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Acid-soluble and degradable lost circulation materials for productive zones: A Review and Outlook

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Abstract

One of the frequently encountered problems in drilling operations is lost circulation. With the growing severity of drilling fluid's loss, consequent increases in costs are required for additional mud, treatments, rig time, and potential damages to the well. Lost circulation can be managed using Lost Circulation Materials (LCMs), which are specially designed to be added to the mud and have the ability to block fractures and pores, forming a bridge to provide a seal in a timely manner. Despite technological advances in new LCMs, they still have drawbacks primarily damaging production areas. This challenge requires the LCMs used in the productive zones to be degradable, acid-soluble, or non-damaging. The goal of this publication is to provide a review of current practices using LCMs at the productive zones and explore new degradable materials as possible LCMs.

The results of the research showed that the majority of existing solutions to remove the plug before the well's production require a post-treatment, most commonly with acid media. Acid-soluble magnesia cement and its variations, engineered composite solutions, acid-soluble gels, and rigid-setting materials are reported. Degradable materials (polylactides, polyglycolides, materials from plants, cellulosic fibers, etc.) are described in this paper. Furthermore, the paper emphasizes the most promising technologies such as smart LCM and degradable pre-formed particle gel. Finally, this work describes the current trends of LCMs for productive zones.

Degradable compositions, which can be effective as potential LCMs in severe-to-total losses, were considered. Future work involves the evaluation of the degradability and efficiency of these polymers as LCMs.

Introduction

Lost circulation remains a significant problem in the oil and gas industry, causing nonproductive time (NPT) in the well construction process. It is defined as an undesirable loss of drilling fluid and can occur in the following formations: permeable unconsolidated (e.g., sand, shell beds, pea gravel, and reef deposits), vugular and cavernous (e.g., limestone, chalk, dolomite, and reefs), with natural or induced fractures, and in every depth with a wide range of severity depending on the loss zone (Luzardo 2015).

Natural fractures serve as flow paths for gas or oil from producing source rock matrix into the wellbore during production, but they can also act as conduits for drilling fluid losses which can be sudden and often severe. By contrast, induced fractures are created when hydraulic forces in the wellbore exceed the formation strength and break down the weaker formations. Excessive wellbore pressures are caused by high annular-friction pressure loss or high surge pressure, which can lead to increased drilling fluid's equivalent circulating density. Poorly managed fluid parameters such as excessive density and elevated rheology can also be a major contributing factor (Addagalla 2020).

The lost circulation can be categorized depending on the severity: seepage - 10 to 20 bbl/hr, partial - 20 to 50 bbl/hr, severe - 50 to 150 bbl/hr, and complete - >150 bbl/hr or no return.

The first type of mud's loss can occur during drilling sandstone, sand, and silt. The second type is loss at porous scale when drilling through large porous, unconsolidated, or highly permeable formations such as loose sand and gravels (Brandl 2011, Javeri 2011). In this case, the loss occurs when the total pressure against formation is higher than formation pressure. The loss can increase gradually since drilling in such weak formations may create induced fractures and eventually a total loss.

The severe losses can occur in the long sections of unconsolidated sand gravel and larger induced fractures. The last type at fracture scale when a loss is due to natural fractures, cavernous or vugular formations, and faults (Bugbee 1953, Ghalambor 2014). This type of loss is mostly sudden or may start gradually and then abruptly become a total loss.

The total loss occurs when drilling in a narrow operational window, such as depleted formations, and deep-water fields (Addis 2001, Zamora 2000). A narrow operational window is also observed in naturally fractured carbonate formations and in deviated wells in which fracture gradient significantly decreases as deviation angle increases (Byrd 1988, Huang 2013, Salehi 2011).

Methods of the well's treatment depend on the type of loss, the severity of the loss, downhole condition, and the type of geological structures and can be classified as preventive and corrective. The preventive treatments are the set of techniques or treatments applied prior to entering lost circulation zones in order to prevent the occurrence of losses (Al-saba 2014). On the other hand, corrective treatments are defined as the methods that are applied after the occurrence of the losses; the main objective of these methods is to stop the loss quickly to regain drilling fluid circulation.

