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Review article

Development the self-healing concept for well cement support integrity maintenance. Theory and practice

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ABSTRACT

Oftentimes oil and gas wells can be affected to various technological as well as chemical and natural stresses. Perforations, fracturing, side tracking from under the casings shoe, formation integrity testings all these lead to the cement sheath fragility and the annulus integrity deterioration causing the emergence of net of cracks in the cement sheath, which contribute to nascence of behind-the-casing flows.

World statistics say that the issues of casing string-borehole annulus unsealing prevention, as well as the effective restoration of the cement sheath integrity in the presence of a wide range of water-shutoff materials and technologies for inflows bounding, do still remain open and require non-standard solutions. In this connection, the development of “self-healing” plugging material, which allows the cement stone to independently regenerate its integrity, thereby excluding technological shutdowns and the intervention of repair equipment, is one of the highest priority tasks and promising methods for eliminating behind-the-casing flows, accompanied by restoring the integrity of the well cement sheath. An advanced alternative to the traditional plugging material is elaboration of "self-healing" cements, which is hopeful in the line of the above-mentioned peculiarities.

Keywords: *"self-healing" cement; cement sheath; modifying additives; plugging material; behind-the-casing flows; well support durability; water influx.*

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Научный обзор

Разработка концепции самозалечивания для поддержания целостности цементной крепи скважин. Теория и практика

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АННОТАЦИЯ

В нефтегазовом деле скважины всегда подвергаются различным технологическим, химическим и естественным нагрузкам, возникающим при перфорации, бурении боковых стволов из-под башмака обсадной колонны, гидродинамических испытаниях пластов, гидроразрыва пласта, углублений и т.д. Такие операции нарушают целостность цементного кольца и ведут к потере герметичности скважины, при этом в цементной крепи образуется система трещин, способствующая возникновению заколонной циркуляции воды.

Мировая практика свидетельствует о том, что вопросы предотвращения разгерметизации затрубного пространства, а также эффективного восстановления целостности цементного кольца при наличии широкого спектра водоизоляционных материалов и технологий ограничения водопритоков до сих пор остаются открытыми и требуют нестандартных решений. В связи с этим разработка «самозалечивающегося» тампонажного материала, позволяющего цементному камню самостоятельно восстанавливать свою целостность, исключая тем самым технологические остановки и вмешательство ремонтного оборудования, является одной из первоочередных задач и перспективным методом ликвидации заколонной циркуляции воды, сопровождающейся восстановлением целостности цементного кольца скважины. Разработка «самозалечивающегося» цемента является прогрессивной альтернативой традиционному тампонажному материалу, что обнадеживает в свете вышеперечисленных особенностей.

Ключевые слова: *самозалечивающийся цемент, цементное кольцо, модифицирующие добавки, тампонажный материал, заколонная циркуляция воды, долговечность крепи скважины, водоприток.*

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Ғылыми шолу

Ұңғымалардың цемент бекіткіштерінің тұтастығын сақтау үшін өзін-өзі емдеу тұжырымдамасын әзірлеу. Теория және практика

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АННОТАЦИЯ

Мұнай-газ саласында ұңғымалар әрдайым перфорация кезінде пайда болатын әртүрлі технологиялық, химиялық және табиғи жүктемелерге ұшырайды, шегендеу бағанасының тоспасы астынан бүйірлік оқпандарды бұрғылау, қабаттарды гидродинамикалық сынау, ойықтар және т.б. Мұндай операциялар цемент сақинасының тұтастығын бұзады және ұңғыманың тығыздығын жоғалтуға әкеледі, ал цемент бекіткішінде жарықтар жүйесі пайда болады, су айналымының пайда болуына ықпал етеді.

