tier involves the diligent work of the drilling engineer, who conducts predrill simulations

and performs accurate calculations about mud density. Additionally, the drilling engineer constructs a geo-mechanical model to gain insights into the formation type being drilled and assess the likelihood of encountering fluid losses. Moving on to the second tier entails the careful selection of drilling fluids. Optimal drilling fluid choices are characterized by having suitable rheological properties that effectively minimize lost circulation. Factors such as viscosity, density, and the specific chemicals used play pivotal roles in designing an effective drilling fluid. The third-tier centers around the proper utilization of wellbore strengthening materials, which can also be referred to as preventive methods. These treatments are applied proactively before experiencing any instances of lost circulation to prevent mud loss altogether. Wellbore strengthening involves proficiently sealing induced fractures during the drilling process, thereby increasing the formation breakdown pressure gradient and expanding the operational mud weight window. These materials, when appropriately sized, form a bridge within the fractures, effectively isolating them from the wellbore. Lastly, the fourth and final tier involves the utilization of lost circulation materials to address ongoing issues with lost circulation. This tier, known as corrective treatment, is implemented after mud loss has already occurred. Its primary objective is to rectify the problem and mitigate further losses. By employing this comprehensive four-tiered approach, the management of lost circulation can be effectively handled, ensuring the smooth progress of drilling operations (8).

4. LCM Classifications

Classification of LCMs is a key factor to plan a correct loss control process for prevention or even controlling lost circulation happenings. Because of the distinctive properties of LCMs which lead to their different applications, the typical classification is based on the both physical and chemical properties as well as their roles. While physical properties include LCMs size and their appearance, the chemical properties consist of reactivity with other chemicals, material solubility in acids and swellability. The lost circulation materials may be placed into the formation, in pores or surface of fractures as a part of drilling fluid or as a separate pill in an attempt to control or prevent lost circulation.

Conventional available LCMs with different sizes are categorized into flaky (i.e. corncobs, cellophane and mica (9)), fibrous (i.e. rice husk (10)) and granular (i.e. graphite, sized calcium carbonate and nutshells (11)) or a blend of them (9). Another technique that has been developed

to control lost circulation involves the placement of a settable composition such as precipitated chemical slurries (silicate and latex), cross linked gel polymer and cements into the wellbore to seal the lost circulation zone. For a number of reasons, these techniques may not provide a desirable level of lost circulation control in all circumstances. Overall, selection of a LCM with desired physical and chemical properties is necessary to ascertain a successful lost circulation control (12).

5. Unconventional Lost Circulation Treatments

Because of the LCMs important role for loss mitigation or prevention, enhancement of their loss control ability can cause noticeable influences on reducing Non-Productive Time (NPT) and drilling problems. As the drilling operation is becoming more complex, the industry is developing newer technologies to efficiently prevent or mitigate loss circulation into formations. Here, some of the unconventional lost circulation materials and newer technologies are introduced:

5.1. Wedge Foam

Foam based system is utilized to address uncertainties in fracture size as well as its shape. This system consists of two main components including highly deformable wedge foams and micro particles. Foam wedges (Figure 1) are defined as small parts of “foam rubber-like chunks” which are highly deformable. This property causes compression of the foam wedges into openings with different sizes and shapes. While the foam fills the openings, a highly permeable filtration bridge will be formed for the micro-sized particles (second component) to form a solid plug on the bridge (13). Alsaba et al. (2014) showed that this unconventional LCM is able to seal fractures up to 5mm where conventional LCM are failed to seal them (14).



Figure 1. Wedges Foam (15).

5.2. Smart LCMs

Shape Memory Polymers (SMPs) have deformation ability and consequent fixing into an impermanent shape. A SMP can recover its original permanent shape just when it is exposed to a specific external stimulation condition (i.e. temperature, magnetic field, pH and moisture). It must be mentioned that fixing in a temporary shape belongs only to some polymers. For example, since a rubber is under a load, its shape can change but its shape returns to its original state after the load removal. However, while the SMPs are deformed under loading, they can trap the mechanical energy as an internal energy. Also, as molecular relaxation rate or the material morphology changes as a result of an external stimulation, the SMPs liberate the internal energy. In addition, low cost, lightweight, non-toxicity, eco-friendly and biodegradability are other advantages of SMPs.

Mansour et al. (2017) concluded that smart LCM had the ability to be programmed to expand and bridge when stimulated by a specific temperature. In addition, they reported that the smart expandable LCM shows promising results in efficiently sealing fractures and minimizing fluid loss. The smart LCM can be synthesized and programmed for any wellbore temperature and fracture size and also its concentration and size should be selected according to the size of the fracture. The tested smart LCM was acid-soluble, so it had no damage to production zones (16).

Mansour et al. (2018) introduced a new smart LCM made out of anionic shape memory polymers. The smart LCM had the ability to be programmed to change in shape, bridge, and expand when stimulated by a specific temperature. They reported that the smart expandable LCM

showed promising results in sealing fractures efficiently and effectively by minimizing fluid loss. In their study, shape memory polymer (SMP) was activated at the temperature of 70°C, and they found that it can plug fractures of 2.54 mm. Also, the concentration and LCM size should be selected according to the size of the fracture, and because the smart LCM was acid-soluble it had no damage to production zones (17).

Taleghani et al. (2018) investigated shape memory polymers as smart LCM for the productive zone. They used various particle size distributions and fracture sizes to evaluate the performance of smart LCMs. According to static fluid loss tests, the smart LCM's seal could withstand up to 5000 psi differential pressure without breaking. They reported that the smart LCM is highly dependent on temperature and if not activated, will not prevent fluid loss. Dynamic fluid loss tests indicated that the smart LCMs work more effective when combined with fiber (18).

Gang et al. (2020) used a deformable plugging polymer (DPP) as a smart LCM. They used sand bed experiments to test the performance of DPP in fluid loss control. Their results showed that the plugging pressure could reach up to 1232 psi when 15% of a DPP was used in drilling fluid, and DPP can form strong plugging after being placed in the loss zones (19).

Cui et al. (2021) evaluated a shape memory polymer (SMP) to prevent losses using a high-temperature, high-pressure water loss apparatus. They increased the pressure by 50 psi every five minutes, and they found that after adding 2% of SMP, it could withstand pressure up to 300 psi at room temperature. According to their results, when SMP was activated at a temperature of 95°C, it withstood a pressure of 800 psi (20).