One of the early efforts to cure losses of preventing them from happening by adding granular materials to the drilling fluid was introduced by M.T. Chapman in 1890. Since then, Lost Circulation Materials (LCMs) have been widely used to stop or mitigate drilling fluid losses (Husam 2018).

Adding LCMs to mud during drilling of hydrocarbon zone causes significant formation damage because in the case of formations with high permeability and naturally or induced fractures, both particle and fluid deep invasion could take place. The forms of formation damage include permeability plugging by particle invasion, wettability alteration and phase trapping, and incompatibility between fluids and rocks (Bennion 2002).

Numerous materials have been tried and recommended over the years with varying degrees of success and efficiency, but most of them have restrictions especially for using them in reservoirs. In this paper, a review of corrective LCM materials for productive zones is presented with an emphasis on the most promising systems.

Conventional LCMs

A wide range of bridging or plugging materials is available for reducing lost circulation or restoring circulation while drilling a well. Each lost circulation material is selected depending on timing, type of losses, cost, phase drilling, mud type, and type of formation (Alkinani 2017).

Alkinani et al (Alkinani 2017) updated the classification of lost circulation treatment and materials. According to the previous classification based on the physical properties only and developed 50 years ago lost circulation materials are divided into four categories; granular, flaky, fibrous, and mixture of LCM's. The new classification is based on the appearance, applications, chemical, and physical properties.

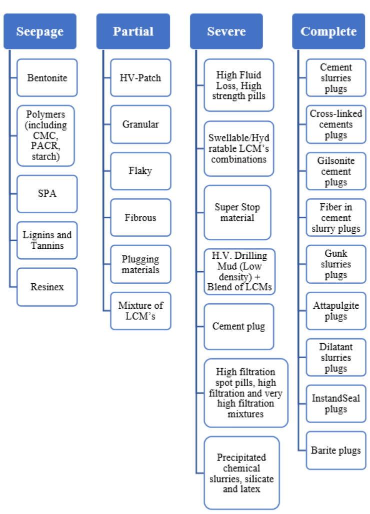

Figure 1. Updated Classification of the Lost Circulation Materials and Treatments

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Traditional LCMs such as nutshell, ground walnut, sawdust with a range of gauged sizes such as fine, medium, coarse, and extra coarse, mica, cellophane, graphite, cellulosic fibers, are not reservoir friendly because they are not removable by acid, enzymes, or other treatments (Luzardo 2015, Bijjani 2019).

Other less traditional methods and products used in cases of severe and complete losses called specialized pills include High Solids High Fluid Loss (this type of pill works by de-watering to leave a solid plug), precipitated chemical slurries (silicate and latex), portland cement slurries, barite plugs, cross-linking (this type of pill sets based on a combination of time and temperature) and resin-based. Most of them are not acid-soluble or degradable. This becomes a hurdle or a barrier in using the reservoir section (Addagalla 2020).

LCMs for productive zones

LCM solutions for a reservoir have to be either degradable, acid-soluble, or non-damaging. With such prerequisites, the choice of LCMs in case of losses in a reservoir can be very limited (Xu 2016).

Acid-soluble materials

The usual definition used by many operators is to equate "non-damaging" to "acid-soluble". Ground marble, as of now, is the most widely used non-damaging LCM in the reservoir zones (Sharath 2011). The particles of calcium carbonate of varied sizes are effective in dealing with seepage losses, while in the cases of severe losses in highly permeable formations the ground marble often fails, particularly if a wide particle size distribution (PSD) is not maintained (Savari 2016).

Several technologies and materials were developed for use in productive zones to cure severe-to-total losses with further removal by acids, such as acid-soluble cement and its modification, settable plugs, fibers, cross-linked gels, etc.