Әлемдік тәжірибе көрсеткендей, құбыр сырты кеңістігінің ашылуының алдын алу, сондай-ақ су өткізбейтін материалдар мен су ағындарын шектеу технологияларының кең спектрі болған кезде цемент сақинасының тұтастығын тиімді қалпына келтіру мәселелері әлі де ашық және стандартты емес шешімдерді қажет етеді. Осыған байланысты цемент тасының өз тұтастығын дербес қалпына келтіруге мүмкіндік беретін «өзін-өзі емдейтін» тампонаждық материалды әзірлеу, осылайша технологиялық аялдамалар мен жөндеу жабдықтарының араласуын қоспағанда, бірінші кезектегі міндеттердің бірі және ұңғыманың цемент сақинасының тұтастығын қалпына келтірумен қатар жүретін бағаналы су айналымын жоюдың перспективалық әдісі болып табылады. «Өзін-өзі емдейтін» цементтің дамуы дәстүрлі тампон материалына прогрессивті балама болып табылады, бұл жоғарыда аталған ерекшеліктерге байланысты жігерлендіреді.

Негізгі сөздер: *өзін-өзі емдейтін цемент, цемент сақинасы, өзгертетін қоспалар, тампонаж материалы, бағана сыртының су айналымы, ұңғыманы бекітудің беріктігі, су ағыны.*

Дәйексөз келтіру үшін:
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Introduction

The cement sheath of a well is the main barrier protection of the casing string from an aggressive environment influence and the prevention of reservoir fluids migration. However, under the influence of regular technological loads, the integrity of the cement stone is oftentimes lost, which leads to flooding of the well due to the behind-the-casing flows. At the same time, statistics depict that in most cases cement stone, prepared according to non-additive formulation, is not able to withstand significant operational loads and thus does not meet expectations for maintaining the integrity of the cement sheath. Moreover, there are many modern water-shutoff materials and technologies aimed at limiting water influx. However, all of them have low duration of process effect, and are also rarely aimed at restoring the well support integrity [1].

Many Russian and foreign scientists focus on improving the quality of cement stone capability to effectively (reliably and continuously) seal the space between the wall of the well and the casing string, as well as eliminating channeling until the system of cracks and behind-the-casing flows occur. Nowadays, an advanced alternative direction in the field of improving plugging material and one of the promising solutions to these problems are the development and application of "self-healing" cements, which in general are "intelligent" cement systems with controlled properties [2].

The theory of self-healing in relation to polymeric materials has been revealed since the 1980s. It outlines the opportunities for healing micro-cracks in various set of materials for much more sustainability and safety of the polymeric components [3].

As it is known, self-healing ability may occur in autogenous and autonomous way. Autogenous healing of a cement stone is primarily achieved by further hydration and carbonation [4], besides it contributes to the closure of cracks with certain limited sizes. The autonomous healing of a cement stone can be achieved by initial incorporation of healers, which are some specific components meant to subsequently recover the cement sheath integrity and maintain well support durability efficiently.

The author has extensively investigated a wide variety of autonomous healers, thus in the next proposes a "self-healing" concept of the affected cements, which consists in sealing the water supply channels with chemically inert modifying additives previously introduced into the cement powder, meant to be activated and acquire the ability to block cracks in the cement stone only after interaction with reservoir water [5, 6]. The principle of the "self-healing" cement operation is to start the water-absorbing mechanism of the additives integrated into regular cement powder. The additive consists of an active water-swelling core covered with a solid water-soluble shell (fig. 1), which temporarily prevents a contact of the water-swelling core with water. Besides, the shell must prevent premature hydration within a cementing time – a time after injecting cement slurry into the well and its setting [7].

Materials and Methods

The recommended formulation of the "self-healing" cement technology is as following: plugging material including a binder (99.0–99.5%) and modifying additives (0.5–1.0%) [8]. Portland plugging cement CEM-I (Class G, sulfate-resistant) is used as a binder. Granules of water-swellable polymer material based on anionic polyacrylamide, so-called super-absorbent, (active core) coated with a water-soluble film of a polymer complex (preventive sheath) [9], made from components of carboxymethyl cellulose and polyvinyl alcohol, are used as modifying additives [8].