Lashkari et al. (2021) studied a shape memory polyurethane for lost circulation applications. They found that shape memory polyurethane can seal wide fractures once activated by formation reservoirs as it withstood the pressure of 1450 psi at 80°C (21).

Jia et al. (2021) investigated a novel high-density bromide-based nano-composite gel (HDGEL). HDGEL consists of polymers, crosslinkers, and Laponite as nanomaterial. They used a fracture width of 2.1 mm, and the highest sealing pressure they obtained was 56.56 psi (344.67 psi/ft). They reported that the gelation time can be adjusted from 8 to 12 hours, and also the presence of nanoparticles in the gel improves the thermal resistance of the nano-composite gel (22).

Ahdaya et al. (2022) Studied re-crosslinkable preformed particle gel (RPPG) as an LCM. The RPPG consists of swellable gel particles that can self-crosslink to form a strong bulk gel in fractures. The effect of the RPPG swelling ratio and fracture width on plugging efficiency was investigated. Results showed that its sealing pressure could reach up to 1,381 psi/ft and permeability reduction of more than 99.99% when the RPPG swelling ratio is five for the fracture with a width of 2.00 mm. RPPG is a good candidate that can be used to control severe or total loss during drilling operations (23).

5.3. Self-Healing Hydrogel

A gel consisting of a macromolecular polymer of cross-linked polymer chains network is named hydrogel. Hydrogels include hydrophilic monomers with a chain or step growth and also with a functional cross-link agent for the network formation enhancement. Recently, hydrogels have been described as two- or multi-component systems which consist of a 3D polymer chains network and water as an agent that fills the spaces between macromolecules. These structures may contain different amounts of water in an equilibrium. Such structures in an equilibrium can contain various amounts of water which depends on the used polymers properties, their nature and density of the network joints; typically, in the swollen state. Also, water mass concentration in a hydrogel is more than that of polymer(s). As expected, synthetic hydrogels were desired alternatives for natural hydrogels because of their higher capacity to absorb water, long service life and variety in their raw chemical resources. A specific type of polymer hydrogels is self-healing hydrogels. The term "self-healing" refers to the spontaneous formation of new bonds while a material breaks the old bonds. The hydrogel structure and electrostatic attraction forces drive the formation of new bonds through rebuilding covalent hanging side chain or non-covalent hydrogen bonding (24).

5.4. Viscoelastic Surfactant

Another type of material that has been used as LCM is Viscoelastic Surfactant (VES). These LCMs are constructed from surfactants that assemble by themselves into micellar structures which are similar to worm and behave as polymers. VES increases fluid viscosity at low shear rates. At high shear rates, the worm-like micelles are destroyed but can be regenerated when the surfactant molecules self-assemble again at low shear rates. In an aqueous solution of some salts with specific concentrations, micelle's structure becomes rod-like similar to that of polymer strands (i.e., worm-like micelles). Entanglement of rod-like micelles leads to formation and development of a

viscoelastic behavior and fluid movement prevention (Figure 2). Pseudo-plastic behavior development causes a noticeable increase in fluid viscosity. If a VES fluid is in contact with hydrocarbons or is diluted by formation water, its viscosity will reduce. Produced oil and condensate change the electrical environment in the fluid which leads to changing the micelle shape from rod to sphere. This is a beneficial characteristic because the fluid can form a gel to prevent lost circulation during drilling (worm-like micelles would probably be formed inside the vugs where shear is lower) and during production phase the viscosity would be reduced when fluid contacts the oil produced (spherical micelles would be formed). Figure 2 displays the transition between worm-like micelles to spherical micelles by oil contact (25).

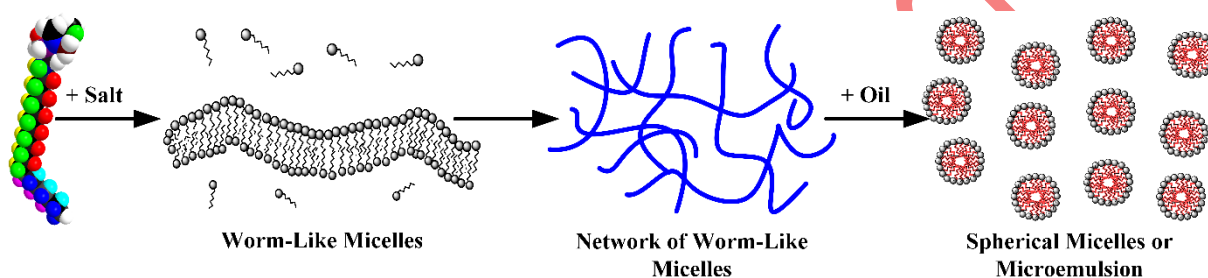


Figure 2. A schematic diagram of the production of worm-like micelles and destruction by oil.

5.5. Oil Swellable Glass

The swellable glass particles swell upon contact with organic liquids such as resins. The amount of swelling that may be induced in the swellable glass particles are a property determined by the type of the used swellable glass particles, the type and amount of the organic liquid that contacts the swellable glass particles and the duration of their contact. The swellable glass particles may swell to a volume about 1.5 times to about 10 times greater than the dried volume of the swellable glass particles. The swellable glass particles generally may be in particulate form for use as a dry powder. The powdered form of the swellable glass particles may have a particle size without limitation, between about 1 micron to about 500 microns and about 10 microns to about 350 microns. However, particle sizes outside this disclosed range may also be suitable for particular applications. Without limitation, the swellable glass particles may be dried by any sufficient means to produce a swellable glass particle that is easily added to the other components of the carrier fluid. With the benefit of this disclosure, by having ordinary skill in the art it is possible to select an appropriate size of swellable glass particle (26).

5.6. Hydrocarbon Gel

A hydrocarbon-based fluid that its viscosity is rapidly increased for plugging and sealing the thief zone or wellbore is named hydrocarbon gel. The main cause of the fluid viscosity increase is related to the reaction between two components blended with a hydrocarbon such as crude oil and refined oils. The first component includes an alkyl-orthophosphate acid ester blended with an alkali metal hydroxide. The other component is an amine complex which has the ability to be solved in oil and is as a result of the reaction between an alkanol amine with an alcohol or water-soluble source of aluminum or ferric ions. The hydrocarbon gel is pumped into the thief zone to seal the zone temporarily and consequently plug it at a desired viscosity (27).

