Well sealing technologies with the possibility of controlling the rheological properties of cement composite by external influence

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Abstract. The problem of long-term tightness of oil and gas wells is extremely acute for the oil and gas industry, both in terms of efficient and trouble-free operation of wells, and the most serious environmental problems associated with leaks and gushers of oil and gas at operating and abandoned wells. The article presents an up-to-date review of experimental studies, promising traditional and alternative technologies for completing and abandoning wells in difficult thermobaric operating conditions or associated with temperature and other influences to activate and control the rheological properties of cement compositions. When cementing wells in difficult geological conditions, the oil and gas industry faces the problems of creating plugs capable of withstanding extremely high pressures, temperatures and loads. In this case it makes sense to consider plugging technologies based on self-healing and regeneration effects, thermite compositions, eutectic metals, thermosetting resins and polymers. Based on the analysis of modern cementing materials and well sealants, the author proposes a set of key characteristics that a cement slurry should have in order to be able to control its physical and mechanical properties and its ability to re-liquefy under the influence of temperature, pressure or other external factors.

1 Introduction

Cementing is a critical phase in the construction of oil and gas wells. This process involves pumping a suitable volume of cement slurry into the annular space between the wellbore walls and the casing string. The primary objectives of cementing are to mechanically secure the casing, isolate adjacent oil, gas, and water-bearing formations, and create a leak-proof foundation for subsequent drilling and operational activities. The quality of cementing not only influences the efficiency of further drilling but also impacts the well's long-term productivity and lifespan. As such, ensuring high-quality cementing is essential, from the initial design stage to field execution.

Statistics indicate that cementing costs for production wells account for 10–25% or more of the total well expenditure [1]. Consequently, there is a need to minimize these costs while

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maintaining stringent quality standards. When opting for more advanced and potentially costlier cementing materials or technologies, it is important to consider the potential savings in labor and repair expenses. These savings arise from reducing the likelihood of leaks and other issues that often occur with conventional cementing materials and methods, thereby justifying the investment in superior solutions.

Well completion, which encompasses drilling into productive zones, designing the bottomhole completion structure, connecting the wellbore to production zones, and installing downhole and wellhead equipment, serves as a crucial bridge between drilling and oil or gas production. As such, selecting the optimal completion method is essential to establish the best conditions for stable and high-yield production from oil and gas wells. The chosen well completion approach directly influences the casing program, drilling techniques, cementing methods, and subsequent production activities, including well stimulation and downhole operations.

During the cementing process, several critical factors must be carefully considered, such as the selection of cement type, cement slurry composition, and cement additives, as well as wellbore preparation and process design. Modern cementing technologies, aligned with global standards, integrate knowledge from various engineering disciplines, including chemical, geological, mechanical, and other scientific fields. These technologies can be categorized based on cementing types, additives, and methods. A deep understanding and ongoing research in these areas are vital to ensure that cementing technologies can adapt to the diverse requirements and challenges posed by various well conditions, such as deep and ultra-deep wells, geothermal wells, high-pressure wells, permafrost wells, and offshore wells.

The problem of long-term tightness of oil and gas wells is extremely acute for the oil and gas industry, both in terms of efficient and trouble-free operation of wells, and the most serious environmental problems associated with leaks and gushers of oil and gas at operating and abandoned wells, both onshore and onshore sea. To avoid the risk of hydrocarbon pollution in the surrounding environment, oil and gas wells must be securely sealed and decommissioned through a process known as plugging and abandonment (P&A) once they reach the end of their operational lifespan.

The key problem of tightness is high-quality casing and cementing of the well during its completion after drilling, the safety of cement and casing during operation, as well as reliable isolation during abandonment. Also problematic are the completeness of filling the annular space with cement, the quality of adhesion with the rock and the casing, the permeability of the cement stone for gases, the formation of microcracks and the loss of continuity in it under the influence of natural and man-made loads, etc. Additionally, executing a successful plugging and abandonment (P&A) operation presents significant technical challenges. This is primarily due to the phenomenon of cement slurry "slumping" further down the well during the placement of cement plugs. This occurs because of the variations in viscosity and density between the cement paste and the drilling or well-suspension fluid. As a result, establishing a stable and reliable base or foundation for the cement plug is crucial to ensure its proper placement and effectiveness [2].

When repairing and abandoning wells, a separate problem is associated with the impossibility of completely extracting the casing string of pipes, which makes it impossible to completely eliminate leaks in the annular space, as well as the inability of cement and metal strings to withstand natural tectonic, corrosive and other influences over the horizon of decades of operation, not to mention the required tightness for hundreds and thousands of years after liquidation.