<u>Acid-soluble cement.</u> Two main types of acid-soluble cement (ASC) used in the wells' construction process:

1. Portland cement-based with up to 300% by weight of cement $CaCO_3$ (Seymour 2013)

2 Magnesia based (Sorel 1867): Magnesium-oxychloride type (MOC) and Magnesium-oxysulfate type (MOS)

Magnesium oxychloride cement is formed by reacting a strong solution of magnesium chloride with calcined magnesium oxide. The main crystalline phase reaction products cement include $5Mg(OH)_2*MgCl_2*8H_2O$, $3Mg(OH)_2*MgCl_2*8H_2O$, $Mg(OH)_2$ and mixtures of these. Important considerations which determine which crystalline phases are initially formed are the reactivity of the magnesium oxide and the concentration of magnesium chloride solution (Vinson 1992). MOC cement exhibits the advantages of quick setting, early and high strength, and brine corrosion resistance.

Foamed MOC-cement was created to be used when total lost circulation is observed while drilling through a highly faulted producing formation. Depending on the fault encountered, it may take several lost circulation pills and/or cement plugs to cure the losses. Lightweight acid-soluble cement, however, has the necessary strength development and an adjustable thickening time to achieve a quicker, successful plug-off (Bour 1993).

According to the results of laboratory comparison of MOC-cement and Portland cement-based system with appropriate amount $CaCO_3$ (Seymour 2013), MOC based systems have unique advantages over conventional Portland-based ASC systems:

- MOC systems are very quick setting and 100% acid-soluble, therefore minimizing chances of damaging the producing zones from plugging due to residues and/or deeper invasion.

- They have longer delayed gel time and very short transition time, which could make them fluid/gas-tight plugs.

Expandable LCM fluid was developed based on MOC-cement using retarder (inorganic acid-based or inorganic phosphate/phosphonate-based materials), viscosifier (Xanthan gum), nitrogen gas generating material and foamer to stabilize the generated nitrogen gas in the fluid. Thanks to the in-situ generation of non-hazardous gas, the LCM can expand depending on the differential pressure and temperature at the fracture space. (Santra 2020).

Magnesium oxysulfate cement is formulated by the reaction between magnesium oxide and magnesium sulfate solution, and it has very good binding properties. The $5Mg(OH)_2*MgSO_4*8H_2O$ composition is the most commonly found chemical phase (Mark 2006).

MOS-cement is less hygroscopic and less corrosive in comparison with MOC-cement (Walling 2016) and has a lower strength at ambient temperature, which increases by elevated temperatures or by adding modifying agents (Qin 2018, Zeng 2019).

MOS-cement was used as a lost circulation material and effectively blocked the simulated porous loss zones, as well as the fractured loss zones and bearing a pressure difference up to 8 MPa. Permeability recovery test demonstrated that MOS cement can be removed by acid treatment to effectively regain the permeability of producing zone. A higher strength of MOS cement at 70°C was achieved by regulating the molar ratio between magnesium oxide and magnesium sulfate. The successful field application in the Junggar Basin, China verified the good plugging effect of MOS cement for severe loss problems. (Cui 2021).

Magnesia cross-linked cement (MCC) consisting of a stoichiometric mixture of magnesium and calcium oxides, carbonates and sulfates, carboxy-methyl hydroxy-ethyl-cellulose as a gelating and fluid loss control agent, a borax-based retarder, a zirconium crosslinker, and calcium carbonate helped to seal critical intervals with severe lost circulation on fields in Venezuela and Argentina. (Mata 2004.) As opposed to conventional cement that sets by hydration MCC sets thanks to a chemical reaction which is activated basically by temperature. The developed cement is dissolvable in hydrochloric and acetic acids.

To increase the penetration of magnesia cement-based LCM, sodium silicate solution was introduced into the formation first according to the following scheme: 1) injection of the Sodium Silicate into the fracture, 2) pumping a small volume of spacer after the Sodium Silicate, and 3) injection of soluble cement into the fracture to plug the fracture zone. Once the sodium silicate solution is in contact with acid-soluble magnesia cement then a rapid gelling effect takes place. The solubility of the resulting gel-cement LCM in 15% HCl acid was around 87% (Al-yami 2014).