The oil-absorbent polymer formed by methylmethacrylate (MMA), hexadecyl methacrylate (HMA), and butylacrylate (BA) prepared by suspension polymerization for high-pressure, high-temperature applications was recently developed by Zhong et al. (2018) to prevent loss circulation issues related to oil-based mud. N, N'-Methylenebis (acrylamide) (MBA) (99%) was the crosslinker employed, while benzoyl peroxide (BPO) served as the initiator. Due to a weight loss of less than 5% being noted at 300 °C (572 °F) and entire pyrolysis being noted at temperatures greater than 436 °C (816.8 °F), Thermogravimetric Analysis (TGA) demonstrated the thermal stability of this polymeric solution. The created combination was capable of entirely isolating high permeability zones, according to fracture sealing and sand pack tests. The gel strength and yield point were enhanced along with the emulsion's high stability and thin filter cake by adding 1.5–3 w/v% of the oil absorbent polymer [40].

5.7. Polymer Emulsion

An emulsion consists of two phases named internal and external (continuous) phases. If the internal phase is well dispersed in the continuous phase, the emulsion viscosity will be more than that of the only external phase. External phase of polymer emulsions is gelled water and addition of diesel, crude oil or kerosene in volumetric content in the range of 0.4 to 0.6 to it leads to viscosity improvement. Oil contents less than 0.3 and more than 0.7 lead to too low and too high emulsion viscosity, respectively. An emulsifier with surface activation property must be added to the aqueous phase to help formation of an oil-in-water emulsion and temporarily stabilize its properties (28).

Polymer emulsion has been introduced because of its advantages over gel polymers and other viscous fluids. There are many efforts on testing and development of gelled water systems. High cost and difficulty to removal of these fluids which cause formation damage in productive zone in some cases are the main disadvantages of these fluids. Viscosity of polymer emulsion fluids can be adjusted by polymer content and the oil volume fraction variations in the aqueous phase. Also, viscosity decreases as temperature and effective shear rate are increased; it is affected slightly by variations in the types of oil, water, utilized polymer as well as the surfactant concentration (29). Polymer emulsion viscosity is not a direct function of oil viscosity because the oil is the internal phase. Some crude oils decrease apparent viscosity slightly because they contain impurities and natural surfactants. As solid content in an emulsion increases, the emulsion viscosity increases, too. If the internal phase volume (oil plus solid volume) increases up to a level more than a threshold value, the emulsion stability will be affected (30).

Saikia et al. (2019, 2020) studied an emulsified polymer gel system for conformance control. An emulsified gel was developed having polyacrylamide and polyethyleneimine as the aqueous phase and diesel as the oleic phase. The developed emulsified polymer gel was a water-in-oil emulsion that formed rigid gel under reservoir temperature conditions. They indicated that the formulated emulsified polymer gel is an effective conformance control, which can be used in high temperature reservoirs (31, 32).

5.8. Quick Foam

Quick-foam is also a high expansion mixture which is applicable in lost circulation zones. This mixture is composed of two or three components and its work life depends on the type of drilling system and is in the range of 1 to 10 minutes. Polyurethane Grouting is a chemical grout that produces a gel or foam through reaction and provides more viscosity, consequently.

Polyurethane polymer is made of organic units linked by urethane joints. Heating does not have any effect on thermosetting polyurethanes melting as the dominant polyurethanes. Experiences show that polyurethane is useful to mitigate loss circulation and stabilize slim holes. Silicone foam polymer system is another one quick foam which is utilized for filling the gaps (33).

5.9. Invert Emulsion

A Shear Sensitive Plugging Fluid (SSPF) is designed in such a way to be gelled rapidly after passing through the bit nozzles and control heavy mud losses in normal drilling operation. A plugging emulsion fluid have the following components; (a) a continuous phase of a hydrophobic liquid, an emulsifier and a cross linking agent (b) water-polymer solution as internal phase. In invert emulsions, the plugging fluid setting mechanism is to cross-link the polymer using the cross-linking agent.

To activate a shear sensitive fluid, it is necessary to achieve a minimum (threshold) shear for start of the chemical reaction between the two reactive components. When a SSPF is affected by a pressure drop, the invert emulsion is rapidly deformed (Figure 3). As high shear rate forces are applied to a water-in-oil emulsion when it goes through drill bit, at the same time the interfacial membrane between the liquids breaks and the emulsion changes to a stable state of oil-in-water emulsion. As a result of the emulsion inversion, the cross linker is released into the water phase as the new continuous phase and cross-linking reaction begins. 30 seconds to 30 minutes time is needed after this state for construction of a rigid gel structure. Setting of the crosslinked gel is quickly, so the setting time depends on temperature. SSPF shear sensitivity is controlled by its emulsifier concentration. Only limited emulsifier contents are applicable for designing SSPFs. Emulsifier concentrations more than the higher applicable value decrease shear sensitivity of SSPFs. It means that the water-in-oil emulsion will be too much stable that emulsion inversion does not occur while it goes through bit nozzle. Also, a SSPF containing too less emulsifier is high shear sensitive that inverts rapidly after passing through the bit nozzles and a rigid gel structure may be constructed before penetration into the loss zone. Rheology of SSPFs is similar to that of many drilling fluids because of their similar solid content. Therefore, it flows easily into high permeable areas or fractured formations. After the set time for the gel construction, it is expected that the gel can seal the thief zone and normal drilling resumes. Using SSPF for loss control has some advantages including no need for trips, pumpable through BHA, easy to maintain for weeks without any reaction, high compatibility with typical mud systems and weighting agents (34, 35).

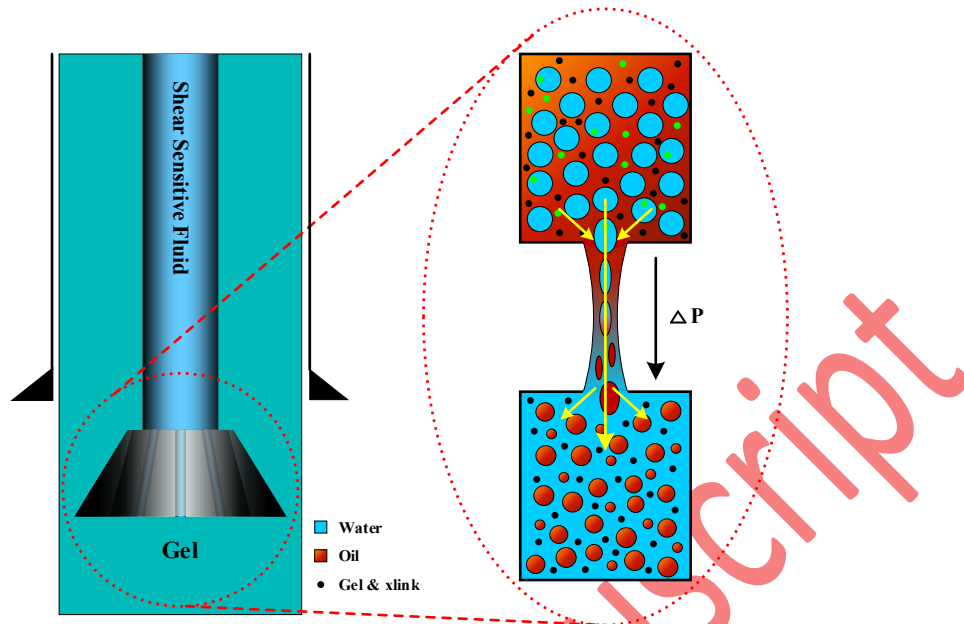


Figure 3. Flipping the Emulsion through shearing.