Increasing the strength and reducing the permeability of cement stone, as well as fixing the oil and gas wellbore, requires the constant development of new technologies with the use of improved additives for cement compositions. To maintain the performance of the well, prevent the destruction of the integrity of its wellbore, increase the tightness, and comply with environmental requirements, various modifiers are introduced into the cements that satisfy the drilling conditions. Cement modifiers are widely used, the addition of which increases the strength characteristics of cement stone – compressive and bending strength, reduces the time of curing and at the same time slows down the primary setting, reduces moisture absorption, increases frost resistance, etc. [3, 4].

It should be noted that while most wells are still cemented with traditional Portland cement slurries with minimal additives, there are more and more situations where special cement mixtures or alternative composite materials are required to create a strong and reliable cement stone. The development of specialized grouting compositions is relevant for gas wells with medium and high pressure, horizontal wells passing through the salt horizons of wells, high-temperature and ultra-deep wells [5]. Under such conditions, there is a risk of microchanneling or mixing of drilling fluids with gas or fluids, which can create pathways for fluids to migrate out of cemented zones.

Recently, one of the most active areas of research in the field of sealing materials and cement additives is the use of nanotechnologies, when some traditional additives are replaced by nanoadditives with new physical and chemical properties [6]. This is partly because the oil and gas industry is facing new challenges in cementing as technology advances in drilling deep offshore or highly deviated horizontal wells followed by the use of multi-stage hydraulic fracturing technologies. For these purposes, cement is required that can withstand extremely high pressures and temperatures. Reducing the size of additives to nanosizes increases the surface area of contact between materials, which leads to an increase in the fraction of atoms on the surface of particles with an increase in surface energy. Due to the small particle size, these materials have a high surface energy and hence a higher reactivity [6].

Recent advances and developments in polymer cement slurry additives, geopolymers, modified polymer-cement composites and gels based on them show excellent results in tightness, and many of them have the very useful property of self-healing and self-healing cement stone in case of potential cracks and leaks [7]. However, a limiting factor in the use of such polymer compositions and gels based on them may be the fact that most of these modifications of cement compositions cannot be used in high-temperature environments due to thermal degradation of polymers.

2 Materials and methods

The objective of the study is to review current developments and technologies in the field of cement compositions applicable in difficult geological conditions of well operation, as well as their practical implementation at oil and gas industry facilities. In the article, we will focus on modern approaches and developments of promising cement compositions suitable for high-temperature well operating conditions or activated due to external factors – temperature, pressure, magnetic field, etc. Such plugging compositions and cementing technologies are consistent with the ultimate goals of the study – the search for an acceptable plugging material for workover, completion and abandonment operations with the ability to control its rheological properties (fluidity, strength, plasticity, adhesion) under the influence of temperature or other external influence at all stages of plugging works and repair of wells.

Relatively new and actively developing research areas to ensure the durability of well cementing include the development of self-healing cements, cement composites and cement additives with self-healing properties and regeneration effects [8]. The essence of this technology is to modify the cement composition with special additives that can show their regenerating properties, increasing in size or causing re-crystallization in the cement stone, upon contact with formation fluids (formation water, hydrocarbon liquids or gas). Through this, the re-isolation of the formed cracks, micro-gaps and restoration of the tightness of the lining in the destruction zone takes place without additional technical operations.

Despite the great progress in the development of formulations of such modified composite compositions, the fact that they are of limited use in high-temperature environments due to thermal polymer degradation can serve as a limiting factor in the use of currently relevant geopolymers, polymeric materials and gels based on them [8].

Therefore, when creating backfill materials to increase strength, reduce the permeability of cement stone and improve wellbore casing, one should pay attention to their applicability for high-temperature or high-pressure well operating conditions.

In articles by J. Lee and M.K. Rahman [9, 10] describes studies conducted to study the compressive strength of cement stone, as well as the rheological properties (plastic viscosity, yield strength and strength) of cement slurries with additives from multi-walled carbon nanotubes (MWNTs) under high pressure and temperature conditions. . The authors emphasize the importance of designing and implementing new technologies for cost-effective cementing in simulated well conditions of high pressure and temperature in oil and gas wells. This complex task deserves special attention when choosing a cement slurry and its modifiers to achieve the required mechanical and rheological properties of the cement slurry. The research of the authors of the article found that even a small introduction (0.1, 0.25 and 0.5%) of MWCNTs into cement slurries leads to a significant increase in the compressive strength of the cement stone, improves the rheological properties of cement slurries and, consequently, their pumpability in difficult thermobaric conditions [9, 10].