New low-solids shear-dependent (LSSD) cement systems develop rapid gel strength when the shear rate decreases and will remain fluid until the system begins to lose shear rate to remediate loss circulation. The thixotropic properties of the cement system allow curing severe and total losses in zones with high permeability, vugs, caverns, and fractures. The system forms a gel when it was injected into the larger flow area loss circulation zone because of a decrease in velocity and associated decrease in shear rate. As LSSD develops rapid gel with high compressive strength upon entering the loss zones, it prevents further fluid from entering, arrests the losses, and helps defend the system against being extruded out of the zone during subsequent drilling and cementing.

The LSSD system can be easily pumped through the drill bit, it is less dependent on the time and temperature necessary to place the system, acid-soluble and fluidity can be regained over a few cycles by reapplying shear (Urdaneta 2015, Urdaneta 2016).

Constituents of typical thixotropic slurries described in the work (Jadhav 2018) are cement, water, strength enhancer, clay, gel strength enhancer, retarder, weighting additive, and defoamer. The system developed by (Duffy 2017) consists of synthetic clay, nanoaccelerators, thixotropic modifiers, and a portland cement-based composition of approximately 20% by weight of the slurry.

LSSD systems were tested on wells in the Santa Cruz, Bolivia, Llason basin in Colombia, the Midland Basin in West Texas and showed high efficiency by remediation lost circulation.

Rigid-setting fluids. The rigid-setting fluid (RSF) systems were developed to cure severe-to-total losses in highly fractured formations by means of right-angle viscosity (RAV) development followed by rapid strength buildup in a short interval of time, depending on the final fluid formulation and exposure temperature. RSF systems have the same properties as LSSD systems regarding the possibility of pumping through bottom hole assembly (BHA), solubility in acids, and formation of the plug with high compressive strength in the zone of loss.

Besides controlling severe circulation losses while drilling the RSF-systems are used in the industry as a zonal isolation material for near-wellbore water and gas shutoff and setting annular plugs in the wellbore (cased hole and open-hole completions in vertical, deviated, and horizontal wells). A variety of case histories are presented from varying types of reservoir and wellbore completions, along with lessons learned after more than 500 well interventions using the RSF system (Tirado 2008, Vasquez 2013).

Right-angle-setting composition (RAS-Co) is rigid-setting fluid formulated from inorganic, nonhazardous powders and fluids mixed in freshwater or seawater and designed to react in zones at a specific bottomhole circulating temperature (BHCT) in a consistent and controllable manner (Savari 2014). The system is available in two options: for use in water-based mud only as a dual pill and for use in water-based and oil-based muds as a retarded temperature-activated single-pill.

RAS-Co can be placed inside the formation by initial dispersion of components in a nonaqueous carrier fluid (NAF). The same principle was used in new chemical sealant LCM

(CS-LCM), which is a mixture of premium quality clay and highly reactive components suspended in NAF and quickly forms a highly malleable viscous mass upon exposure to an aqueous reactant fluid and then sets harder under a wide range of temperatures below the bit (Abdulrazzaq 2018).

Another rigid-setting material is composed of the main material, suspending agent, curing agent, and filter aid. (Feng 2019). The formed plug has good stability at 180°C, high pressure-bearing capacity, and is soluble in HCl acid up to 91%.

Engineered composite solution (ECS). Effectively controlling lost circulation is more than just selecting LCM; it requires an engineered approach (Miller 2013). The approach which was used for an ECS design based on the concept of a multi-modal particle size distribution (PSD) and allow to manage any uncertainties in the pore/fracture size. The ECS composition has an optimal ratio of particles at lower-size, mid-size, and larger-size ranges and fibrous materials, which are acid-soluble for use in reservoir zones, that provides the flexibility of working in varied pore/fracture sizes. The ECS is recommended for application in the form of a pill for severe to total losses and when the ECS is ineffective on its own, it is recommended that the larger-flake supplemental material be added to the pill. (Savari 2016, Savari 2017, Savari 2019)

Crosslinked Gels. Crosslinked polymer gels, which are viscoelastic materials composed of natural or synthetic polymers and crosslinkers, are widely used in many petroleum applications including lost circulation treatment.