Johnson et al. (2001) described the technology and performance of the shear sensitive plugging fluid/cement in lost circulation control. They presented field case studies showing its success in curing problems with total loss of circulation. They showed that the gelation process occurs at pressure drops as low as 1 mPa. The lower the pressure, the longer the gelation times. This gives more flexibility in gelation times and pump rates (35).

Mora et al. (2021) designed a Shear Sensitive fluid (SSF) for lost circulation treatment. The main purpose of their study was to evaluate and optimize a shear-sensitive fluid formulation compatible with synthetic drilling fluids. The fluid formulation consisted of olefin, bentonite, surfactant, polyacrylamide and water, which is useful for non-reservoir zones due to damage to the formation. In their study, SSF was prepared in two stages. First, two separate parts of the fluid formulation are prepared. Part I consisted of mixing olefin and surfactant, followed by adding bentonite. Part II was a solution of HPAM in water. After individual preparation, both parts were mixed manually at a low shear rate with a metal spatula for 5 min. Following, the mixture was placed in a plastic container, and high shear forces were applied by a mixer at low velocity for 30, 90, and 150 s. According to their results, the elastic modulus was 4 to 11 times higher than the viscous modulus, indicating the solid-like behavior of the formed materials. They expressed the best composition of SSF as weight percent normalized to the bentonite value, which includes 1

wt% olefin/bentonite, 2 wt% water/bentonite, 0.02 wt% HPAM/ bentonite, and a mean level of stirring time (90 s) (36).

5.10. Water and Oil Absorbent Resin

A water-absorbent resin is a type of polymer characterized by its cross-linked structure, which impedes the dissolution of the resin in water. This structural feature is crucial, as it confers upon the polymer the ability to absorb and retain water quantities significantly larger than its own weight (often several hundredfold). The resin accomplishes this through its three-dimensional network, which effectively traps water molecules, facilitating substantial water uptake and retention.

The polymer is deformed and then squeezed into the fractures and pores and also absorbs water. Since the polymer can absorb on the rock surface, it stays in the loss channels and provides a strong and flexible plugging. According to the mentioned benefits of water absorbent resins, they have been widely utilized in water-based drilling fluids as high-performance LCMs. Oil absorbent resins (Figure 4), which have similar properties to water absorbent resins as unconventional LCMs, are mainly applicable in environmental pollution treatments to absorb oil for lost circulation control and aslo zonal isolation (37).

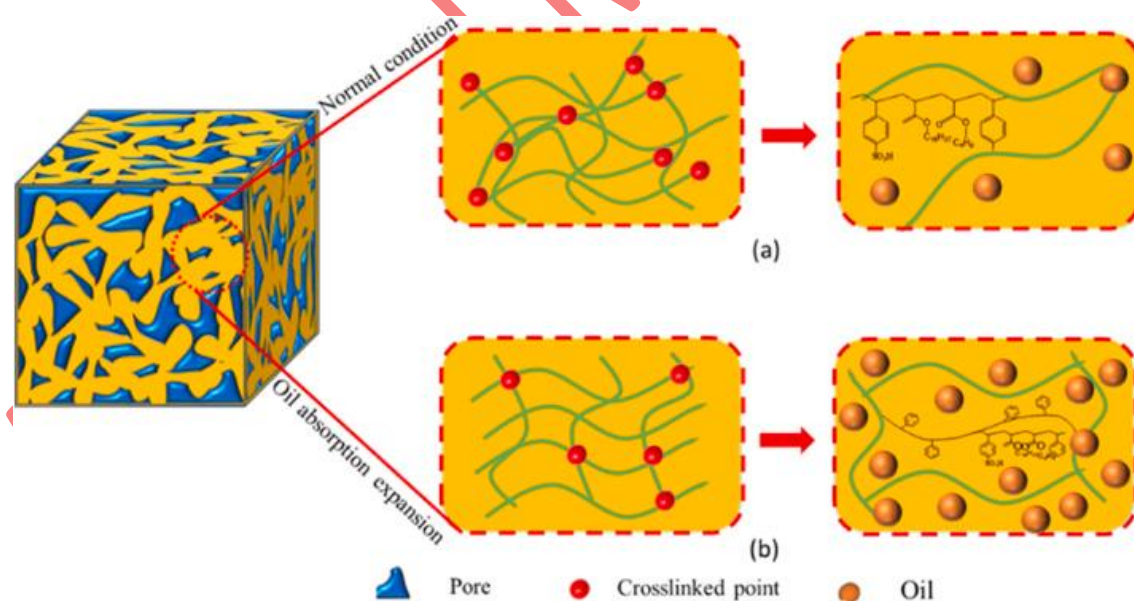


Figure 4. Rheological analysis curves of the high-oil-absorption resin after oil absorption swelling (38).

5.11. Nano Technology

Nanotechnology has attracted an increasing interest in the materials science field because of the unique properties of Nano-Particles (NPs) that can be useful in various field of oil and gas

industry including exploration, drilling and completion, reservoir management, production and process and refinery. NP size is almost in the range of 1 to 100 nm (39). Figure 5 shows the size of a typical nanoparticle (a nanomaterial) by comparing it with micro sized, milli-sized, and normal particles. These very small particles can invade into the smallest pores and seal pore throats even in low permeable formations. Figure 6 illustrates combination effect of NPs and a conventional LCM. Utilizing only conventional LCMs in drilling fluid results in more particle invasion due to looser filter cake. NPs fill the gaps among large LCM particles on the mud cake and provide an effective seal to prevent particle invasion into the porous media. In addition, NPs can reduce mud filtration through precipitating on the wellbore wall at the initial time of filtration which results in creation of a thin and low permeable cake (40).