E. Therond et al. [11] describe a successful field test of a self-healing cement system as a secondary barrier to restore zonal isolation in the Khuff gas field in the Middle East, which had intermittent problems with constant casing pressure due to wellbore stress and other factors. The wells drilled in the Khuff formation have quite challenging operating conditions due to high downhole temperatures (in the order of 150°C), high pressure gas reservoirs, and the formation's shale structure.

The self-healing cementitious composite, used as a secondary barrier to restore zonal isolation in the event of a gas leak due to failure of the primary cement, was based on a hydrocarbon (in this case gas) activation technology in the event of a breach, with a mechanism to close the leak paths by swelling. Thus, a self-healing slurry was developed for specific field conditions (gas is 90% methane) and included a defoamer to reduce foaming during mixing, a dispersant to reduce friction and control rheology, a fluid loss control agent and a retarder [11].

Twenty days after cementing, logging (acoustic cement logging and phase correlation diagram) showed complete cement coverage of the entire zone of the required area. The cement was evenly distributed throughout the casing due to good centralization, slurry design measures and good mud removal. Overall, the use of a self-healing cementitious composite as a secondary barrier has proved to be a very effective and cost-effective measure to provide long-term zonal isolation, and no leaks have been observed in hydraulic testing [11].

The work [12] investigates the productive reservoir of the Tarim oil field in China, which is characterized by serious heterogeneity and complex tectonics, having a high temperature (150°C) and salinity (240,000 mg/l). Production or injection well failures are frequent here, which is becoming an increasingly noticeable problem. Over a long period of operation, corrosive perforation, deformation and damage to casing strings in cemented and non-cemented intervals caused sand production, water breakthrough and formation leakage, which seriously affected the operation of production and injection wells, limited the use of production technologies, complicated well workover. By the end of 2017, 160 oil and gas wells experienced casing failures.

As part of the solution to the problem of eliminating well disturbances in high-temperature reservoirs of the Tarim oil field, a chemical plugging agent "LTTD" was synthesized for repairing casing pipes of ultra-deep wells, which is characterized by low cost, high strength and microdilatancy, as well as resistance to acids, high temperatures and high salinity [12].

The newly synthesized chemical bridging agent basically consisted of a heat-resistant and salt-resistant compound, an active filler, and a fiber-gel element. In percentage terms, the LTTD plugging agent included: gel base (40–50%), suspended material (10–15%), filler (5–10%), reinforcing agent (10–15%), hardening agent (5–10%), structure supporting material (10–15%), other additives (5–10%).

A reservoir at a depth of more than 6000 m, with a reservoir pressure of 52 MPa, a reservoir temperature of about 150°C, and reservoir water salinity of –24×104 mg/l $CaCl_2$, was used as a natural object of study. As of December 31, 2017, 105 wells with damaged casing pipes were processed, and the success rate of plugging operations was 90.11%.

According to laboratory and field studies [12], the new plugging agent had a thickening time of more than 480 minutes, was able to withstand pressures of more than 35 MPa, had heat resistance at 180°C, and was immune to salinity of more than 27×104 mg/l.

Thermosetting polymers (resins) can act as alternative backfill materials with the effect of temperature influence. Fundamentally, these are liquids free of particles that, once cured, transform into a solid, impermeable material. The curing process is typically activated by temperature or occurs at a specific, predetermined temperature. Moreover, their viscosity and density can be tailored for different applications by incorporating particles. Resins have been utilized as plugging materials in regions like the North Sea and the Gulf of Mexico. However, laboratory tests have indicated that their durability may be compromised in downhole conditions, such as exposure to crude oil and hydrogen sulfide (H_2S), with some loss of strength observed [2]. Other applications for resins are the restoration of zonal isolation in the annulus between two casing strings, as well as repairing casing leaks and repairs through the casing string.