Among synthesized water-soluble polymers the polyacrylamide and the partially hydrolyzed polyacrylamide are the most used polymers due to the unique rheological properties, a wide range of molecular weight, and variety of possible formulations for different downhole conditions (Omer 2012, El Karsani 2014). Chromium(iii) acetate, ferric acetylacetonate, ammonium ferric oxalate, polyethylenimine (PEI), borate are defined as crosslinkers for polymer gel formation. The nanocomposite organic/inorganic gel pill prepared by polyacrylamide and chromium acetate showed high gel strength aiming at plugging highly permeable layers. The gel can be cleaned with acid treatment or hydrogen peroxide (Lécolier 2005).

It is worth noting that a lot of crosslinked gels systems and absorbent polymers were developed for the prevention of loss circulation and were not reviewed in this paper. One of the last technologies which were created for lost circulation control is a solid-free polymer gel containing acrylic acid (monomer), carboxymethylcellulose (thickener), ammonium persulfate (initiator), chromium (III) salt (crosslinking agent), and 240,000 NaCl brine as a solvent. However, the removable properties of gel have not been studied yet. (Pereira 2022)

An interesting approach was used for the development of the acid-soluble crosslinked gel LCM pill: the LCM was prepared with invert emulsion, cross-linked with magnesia. The phase change of invert emulsion and addition of light burned magnesia form the viscous fluid and remain stable till activator is not added. By the addition of an activator, the control process of static gelation starts and forms the magnesia cement. This pill can be retarded for desired time of placement, gives its vertical setting, and can be used in productive zones. (Suyan 2009)

Systems with viscoelastic surfactants. Viscoelastic surfactants (VES) are a class of surfactants that have viscoelastic properties due to the ability to form wormlike micelles and entangled structures through hydrophobic interactions, electrostatic interactions, and hydrogen bond interactions in aqueous solutions (Hu 2020)

Over the past three decades, viscoelastic surfactant-based fluids have started replacing the polymer systems in technologies such as hydraulic fracturing, diversion, matrix stimulation, sand control, and acid fracturing thanks to non-reservoir-damaging properties, stability at high temperatures, and compatibility with divalent ions.

The first viscoelastic surfactant-based fluid-loss pill was made by mixing 10 to 20% of a blend of zwitterionic viscoelastic surfactants in a heavy brine and was used in the field up to 310°F (Samuel 2013). As a typical VES system the pill breaks upon contact with formation fluids. Moreover, in case of severe fluid loss, the developed viscoelastic surfactant-based fluid-loss pill can be used as a carrier fluid for sized bridging particles, such as ground marble, which can be removed by acid treatment.

The new LCM pills use VES to create thixotropic systems by mixing novel amphoteric surfactant with sealant powder. The surfactant forms an elongated worm-like micelle structure in presence of monovalent and divalent salts while sealant powder reacts with water and makes a solid plug. The time of the beginning of the reaction is managed by adding the special reagents. The system is pumped easily and like other thixotropic system creates a rigid plug with high compressive strength in a zone of interest. The performance of the new LCM was evaluated in the laboratory and in fields in the Middle East and Africa. The single application of the LCM pill allowed for curing the losses and completing wells drilling in a quick and effective manner. (Addagalla 2020, Elkatatny 2020, Yadav 2017).

Degradable materials

The main advantage of degradable materials is the non-necessity of post-treatment after their usage that is why they have been applied in recent years in various oilfield applications, such as fluid-loss control, fluid diversion, hydraulic fracturing, etc. (Liang 2018, Rahim 2017, Malik 2018, Liang 2014).

Polyglycolic acid and polylactic acid. Typically, polyglycolic acid (or polyglycolide), polylactic acid (or polylactide) polymers (PGA and PLA), and copolymers are meant in the industry under the definition «degradable materials».

The chemical formulas of PGA and PLA are shown in Figure 2. Ester bonds in PGA and PLA are susceptible to hydrolysis, and polymers through reaction with water can form acid and alcohol (Figure 3) (Tu 2019). It should be noted that PGA degrades quicker than PLA.