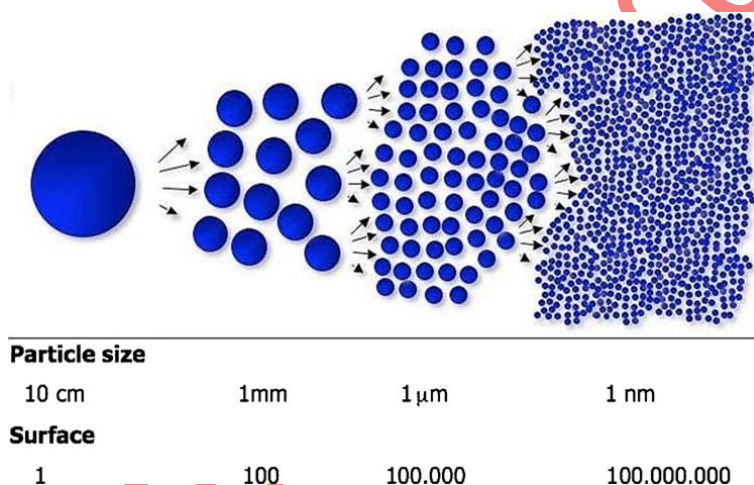


Figure 5. The size of a typical nanomaterial (41).

In the industrial domain, an extensive variety of nanomaterials is employed, including but not limited to nanoparticles, nanocomposites, functionalized nanoparticles, nanosheets, coatings nanoparticles, nanotubes, and nano sensors. Notably, nanoparticles are distinguished as the predominant category of nanomaterials in terms of utilization across industrial applications (42). Within the context of drilling fluids, nanotechnology proves particularly advantageous in addressing two critical aspects: rheology and fluid loss management. Various nanomaterials exhibit viscosifying properties due to their strong particle–particle interactions. For instance, consider the straightforward addition of graphene oxide (GO) to a freshwater slurry composed of bentonite and barite. This simple modification significantly influences the viscosity of the mixture (43). Furthermore, carbon nanotubes (CNTs) have been rigorously evaluated as stabilizers for ultra-high-temperature, high-pressure (HTHP) nonaqueous drilling fluids. Even at modest

concentrations, both CNT materials effectively stabilize the rheological profile under these severe HTHP conditions. In a separate study, researchers led by Friedheim et al. (2012) explored the potential of CNTs. Following this screening process, two specific types of CNTs were selected for further assessment in formulating fluids capable of withstanding temperatures up to 600 °F. Remarkably, these CNT materials demonstrated robust performance in terms of rheological stability under extreme conditions. Additionally, Li et al. (2012) introduced a novel nano additive, further expanding the toolkit for enhancing drilling fluid properties.

The nano additive can adhere to clay particles, preventing cations from binding with a thick hydrated coating and minimizing clay swelling and dispersion. Due to its small size, the nano additive can form a robust and compact mud cake, significantly reducing drilling mud loss and maintaining wellbore stability. So that when the new nanomaterial was used, it led to decreased pressure transmission through the shale and increased shear strength coefficient for the filter cake, demonstrating its effectiveness in sealing the shale.

A summary of the most commonly used nanomaterials, such as Lost Circulation Materials (LCMs) for treating lost circulation problems, is provided in Table 1. Nanotechnology continues to revolutionize the oil and gas industry, offering innovative solutions for drilling challenges.

Table 1. Common nanomaterials used as LCMs.

Type of nanomaterial	Description	Reference
TiO ₂ /polyacrylamide nanocomposite	TiO ₂ /polyacrylamide nanocomposites improved the rheological characteristics of water-based drilling fluid and reduced fluid loss by 64%	Sadeghalvaad and Sabbaghi (2015), (44)
Nanocomposite organic and inorganic gel	Sealing pill containing cross-linked polymer gel containing polymer and colloidal particles	Lecolier et al. (2005), (45)
Iron (III) hydroxide and calcium carbonate	An LCM drilling mud blend with the optimal concentration of in-house produced NPs and graphite was made	Nwaoji et al. (2013), (46)
Iron-based and calcium-based NPs	When compared to fluids containing only LCM, the combination of NPs and LCM could dramatically minimize fluid loss and result in a thinner filter cake	Borisov et al. (2015), (47)
Iron-based and calcium-based NPs	As a conventional LCM in oil-based drilling fluids, iron- and calcium-based NPs in combination with graphite were examined	Contreras et al. (2014a), (48)
Silica and iron oxide NPs	In terms of fluid loss reduction, silica NPs outperformed iron oxide NPs as LCM	Shibeeb et al. (2020), (49)

Silicon NPs	Silicon NPs are utilized as drilling fluid additives to reduce lost circulation as well as differential sticking	Javeri et al. (2011), (50)
Carbon black NPs	An additive package containing carbon black NPs and polymers significantly reduced fluid loss	Bicerano (2009), (41)
In situ and ex situ in-house synthesized NPs	Drilling fluids produced using in-house manufactured NPs reduced fluid loss as compared to the control sample	Zakaria et al. (2012), (51)

In the last years, nanocomposite materials have shown their great potential in overcoming a number of technological problems. These materials are based on a polymeric matrix with dispersed nanofillers and their performance indicates improvements in thermal and mechanical properties. The employed nanofiller properties can be different in chemical nature, shape, and particle size. They can be of inorganic, polymeric, or carbon nature and can present a granular, platy, or fibrous shape. The employed polymer as matrix can have a large variety of chemical structures and its chemical nature will affect the process that can be employed to produce the nanocomposite (45).

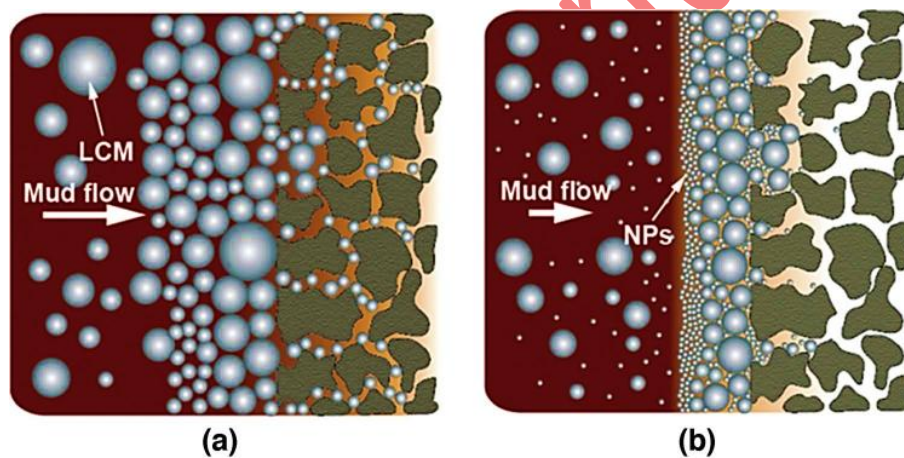


Figure 6. Effect of NPs combined with conventional LCM.