Addressing the challenge of adapting polymer modifications and insulating composites for high-temperature environments, a team of researchers led by M.I. Childers from the Pacific Northwest National Laboratory and the US National Energy Technology Laboratory has pioneered the development of the first polymer-modified self-healing cement designed for high-temperature geothermal wells [13]. This innovative material combines heat-resistant, self-healing thermosetting epoxies uniformly dispersed within "H" grade cement. The resulting polymer-cement composites exhibit remarkable self-healing capabilities, enhanced cohesive strength, improved rheological and mechanical properties (including greater plasticity), and suitability for geothermal conditions. A key component of this material is thermosetting epoxy resins featuring disulfide bonds in the main monomer chain, along with multifunctional thiol crosslinkers that enable self-healing through reversible interactions. The self-healing mechanism operates via a substitution reaction, where a free thiolate group replaces a disulfide, forming a new disulfide group and releasing a free thiol. The polymer-modified cement demonstrated exceptional thermal stability (withstanding temperatures up to 350°C) and a substantial reduction in permeability (up to 87%) after self-healing mechanically induced cracks as wide as 0.5 mm. Experimental results also confirmed that the polymer-modified cement samples could undergo multiple self-healing cycles at the same location. With their outstanding thermal stability and repeated self-healing properties, these materials offer a highly promising solution for well operations in demanding subsurface environments [8, 13].

Among the new and promising alternative well completion and abandonment technologies that can actively compete with both traditional plugging materials and popular cement composites based on polymer additives and gels, we can single out technologies for eliminating leaks and forming plugs based on temperature effects and chemical reactions.

This type of backfill materials includes thermite and thermite technology, as well as eutectic metals with a low melting point. Although there are not yet a large number of publications with the results of large-scale industrial tests of these technologies, their successful experimental studies are mentioned in detail in several works [14-20].

The thermite reaction is a chemical process that can release large amounts of heat. The released energy is sufficient to heat the reaction products to the melting point. For example, the thermite reaction:

$$2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3 \ (1)$$

can proceed at temperatures above 3000°C (above the melting points of both Fe and Al_2O_3) [19].

The concept behind thermite-based formulations and technologies involves initiating a controlled, slow-burning exothermic reaction at a specific depth within the well. This reaction generates enough heat to melt the thermite plug, along with the surrounding casing, cement, and formation, integrating them with the adjacent rock. Upon cooling, the physicochemical reaction produces a robust and impermeable plug that spans the entire cross-section of the well. Essentially, self-propagating high-temperature synthesis (SHS) is triggered directly within the well to create composite materials. Notably, this process does not require an external high-temperature heat source, as the highly exothermic nature of the reaction provides sufficient heat and activation energy for the reagents to melt and bond effectively [17].

In a recent study by N. Shaikh et al. [17], it is proposed to use self-propagating high-temperature synthesized ceramic materials for the abandonment and plugging of oil and gas wells, especially under conditions of high reservoir pressures and temperatures. For high-temperature melting of ceramic materials formed in the SHS process, it is proposed to use thermites as an energy source, which initiate redox reactions occurring between a metal or alloy (usually aluminum) with the corresponding oxides of metals or non-metals. Aluminothermic reactions are well established, where aluminum is the fuel and iron oxide is the oxidizer, resulting in iron and alumina with a large amount of energy released. This process can be compared to welding performed in a borehole between a steel casing and a high-temperature iron melt, resulting in a strong steel plug with minimal porosity. And since it is welded to the casing string, it creates excellent sealing conditions for the well [17].

Thus, ceramic plugs obtained with various additives have unique and diverse properties, such as high thermal conductivity, extremely high chemical inertness and high temperature resistance, and can be used for various plugging and completion purposes. The monolithic ceramic plug formed by this process is similar to man-made rock. Ceramic plugs can be formed with the addition of a large number of reagents and a range of available additives to control the various properties of the composition (porosity, strength and thermal stability), which makes them suitable for use under various pressure and pressure conditions and types of reservoirs. It is assumed [17] that such plugs, made from cheap raw materials, will be cost-effective compared to traditional well completion and sealing methods.

In the J.M. Skjold [18] reported on a recently patented technology for decommissioning wellbores by an exothermic thermite reaction that melts steel pipe, cement and dolomite. In computer simulation of such high-temperature synthesis, one may encounter two difficulties: the phase transition problem and the dependence of thermal properties on temperature. The article [16] proposes a method for simulating a thermite reaction in a graphics processor by solving a non-linear three-dimensional heat diffusion equation with a phase transition. During the computational study and numerical analysis, it was found that a high power thermite reaction is required to obtain a dolomite melt. During the melting of dolomite at high temperature, an impermeable plug can form between the cracks in the cement and liquid dolomite, successfully sealing the well.

A rather innovative and promising way to kill wells by the scientific community is the use of eutectic metals with a low melting point. They have been tested in well-bore casing operations in the presence of both oil and water-based drilling fluids [15].