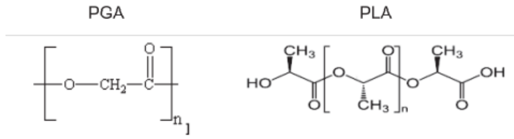

Figure 2. The chemical formulas of PGA and PLA

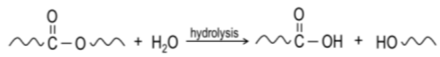

Figure 3. Hydrolysis of polyester

The properties of PGA and PLA may be varied depending on the polymerization process. Figures 4a and 4b show different forms of PGA and PLA materials (grain, powder, fiber) which are available on the market (Yoshimura 2015).

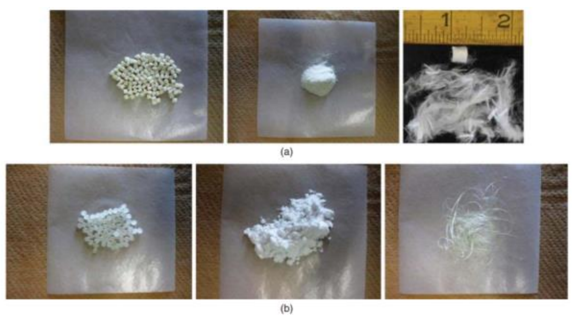

Figure 4. (a) Various PGA (b) Various PLA

Polylactide fibers (5-15% V/V of LCM) of lengths greater than 2000 microns in combination with ground marble were successful in completely plugging the tapered slot with controlled fluid loss. The degradation period of PLA fibers 225°F was 16 hours (Sharath 2011).

In the case of using the blend of PGA and PLA fibers, grains, and powders, the ratio of components in the LCM pill should be selected thoroughly, because PGA has a high strength during the first several hours and PLA has the pro-longed strength although its initial strength is low. Moreover, the dissolution time is 3 days at 60°C of PGA LCM while it was several weeks for PLA LCM (Matsui 2012)

Several successful case studies of curing severe and total losses of drilling fluids by injection of pills with degradable fibers are described in articles (Droger. 2014, Nana 2016). The time of degradation of pills was adjusted by special additives regulating the pH. The field trials proved the high efficiency of degradable LCM mitigating further reservoir damage.

Biodegradable materials. It must be noted that the aforementioned PGA and PLA are biodegradable polymers as well. In this chapter, we reviewed the systems which consist of other polymers obtained from renewable resources.

Natural polymers can be called the most used materials in the oil and gas industry for the reason that a lot of them are components of water-based mud, hydraulic gels, diverting agents, etc. Biopolymers and fibers in cases of lost circulation are mainly utilized as wellbore-strengthening materials and fluid loss control agents to prevent seepage and partial losses (Aziz 1994, Taufik 2011, Omer 2020). Plant-based materials such as date-tree, corn cob, coconut shell, eucalyptus bark, banana peels, and other residues from agricultural sectors are proposed to be preventive LCM since they are available and environmentally friendly (Amanullah 2019, Onuh 2017, Sedaghatzadeh 2020, Sauki 2017).

Nonetheless, natural fibers and polymers can be used for arresting fluid losses in the reservoir sections, for an example, the cellulose fibers and cross-linked biopolymer plug (Sharath 2011, Soliman 2015). An acid, enzyme, or oxidizer solution may be circulated to break the polymers. However, the cross-linked biopolymer pill can also break with time and temperature due to bacteriological decomposition.

The most promising technologies

Shape memory polymers (SMPs). Representing a family of smart materials, shape memory polymers (SMPs) are attracting noticeable attention within the industry.

SMPs can be defined as stimuli-responsive materials, which may recover their original shape from large deformation and extended period of cold hibernation if they are exposed to a specific external stimulus such as light, magnetic field, temperature, moisture, or pH (Yan 2012).