Lecolier et al. (2013) developed a nanocomposite gel to plug fractured formations. The nanocomposite gel consisted of a high molecular weight polyacrylamide, chromium acetate as a crosslinking agent, and colloidal particles. To obtain swelling sealing treatments, they incorporated cross-linked polymer grains in the composition of the nanocomposite gel. They reported that the concentration of polymeric grains has a strong effect on the gel strength and in case of high differential pressures are expected, increasing the number of polymeric grains can reinforce the strength of nanocomposite gels. Also, the strength of the nanocomposite gel is not lowered by shifting from deionized water to brine (45). According to their results, no degradation of properties was observed for nanocomposite gels aged at 120°C for 16 hours.

Alsaba et al. (2014) investigated the feasibility of sealing wide fractures using conventional LCMs with nanoparticles. The ability of different LCMs in sealing fractures was evaluated using a set of tapered slot sizes up to 2000 microns fracture width. They investigated parameters such as LCM's type, concentration, tapered slot size, particle size distribution (PSD), temperature, and injection rate. They concluded that selecting the right LCM concentration and PSD is critical to avoid screening out at the fracture openings. Using nanoparticles increased sealing pressure and reduced mud loss (15).

A successful field application reported by Borisov et al. (2015) showed that nanoparticle-based invert emulsion drilling fluids could significantly reduce fluid loss and create a thinner filter cake compared to fluids containing LCMs alone. Due to their superior properties, NP can fill the gaps between the micron-sized LCMs, which leads to lower permeability and decreased filtrate flux (52).

Akhtarmanesh et al. (2016) reported that barite nano/micro particles with LCM seal fractured formation better in weighted water-based drilling fluids. In their laboratory evaluations, barite nano/micro particles were prepared chemically and mechanically, and substituted 3% by the total sample weight of API barite in the base case. Based on the obtained results, the combination of both nutshells and nano/micro particles improved the sealing pressure by more than 205% using the mechanically generated nanoparticles as compared to the base case (53).

5.12. Gel Polymer

Due to their comparatively low cost when compared to other chemicals, polymers are employed in numerous applications in the oil and gas industry. Polymer gels are three-dimensionally networked polymer substances. Typically, water, oil, or gas is filled inside their structural pores. Materials made of polymer gel are frequently employed in oil fields to address a variety of challenging issues related to oilfield development. There are many action forms for various application fields. In the drilling fluid industry, polymer gels are frequently employed as plugging agents and drilling fluids. The need for reservoir development has increased the difficulty of drilling a variety of high-temperature and high-salinity reservoirs, and this has also increased the need for polymer gels in the drilling fluid industry (54, 55). Polymer gels may effectively plug holes and fractures of various sizes in a formation due to their great self-adaptive flexibility. Additionally, because of their physical and chemical characteristics, notably their pumpability,

they are suited for an operational purpose. Because of their suitable viscosity, polymers can penetrate a formation's depths without losing their characteristics. Polymers often have high molecular weights that can reach millions of Daltons, and some of them can be dispersed in liquids, increasing the viscosity of the solution.

Polymers are categorized in a wide range of ways due to their diversity. For instance, the origin, structure, molecular forces, manner of polymerization, and diversity of monomer structure can all be used to categorize polymers. For the improvement of conformance control, bio-polymers like xanthan gum (XG) and synthetic polymers such as acrylamide-based polymers are both utilized. Based on the various crosslinking processes, the polymer gel used in oil-gas drilling may be divided into chemically crosslinked gels and physically crosslinked gels. Chemically crosslinked polymer gels are created when a crosslinker and a polymer perform a covalent bond crosslinking process. Gels created via hydrophobic associations, hydrogen bonds, and other noncovalent crosslinking between polymer molecules are known as physically crosslinked polymer gels. Chemically crosslinked polymer gels are superior to conventional oil-gas drilling gels in terms of gel strength, temperature resistance and salt resistance. They are also ideal for high-temperature and high-salt formations. Physically crosslinked polymer gels are appropriate for temporary plugging in the context of protecting oil-gas reservoirs because they are quick to make, safe for the environment, and simple to plug (56, 57).

As mentioned, systems with a polymer basis and crosslinker are known as polymeric gels. They typically include additional reagents and crosslinked monomers. According to the crosslinking procedure, polymer gel systems can be divided into three categories:

1. In-situ crosslinked polymer gels (immature gels)
2. Pre-formed gels (mature gels)
3. Foamed gels

There are two types of crosslinkers:

1. Organic (such as polyethyleneimine (PEI) and phenol/formaldehyde)
2. Inorganic (such as zirconium and chromium)

In situ crosslinked polymer gels may be classified as free-radical-based monomer crosslinked gels, ionic-bond-based metal crosslinked gels, and covalent-bond-based organic crosslinked gels

depending on the mechanism of crosslinking. In situ chemically crosslinked gels are widely used to address the problem of lost circulation in fractured formations (54). Classifications of polymer gel systems are shown in