Bismuth was chosen as the base metal for this kind of plugs because of its unique properties [15]:

- Has a relatively low melting point compared to other metals – 273°C;
- In liquid (molten) form it has a viscosity comparable to water;
- Non-corrosive and unaffected by H_2S or CO_2;
- Expands approximately 3% after solidification (similar to water turning into ice), creating a good metal-to-metal bond;
- Non-toxic;
- Being a eutectic metal, when cooled, it almost instantly passes from liquid to solid state, bypassing the gel phase.

The problem with making a bismuth plug has always been how to place the metal in the hole and then effectively melt it in the right place. All early attempts at this technology were based on electric heaters that had to be lowered into the well.

The work of C. Carpenter [15] refers to the innovative development of mixtures of bismuth with modified thermites. Such mixtures melt at temperatures from 200°C to 800°C from 15 seconds to 45 minutes. Since the heat is generated by a chemical thermite reaction, this composition is non-explosive and does not require any permits or special equipment in the form of heating elements in the well. This allows a rig-less kill operation, which not only saves operators money, but also reduces the safety risks associated with rig operations.

After combining bismuth with modified thermite heaters, it became apparent that the material with a melting point of 273°C was not ideal for various downhole conditions. In order to control the plug formation process and ensure that the bismuth reliably fills the plugged area, solidifies and expands, it has been proposed to use a downhole fluid as a cooling agent to extract heat from the bismuth. And to reduce the melting point of the metal for the plug, bismuth alloys were developed. By adding small amounts of other metals to bismuth, it is possible to change the melting point, creating alloys with melting points from 93°C to 263°C. By combining these alloys with modified thermite heaters, it is possible to form gas-tight seals in wellbores over a temperature range of 4°C to 150°C. Recently, bismuth alloys have been offered on a regular basis as plugging material for completions and abandonment operations [15].

When the idea of combining bismuth and thermite first came up, the challenge was to create a gas-tight bridge plug in tubing where conventional well abandonment materials had failed. So, for the first time, the reaction of bismuth and thermite was involved in 12 test wells in Oklahoma. Bismuth plugs were installed inside the tubing at a depth of 600 to 2500 meters with a slope of up to 50°C. After installation, each of the plugs was pressure tested up to 350 kgf/cm^2. After pressure testing, the pipes were removed from each well to evaluate the created metal seal [15].

Following successful field trials in Oklahoma, the technology was tested in Alaska during zonal isolation and shut-in of two wells. Then there were several more tests of the applicability of the method for zonal isolation during the abandonment of a well in the Norwegian sector of the North Sea, where the productive zone was isolated by a mechanical bridge plug and cement. Testing at a pressure of 350 kgf/cm^2 for 1 hour showed no gas breakthrough to the surface [15].

After successfully deploying the technology inside the tubing, the next step was the idea of sealing the annulus with bismuth. The first thermite bismuth technology for sealing not only inside the tubing, but also the isolation of the casing annulus was demonstrated in the Norwegian sector of the North Sea. The formed plug was tested at a pressure of 280 kgf/cm^2 with no signs of gas leakage to the surface [15].

Hua Zhang et al. [14, 20] in collaboration with the Schlumberger Research Center propose a bismuth-tin (BiSn) alloy containing 58% mass fraction of bismuth (Bi) and 42% tin (Sn) as an alternative to cement for well plugging. According to laboratory experiments [20], a bismuth-tin alloy is an inexpensive alternative method for installing reliable and durable plugs for the abandonment of hydrocarbon wells (including offshore ones), since the volumetric expansion during solidification of molten substances (melting temperature range from 138 to 271°C) forms a liquid-tight seal with the strength to withstand both compressive and tensile loads without destroying the material itself. The dense plug obtained in the course of experiments [20] from an alloy and a consolidated rock mineral had excellent shear and tensile strengths, exceeding those of cement. The cost of such plugging materials can be offset by the relatively small size of the plug (about 5 meters) compared to cement plugs (at least 100 m). The main obstacle to the use of such an alloy is the necessary control over the proper quality of the connection of the alloy with various types of lithological composition of rocks (in contact with the pore space and capillary penetration) to prevent displacement of the plug, maintain its integrity, and prevent leaks caused by cracks and stresses in the reservoir.

Vrålstad et al. [2] note that the considered high-temperature technologies can significantly change the methodology and approach to completion and abandonment of wells, if everything works as intended. Currently, they are still under development and are undergoing full-scale tests with practical confirmation. A potential issue and a current problem in such studies is to determine whether the surrounding rock is not damaged with the appearance of leakage paths around the plug formed after cooling.