The shape-memory effect of SMPs (Figure 5) is mainly influenced by the presence of phases linked to the coiled or cross-linked polymer structure. The SMPs are deformed at a temperature below the glass temperature (Tg), and the percentage of deformation is mainly depending on molecular chains of polymer, which are controlled by the chemical composition and physical cross-linked structure of SMPs. After preheating the deformed polymers, these molecular chains are able to return back to the original coiled-shape structure. The shape-memory transformation varies according to the apparatus in which polymer molecules transpose between the restricted together with random entangled conformations. (Al-Humairi 2019).

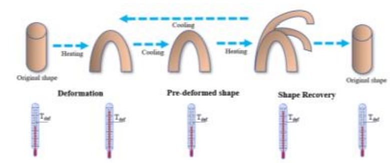

Figure 5. The shape-memory effect of SMPs

The polymer or blends namely polyethylene, polyethylene/poly(vinyl alcohol) and polyethylene/polyamide blends, and poly(vinyl chloride), exhibit shape memory property, when they are suitably crosslinked. Recently, shape memory effects have been reported for the copolymer of corn oil, styrene and divinylbenzene, filler-modified epoxy, and epoxidized natural rubber crosslinked with 3-amino-1,2,4-triazole, and smectic liquid crystalline (LC) elastomer. The thermosetting PU also has shape memory properties as well as PGA, poly(L-lactide) (PLLA), and polycaprolactone. (Ratna 2007).

Mansour et all (Mansour 2018(a), Mansour 2018(b), Mansour 2017) developed a new smart lost circulation material that is activated via the temperature of the bottomhole to effectively seal fractures and strengthen the wellbore.

The smart LCM is made out of ionic shape memory polymers in the form of disks, with a melting temperature of

248°F and the activation temperature at which the material starts to expand and become a rubbery state of 158°F. Disk-shaped particles settle down in the fractures along with their thickness; hence, their expansion will occur normal to the fracture plane that is required to get a better sealing. However, these particles have limited capability to seal wide-opened fractures because they are programmed by compression to reduce their volume, and hence, their subsequent volume growth is also limited.

The novel shapes of SMP for their application as smart LCM were fabricated through different approaches. Different material categories such as granular, 1D fiber, 1D members/fibers, 2D planar, 2D elements/ladder-shaped configurations can allow to seal large-width fractures and can be pumped through BHA (Tabatabaei 2021(a), Tabatabaei 2021(b)).

The used SMP was an ionomer resin composed of polyethylene-comethacrylic acid that behaves in between the thermoset and thermoplastic SMPs. The permeability plugging apparatus tests showed that developed members and fibers can generate after activation an entangled network over the slot width which could form a network providing a sealing by trapping granular particles.

The stability of other thermally stimulated SMPs in high-temperature and high-pressure conditions (120°C and 20 MPa) indicated that the growth rate of D90 particles can be more than 40%. After reaching the activation temperature, flaky shape particles became the massive 3D structure, that can adaptively match the width of fractures, demonstrating high plugging efficiency (Dan 2020).

The main difference of smart LCMs compared to the afore-described systems is that SMPs can be programmed by adjusting their chemical composition to get the ability of withstanding HPHT conditions as well as activating their shape memory effect through phase transformation by temperature and pressure. Moreover, the stability of the smart LCMs in water-based and oil-based muds and lower temperature at the surface compared to the bottomhole temperature secures that the equipment used in the field during injection will not be plugged. The SMPs will activate when they leave the bit nozzle and will be able to take the shape of the fracture and seal it. Finally, the smart LCMs are acid-soluble, they can be produced from degradable materials, which make them reservoir-friendly and the most promising materials.

Degradable pre-formed particle gel

Temporary plugging technology has been widely used in drilling and production operations (Kang 2014, Xiong 2018). The degradable pre-formed particle gel (DPPG) was developed as temporary plugging material, however, it can be utilized as LCM in productive zones due to its high plugging and non-damaging properties, which were evaluated during core displacement experiments.