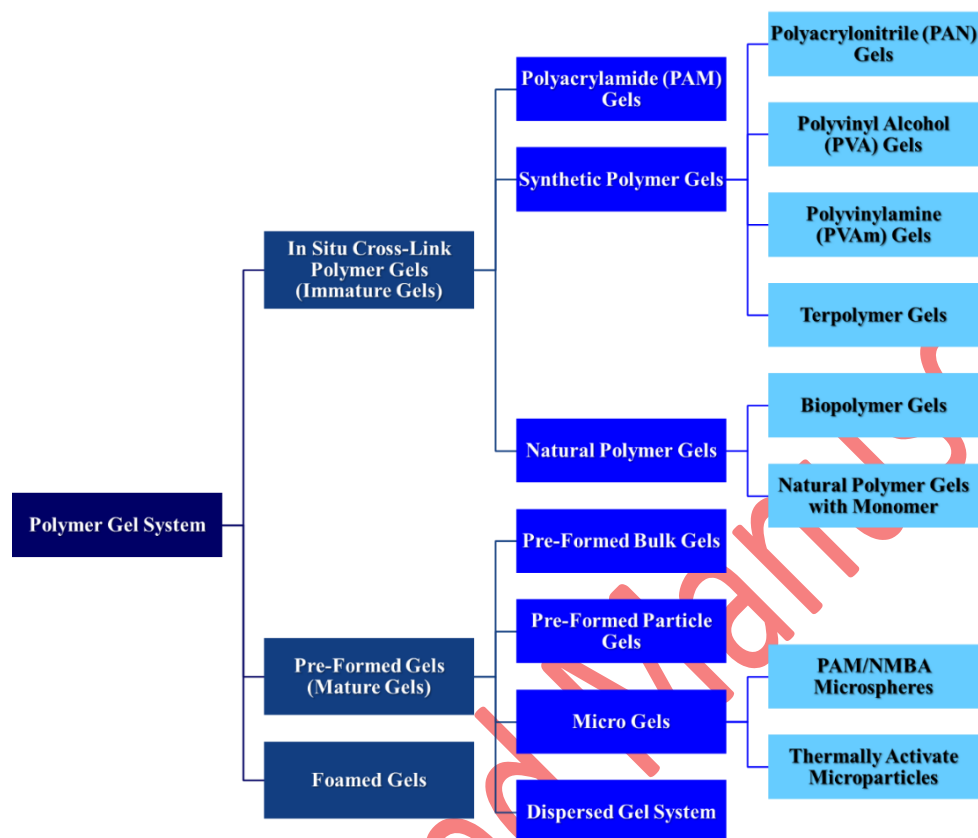


Figure 7.

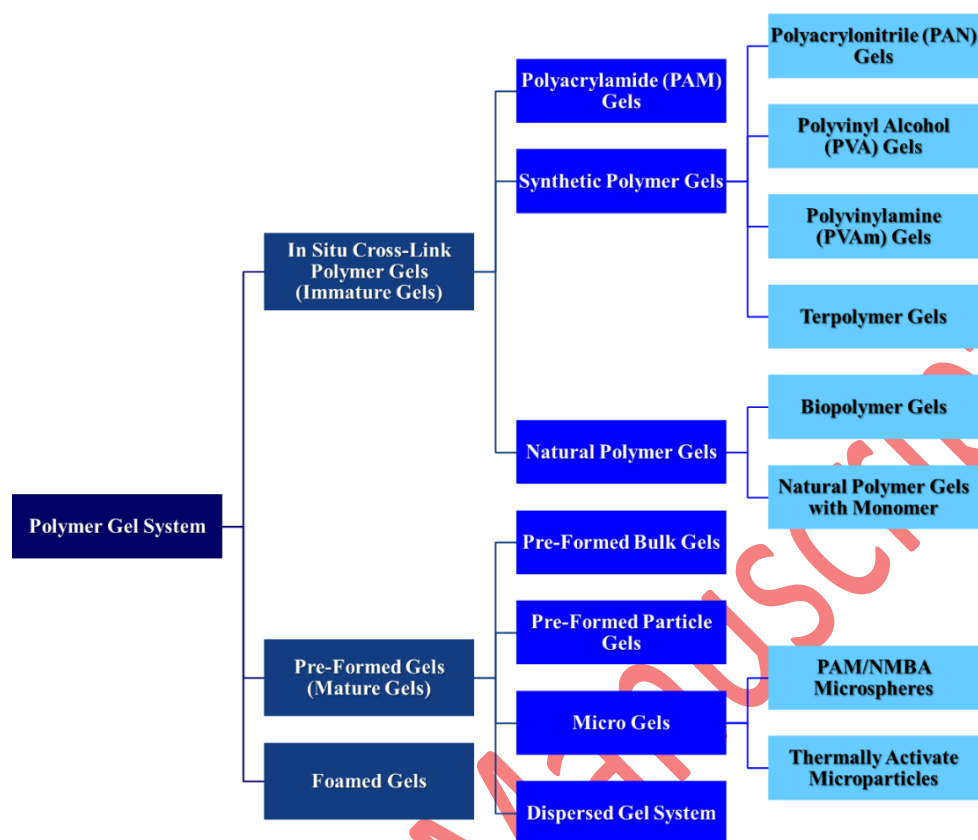


Figure 7. Classifications of polymer gel systems.

Gamage et al. (2014) studied fluid loss pills for high-temperature applications up to 140 °C. This fluid loss pill consists of a modified polyacrylamide and a metal-based crosslinker; however, the gelation time was one hour, which limits its application. They reported that gelled samples maintained their integrity for up to 3 weeks under high pressure/high temperature (HP/HT) conditions in laboratory testing, with minimal signs of disintegration. Also, the gel can be easily removed with an oxidative breaker that significantly reduces the viscosity (58).

Hashmat et al. (2016) studied the crosslinking of HPAM (polymer) and PEI (crosslinker) using a transparent apparatus to prevent drilling fluid loss. They filled a transparent tube with glass beads of different sizes to simulate porous media. They found that HPAM/PEI gelant had successfully prevented mud loss in a zone having 36% porosity and 300D permeability at room temperature and differential pressure of 150 psi (59).

Jia et al. (2017) studied a polymer gel pill based on multi-crosslinking which consists of polyacrylamide as polymer and chromium acetate, PEI, and hexamethylenetetramine (HMTA) as crosslinkers. Their finding was that the mature polymer gel pill based on multi-crosslinking had

an obvious viscoelasticity characteristic at a high temperature of 150°C. They reported that this multi-crosslinked polymer gel could act as a fluid loss pill to withstand high positive pressure during overbalanced well workover and completion (60).

Deng et al. (2018) studied a cross-linked polyacrylamide gel. They used a microencapsulated initiator to control the gelation process. Microencapsulation of the initiator can increase the gelation time because the concentration of initiator is controlled effectively by microcapsules. The results indicated that by the encapsulated initiator, the gelation time was prolonged to be eight times greater than that initiated by the free initiator. They showed that cross-linked gel had notable potential for recovering lost circulation, but the temperature limitation for this gel was 90°C (61).

Magzoub et al. (2021) studied the gelation kinetics of the PAM/PEI cross-linkable polymer. They used the HPHT permeability plugging apparatus. Their results showed that the sealing pressure was 400 psi with mud loss of around 200 cc when the waiting time was zero. However, it reached 900 psi with about 40 cc of mud loss when the waiting time was 120 minutes. They concluded that the produced gel is thermally stable at 70°C, which could lead to increased wellbore strengthening (62).