As part of the search for grouting compounds with controlled properties (fluidity, strength, plasticity, adhesion) and the possibility of re-liquefaction under the influence of temperature or other external factors for workover, completion and abandonment of oil and gas wells, it seems quite interesting to study magnetorheological cements (MRBC) for plugging and liquidation works (P&A) in oil and gas wells [21].

Typically, magnetorheological fluids are prepared using carrier fluids such as mineral oil, water, or ethylene glycol. These fluids consist of a base liquid in which magnetic particles are suspended, enabling them to rapidly change their apparent viscosity when exposed to a magnetic field. This transformation in viscosity is reversible; once the magnetic field is removed, the fluid returns to its initial state. This unique ability to switch between solid-like and liquid-like states on demand has led to the widespread application of magnetorheological fluids across various industries [22].

Consequently, cement slurries can function as efficient carrier fluids for magnetic particles. Magnetorheological-blended cements (MRBC) represent a highly promising solution for plugging and abandonment (P&A) operations in oil and gas wells. This is due to their unique ability to reversibly adjust viscosity by incorporating magnetic particles and applying an external magnetic field, offering precise control over their flow and solidification properties.

Research conducted by Nair and Ferron [23] revealed several key findings: the rheological properties of cement paste infused with magnetic particles can be effectively regulated using magnetic fields; the yield stress of magnetorheological-blended cement (MRBC) (cement paste with magnetic particles) remained unaffected by the rheological properties of the carrier fluid (cement paste) when a magnetic field stronger than 0.4 T was applied; the inclusion of a small amount of magnetic particles (up to 4% by volume of cement) did not impact the compressive strength, hydration behavior, or initial setting time of the MRBC formulation in the absence of a magnetic field; and the application of a magnetic field to MRBC did not change the morphology of the hydration products.

The study by Krezinski et al. [21] explores the development of magnetorheological-blended cement (MRBC) formulations designed to achieve optimal rheological and mechanical properties (without magnetization) and effective pressure-holding capabilities (when magnetized) for creating both permanent and temporary barriers in oil and gas wells. Experimental MRBC mixtures were prepared by incorporating carbonyl iron powder (CIP) in concentrations ranging from 0 to 50% by volume of Class H cement. All tested MRBC formulations exhibited compressive strengths exceeding the minimum required threshold of 13.8 MPa after 24 hours of curing. However, the study found that the application of a magnetic field did not have a statistically significant impact on the compressive strength of the MRBC slurries. The pressure-sealing performance of the MRBC slurries was influenced by factors such as CIP content, slurry rheology, water-to-cement ratio (w/c), and the presence of dispersing agents. Based on rheological analysis and breakthrough pressure tests, the MRBC formulation with a w/c ratio of 0.5 and 30% CIP content (30% 0.5w/c) emerged as the optimal mix, offering favorable rheological properties and strong pressure-sealing capabilities.

The study concluded [21] that a 30% 0.5w/c MRBC plug with a height of 320 mm would be capable of achieving the threshold pressure of 345 kPa when activated by a magnetic field as low as ~0.1 T. Additionally, a magnetic field of ~0.1 T can be effectively generated in the annular space outside a carbon steel casing by positioning the magnet inside the casing. This demonstrates the potential for MRBC slurries to be used not only in open-hole applications but also for creating temporary barriers or plugs in casing annuli. For instance, they could be employed to secure annular cement slurry in place after a cementing operation, preventing contamination and gas migration.

3 Results and discussion

Thus, the main goals of using cement slurries with their large number of modifications and the cement stone formed with the help of them are sealing the annulus and eliminating annular manifestations and cross-flows from reservoirs to reservoirs, which reduce reservoir pressure of productive horizons. For this reason, cement slurries at the stage of preparation and in the state of hardening must have the necessary rheological and structural-mechanical properties due to certain features of the mining and geological conditions of deposits and wells. Therefore, it is not possible to offer a universal plugging material for all sealing and completion tasks.

For example, when cementing wells in the fields of the Far North, Western Siberia, the Middle East, sea shelves, a problem arises associated with such geological and technical conditions as low temperatures in the upper part of the reservoir, high bottom hole temperatures and weakly connected rocks with abnormally low reservoir pressures. Such rocks, which are prone to fracturing and hydraulic fracturing, can absorb cement slurry during cementing, and incomplete tightness of the annulus leads to a decrease in well flow rate and violation of subsoil protection laws.