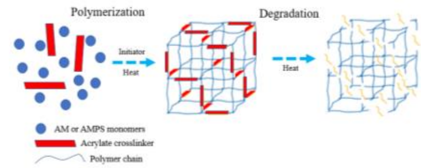

Figure 6. Synthesis, expansion, and self-degradation mechanism of DPPG

The DPPG synthesis and mechanism of self-degradation can be described by several steps (figure 6): 1) Free-radical polymerization of the low molecular weight monomers of acrylamide (AM) and 2-acrylamide-2-methylpropanesulfonic acid (AMPS) using the crosslinker and initiator with the formation of a microscopic three-dimensional network. 2) Swelling of the DPPG by water absorption 3) Self-degradation of DPPG due to the spreading effect of the crosslinker into an aqueous solution with resulting ultra-low molecular weight residues.

The swelling volume and time of degradation can be adjusted by changing the monomers or crosslinker concentration. The main advantages of these systems which make them attractive for curing lost circulation are high-temperature resistance (150 °C), high-salinity resistance (200,000 mg/L NaCl), plugging effect, and ability to degrade without post-treatment (Zhu 2020).

Potential LCM

Biocomposites are fully degradable composites consisting of natural fibers as reinforcing agents with a biopolymer matrix. Biocomposites from local and renewable resources offer significant sustainability and are used in building materials, aerospace industry, circuit boards, and automotive applications over the past decade, but application in other sectors until now has been limited (Bharath 2015). Nevertheless, with suitable development, biocomposites can be applied in the oil and gas industry, particularly as lost circulation materials.

The properties of biocomposites depend on a matrix, natural filler, and interfacing between them (Reddy 2016).

Natural fibres for reinforcing can either be obtained from plants or animals. Fibres obtained from plants can be either from wood or non-wood sources. Non-wood fibres can be produced from plant straw, bast, leaf, seed, fruit, or grass. (Mukherjee 2011). Lignocellulosic natural fibers are widely used among natural fibers as reinforcements for the production of biocomposites. (Cazacu 2016.)

The tensile properties and the flexural stiffness are improved when the fiber, matrix, and method of fabrication are selected thoroughly (Largos 2016, Khan 2012, Mohanty 2004). The PLA or PGA reinforced by the natural fibers, that can easily degrade, theoretically, can seal wide-open fractures in production zones. This suggestion will be verified during a meticulous laboratory study.

Another material that can become LCM is applied to provide in-depth conformance control. It is degradable cross-linked polymeric microspheres (Yu 2015), called DCPM, which was prepared by inverse emulsion polymerization of acrylamide (AM), 2-acrylamide-2- methyl propanesulfonic acid (AMPS) and alpha methyl styrene (HM). The main concern related to the application of this material for curing lost circulation is high post-degradation solution viscosity.

Conclusion

Lost circulation does not only result in non-productive time and an increase in the cost of the well's construction, but it can also damage the reservoir's formation and therefore, it has a negative effect on its production potential. Moreover, the lost circulation materials that are widely used in the industry can reduce reservoir porosity and permeability by particle invasion, alter wettability and phase trapping, and induce incompatibility between fluids and rocks. The quantity level of available solutions that are both efficient and reservoir friendly is moderate and is covered in this article.

Non-damaging LCMs are divided into two groups: acid-soluble and degradable. The majority of acid-soluble LCM systems create a rigid plug with high compressive strength in the zone of interest. The performance of magnesia cement, thixotropic cement, the rigid-setting fluids, and systems with viscoelastic surfactants, was not only evaluated in the laboratory, but the developed systems also showed high efficiency by remediating lost circulation during field trials.

Degradable systems are preferable because their usage does not require an acidizing treatment, which can cause environmental and operational safety issues as well as additional cost and time to the operations. PGA and PLA are the most used degradable polymers in the industry and are available in a wide range of densities and strengths and can be produced in a variety of shapes. However, the main limitations of PGA and PLA LCM are the mechanical properties and temperature dependency. That is why the usage of biocomposites as LCM could be prospective.

The smart LCMs are the most promising materials for curing lost circulation due to their undeniable advantages: stability under HTHP conditions and in different types of drilling fluids. Moreover, they can be produced from degradable materials. The new smart LCMs should be field tested to prove their effectiveness.

Future work includes the testing of biocomposites as possible LCM with the evaluation of their plugging ability and rate of biodegradability.

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