Xie et al. (2021) developed a novel cross-linked gel (HMP-Gel), which consisted of a hydrophobically modified polyacrylamide (HMP) with polyethyleneimine (PEI) as a crosslinker. HMP-Gel also showed high elasticity, gel strength, and excellent thermal stability at 90 °C. They used a customized design to test the plugging efficiency utilizing fracture slots. Their results indicated that HMP gel could withstand a pressure of 600 psi and 900 psi when fracture widths of 2 and 1 mm were used. They suggested that HMP-Gel could be considered as an efficient plugging material for lost circulation in high-temperature wells (63).

Bia et al. (2022) studied the plugging performance of a cross-linked gel on fractures with different widths and roughness. The results showed that the bearing resistance capacity of the gel gradually decreases as the fracture width increases. Also, the performance of gels in lost circulation control is significantly better on rough walls than on smooth walls. To improve lost circulation control performance, the gel strength and the cementing force between the gel and the fractured wall must be improved (64).

Yang et al. (2022) investigated the physical and chemical properties of a shear thixotropic polymer gel (Acrylamide base) to control lost circulation in fractured formation. Rheological tests showed that the smart gel has good mechanical properties and anti-dilution ability.

Using the scanning electron microscope, they observed that the shear thixotropic polymer gel system has a stable three-dimensional network-like framework under high salt conditions, demonstrating its remarkable capacity for salt tolerance (65).

A Summary of polymeric solutions used as LCMs is shown in Table 2. There are not many case studies in the literature that demonstrate the practical application of polymeric solutions as LCMs for treating losses and reinforcing wellbore. There have been no observed differences between LCM performance in the field and lab results.

Table 2. Summary of polymeric solutions used as LCMs.

Polymer(s)/Crosslinker(s)	Temperature (°C)	Gel strength/Gelation time	Reference
3 wt. % HPAM/1.2 wt. % PEI	120	9.8 times the base solution/200 min.	Hashmat et al. (2016)
2 wt. % HPAM-derivative/1.2 wt. % PEI	100	3 times the base solution/204 min.	
0.5 wt. % PAM/(0.4 gm) phenol and (0.37 gm) formaldehyde	Room temperature	Class C	Hashmat et al. (2017)
Multifunctional gel solution	Up to 100	-	Amanullah et al. (2006)
HPAM/chromic III carboxylate	-	400 times the original size	Ghassemzadeh et al. (2011)
Modified polymer	-	-	Zhu et al. (2018)
CACP mixed with retarder, fibrous cellulose polymer and polymer with calcium carbonate	90	3-7.5 MPa.	Bruton et al. (2001)
Urethane 902, Butyl Sealant, polysulfide polymer and Hotpour 164	-	Gelation time about 5-30 min.	Boukadi et al. (2004)
7 wt. % copolymer of acrylamide and PATBA, 2 wt. % KCl and 8 wt. % carbonate retarders	Up to 176.7	40 min without retarder and 600 min with 8 wt. % carbonate retarders at 176.6 °C	Mercado et al. (2009)
Acrylamide-based solution mixed with hydroXyl and carboXyl-based ingredients (commercially named as XNGJ-3)	Became a gel at 80	Bear up to 21 MPa	Fan et al. (2018)

6. Conclusions

Findings from this study include:

1. Polymer nanocomposite materials can combine desirable solubility in aqueous media with good mechanical properties to form strategic reservoir friendly LCMs.
2. NP can work together with LCM in porous media. Smaller particles work with larger particles and block the fluid flow and thereby leading to a better sealing through formation of a thinner impermeable filter cake in comparison to just using LCM.
3. VES systems are attractive as LCM because their viscosity can be reduced in contact with hydrocarbons or with an internal breaker which is useful for elimination of the need for remedial treatments, decrease of operating cost/time and formation damage reduction.
4. In quick foam systems, viscosity and setting time can be controlled to form a rigid plug and also expansion foams decrease the plug cost and cause material squeezing into the loss/thief zone.
5. Some of the advantages of polymer emulsion over gel polymers are lower cost, ability to control its properties and rapidly breaking after the treatment.
6. The damage of polymer emulsion on rock is less than that of gel polymer as well as it can be completely broken with a common gel breaker.
7. The smart LCMs can be synthesized and programmed for any wellbore temperatures and fracture sizes and they have no damage on productive zones because of their solubility in acid.
8. The advantages of shear sensitive plugging fluid include eliminating the problem of crosslinking polymer setting time, quick gelation and temperature-independency.
9. The compressible and permeable nature of wedge foam, that is form foam rubber-like polymer chunks, facilitates the accumulation of fine particles, forming a durable plug along the bridge. This unique characteristic of wedge foam enables the creation of a long-lasting and robust barrier.

7. Future Research Directions

Despite the significant advancements in unconventional lost circulation technologies, several critical knowledge gaps remain that must be addressed to effectively guide future research and maximize industrial application:

7.1. Standardization and Dynamic Validation:

Future research must focus on developing standardized, dynamic testing protocols that go beyond simple static tests. These protocols must realistically simulate actual downhole conditions (e.g., pressure cycling, thermal stability, and fluid flow dynamics) within complex fracture and vugular networks to accurately evaluate the real-world performance of advanced materials (like hydrogels and foams).

7.2. Integrated and Predictive Modeling:

It is essential to develop integrated numerical models capable of combining geomechanics, fluid dynamics, and material properties. These models must provide a precise predictive capability regarding the success rate, penetration depth, and placement pattern of LCMs in complex and heterogeneous formations.

7.3. Robustness in Harsh Operating Conditions (HPHT):

Research is needed to synthesize ultra-stable LCM materials that maintain their structural integrity and sealing capacity under severe conditions, including High Pressure/High Temperature (HPHT) environments, aggressive non-aqueous drilling fluids, and high-salinity brines.

7.4. Economic and Environmental Sustainability Analysis:

Future studies must include comprehensive Cost-Benefit Analyses (CBA) to provide financial justification for adopting these newer, often more expensive technologies by quantifying the savings from reduced Non-Productive Time (NPT). Concurrently, a focused effort is required to develop environmentally friendly and fully biodegradable LCM alternatives to minimize the ecological footprint.

Authorship Contributions

Conception and design of study: Khalil Shahbazi, Hamid Zafari Dehkohneh, and Rasoul Nazemi; Drafting the manuscript: Hamid Zafari Dehkohneh, Khalil Shahbazi, Rasoul Nazemi, and Benyamin Zaheri Abdehvand.

Declaration of competing interest

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

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