When repairing and abandoning wells, a separate problem is the impossibility of completely extracting the casing string, which does not completely eliminate leaks in the annulus. Within the framework of the methodology developed by the team of authors for repair, completion and abandonment of wells, the idea was proposed to create a cement composition with controlled rheological properties (fluidity, strength, plasticity, adhesion) and the possibility of re-liquefaction under the influence of temperature based on bituminous composite materials or liquefied sealants. Despite the large amount of data on the properties of these materials, their performance as cementing materials, especially at high pressures and temperatures, is not as widely studied as cementing compositions based on Portland cement. This implies the need for complex analytical and experimental studies, including the substantiation of recommendations for the selection of the recipe depending on the characteristics of the object.

As part of the study of the final parameters of a suitable cement composition formulation for reliable sealing and abandonment of wells, the author sees the following set of its necessary characteristics:

- Sealing agent (plugging composition) based on composite materials should be able to harden (gain strength) in the pressure and temperature range required for sealing wells (up to 25-30 MPa and more, up to 60-80°C and more) and liquefy (acquiring fluidity) under thermal or other exposure;
- The grouting compound must have high resistance of the main sealing agent to alternating deformations without destruction (discontinuity), resistant to adhesion effects in contact with the rock and the metal column;
- The sealing agent must have a high shielding ability in relation to the leakage of hydrocarbon fluids, including gases (that is, have almost zero porosity and permeability of the sealing plug);
- Plugging material should combine the possibility of active control and management in relation to the completeness of filling the annulus during workover and completion of the well due to local thermal or other effects, regulation of the injection rate and pressure or composition variation;
- The sealing agent must be able to re-liquefy (during thermal or other exposure) to extract the metal pipe string during the repair and/or abandonment of the well;
- The sealing agent, due to the appropriate viscoplastic properties, should have a minimum possibility of cracking in the sealing plug, and in case of their occurrence, activate the ability for their self-healing and regeneration of the plug.

Based on modern publications given in this review, there are many promising methods for carrying out cementing operations with the creation of technological cementing slurries. Additives from multi-walled carbon nanotubes (MWCNTs) are well suited as a modification of cement composition for their applicability in difficult thermobaric operating conditions [3, 9, 10]. Even a small amount of their addition to cement slurries (0.1 – 0.5%) showed an increase in the strength of the cement stone and an improvement in the rheological properties of the cement slurry. Quite promising are the developments of polymer-modified self-healing cement (thermosetting epoxides) suitable for high-temperature geothermal wells [13]. Thermosetting polymers (resins) can act as alternative backfill materials with the effect of temperature influence. The curing process of thermoset polymers is temperature activated or occurs at a predetermined temperature. In addition, their viscosity and density can be adjusted by adding special additives. Among the new alternative well completion and abandonment technologies that can actively compete with both traditional plugging materials and popular cement composites based on polymer additives and gels, one can single out thermite and thermite composition technologies, as well as eutectic metals with a low melting point [19].

As part of the search by the team of authors for cement compositions with controlled properties and the possibility of re-liquefaction under the influence of temperature or other external factors for the complete extraction of the casing string in relation to the operations of workover, completion and abandonment of oil and gas wells, the study of magnetorheological cements (MRBC) seems to be quite interesting. Their viscosity can be reversibly controlled by adding magnetic particles and applying an external magnetic field [21].

The rheological properties of cement paste containing magnetic particles can be regulated using magnetic fields. Importantly, the rheological characteristics of the cement paste itself do not influence the yield stress of magnetorheological-blended cement (MRBC) when a magnetic field stronger than 0.4 T is applied. Additionally, incorporating a small amount of magnetic particles (up to 4% by volume of cement) does not affect the compressive strength, hydration behavior, or initial setting time of the MRBC formulation in the absence of a magnetic field. Furthermore, a magnetic field of approximately 0.1 T can be effectively generated in the annular space outside a carbon steel casing by placing the magnet inside the casing. This highlights the potential for MRBC slurries to be used not only in open-hole applications but also for creating temporary barriers or plugs in casing annuli, offering versatile solutions for well operations.

It should also be noted that cement production accounts for almost 7% of global carbon dioxide emissions [24]. And if some of the cement in the solution can be replaced with some additional binders, then this can reduce the consumption of conventional Portland cement and thus reduce greenhouse gas emissions associated with cement production.

Reducing greenhouse gas emissions during the development of alternative cement compositions can be significantly reduced by using geopolymer cements or geopolymers, which have, among other things, excellent mechanical and physical properties, low production costs, and the ability to self-regenerate cement stone [8]. Geopolymers are alkali-activated aluminosilicate materials with a low calcium content. Unlike conventional cement, which is activated by contact with water, geopolymers are activated by alkali (alkaline activators) and form aluminosilicate gels that do not absorb water when cured. This method of activation leads to a smaller reduction in volume and low shrinkage of the geopolymer [25].

The main problems hindering the use of geopolymer materials in oil and gas wells are considered to be their short thickening time and temperature sensitivity. At the same time, it has been experimentally shown [25] that an acceptable thickening time of geopolymers can be ensured by selecting the correct composition of additives (plasticizers, setting retarders, etc.). Thus, in the studies of M. Nasvi [26], good pumpability of geopolymer compositions was observed under temperature conditions up to 120°C. And the results of the analysis of the thickening time of geopolymers based on fly ash [25] showed that the completion of this process lasting more than 300 minutes can be achieved at temperatures up to 80°C, and a comfortable thickening time (several hours) can be achieved already at temperatures up to 93°C without the addition of any retarders and superplasticizers.

One way or another, further research is required to substantiate, as a specific result, the technology and technical means for workover, completion and abandonment of wells using new formulations of cement compositions, including with the control of their rheological properties due to directed external influence, as at the stage of preparing a solution, and at the stage of cement plug curing.

4 Conclusion

To prevent contamination of the surrounding environment with hydrocarbons, oil and gas wells are required to be permanently plugged and abandoned (P&A) at the end of their productive life. Therefore, in the cementing process, it is necessary to take into account key factors: the choice of cement slurry and cement additives, wellbore preparation, process flow, etc.

Considering that cement production accounts for almost 7% of global carbon dioxide emissions, modifying some of the cement slurry with active additives or using new cement materials for workover, completion and abandonment of wells will help reduce the consumption of Portland cement and, therefore, reduce greenhouse gas emissions. Reducing greenhouse gas emissions during the development of alternative cement compositions can be significantly reduced by using geopolymer cements or geopolymers.

The key problem of long-term tightness is high-quality casing (cementing) of the well during its completion after drilling, the safety of cement and casing during operation, as well as reliable sealing during abandonment.

The conditions for repair and liquidation work can be complicated when operating wells with high reservoir temperatures, pressures and heterogeneities in the reservoir structure. For such extreme conditions, it makes sense to consider plugging technologies based on the effects of self-healing and regeneration, thermite compositions, eutectic metals, thermosetting resins and polymers.

When repairing and abandoning wells, a separate problem is the impossibility of completely extracting the casing string, which does not completely eliminate leaks in the annulus. For this reason, cement slurries at the stage of preparation and in the state of hardening must have the necessary rheological and structural-mechanical properties due to certain features of the mining and geological conditions of deposits and wells. Such cement compositions with controlled rheological, physicochemical and mechanical properties, as well as the function of re-liquefaction under the influence of temperature, pressure or other influences (for example, using magnetic fields) seem to be quite promising in relation to the repair and abandonment of wells.

Based on the current realities of the development of the oil and gas industry, the natural conditions of development, environmental standards, as a replacement for traditional cement compositions, it is proposed to pay attention to cement compositions based on bituminous composite materials or liquefied sealants.

For reliable sealing and abandonment of wells, the cement composition, according to the author's ideas, must have a set of the following important characteristics: the ability to acquire strength in the range of pressures and temperatures required for sealing wells, high resistance to discontinuities and cracks, resistance to adhesion effects in contact with rock and a metal casing, high screening ability in relation to leakage of hydrocarbon fluids, the possibility of active control and management in relation to the completeness of filling the annulus during workover and completion of the well, the ability to re-liquefy (during thermal or other form of exposure), the ability to activate the mechanisms of self-healing and regeneration grouting plug in case of crack formation.

This implies the need for further comprehensive analytical and experimental studies to substantiate the technology and technical means of overhaul, sealing and abandonment of wells without damage to the environment and ecology, as well as the development of modern formulations of grouting compositions with the ability to control their rheological properties due to directed external influence, as at the stage of preparation of the cement slurry, and at the stage of hardening of the cement plug.

The work was carried out within the framework of the state task of the Oil and Gas Research Institute of the Russian Academy of Sciences (OGRI RAS) on the topic number 125020501405-1 "Development of new technologies for efficient and environmentally friendly hydrocarbon extraction in challenging mining and geological conditions based on a systematic approach to studying and modeling the full life cycle of oil and gas fields".

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