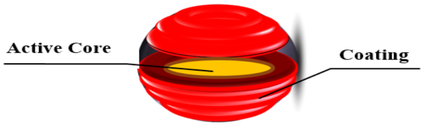

Figure 1. A model of the modifying additive [7]

After justifying the composition and implementing the "self-healing" cement slurry basic studies, an experimental batch of modifying additives was produced. The method of the modifying additive test samples manufacturing included preliminary mechanical activation of the active water-swellable core and its coating, i.e. the application of a film shell by structural granulation in fluidized bed apparatuses. The viscosity of the polymer complex solution was close to the atomization limit and empirically selected to ensure a uniform layer during dispersion of the solution. The thickness of the applied shell was verified in accordance with the rate and degree of its solubility depending on temperature, mineralization of reservoir water as well as the contact time. Thus, all the trigger factors of the "self-healing" mechanism which are vital in order to exclude premature swelling of the modifying additive and ensure its chemical inertia to the liquid phase during the entire cycle of preparation and injection of cement slurry into the well, are taken into account.

A number of laboratory studies of slurry and stone made of "self-healing" cement, which included the study in accordance with the regulatory

Figure 2. The bench equipment [10]

documentation for plugging materials of the main indicators of rheological, strength and filtration properties, demonstrated a complete absence of the swelling additives influence on the rheological properties of cement slurry during mixing, thickening and setting of slurry. The tests also showed that the swelling additives did not worsen the mechanical properties of the cement stone.

To test the validity of the concept and the proposed "self-healing" cement formulation, a technique was developed using specially manufactured test-bench equipment [10]. The stand was mounted on the testing site of NIPI USPTU LLC, which provided an opportunity to observe the behavior of the hydraulic system, to investigate the filtration properties of the modified cement stone, as well as to study the effect of the modifying additives on the technological properties of the cement slurry and the cement stone over time, observing them in conditions close to the ones of a well (fig. 2).

The method of conducting the bench experiment was as follows: the working agent (water) was pumped through a flexible hose into a working cylinder containing a stone made of "self-healing" cement. The agent was released from a hermetically sealed pressure vessel under a set pressure from the compressor, while the volume of the liquid entered and filtered through the stone was fixed [10].

In order to physically simulate the process of cracking in cement stone, the operating cylinder with the cement stone inside was subjected to mechanical stress, loading up to the formation of a system of cracks using a pneumatic hammer. After creating artificial cracks in the cement stone, the operating cylinder was piped with the circulation system. The circulation system was started by turning on the compressor with a gradual increase in the water injection pressure up to 4 atm, according to the calculations and taking into account the design features of the operating cylinder, this figure corresponds to the pressure of the water break through the cement stone.

The study of the throughput of the cement stone modified with the additives was carried out by passing different types of associated water produced from the deposits of the Republic of Bashkortostan. Thus, three types of water were used: fresh water, bicarbonate-type water and chlorocalcium-type water.

The bicarbonate-type water had a degree of mineralization up to 1g/l, was produced from a well with a depth of 2173 m and located on Uzybashevskaya site, which uncovered Namur-Serpukhov deposits. The chlorocalcium-type water had a degree of mineralization up to 262.33 g/l, was produced from a well with a depth of 1420 m and located at the Shelkanovskoye field, which uncovered the Tournaisian deposits.

In order to test the "self-healing" cement on a real site, a small-scale field experiment was modeled and conducted shortly afterwards, what made it possible to thoroughly investigate the functional activity of an unconventional cement system and observe its behavior in real reservoir conditions.

Results

Onwards, a comparative analysis of the water-carrying capacity of three cement stone samples was carried out, the first of which, being modified with the "self-healing" additives, filtered bicarbonate-type water; the second, being modified with the "self-healing" additives, filtered

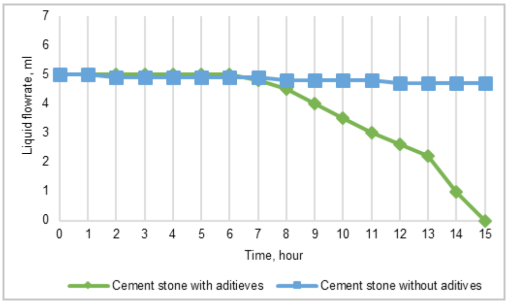

Figure 3. Study of reservoir water filtration through the cement stone samples at a temperature of 60°C and the minimum degree of mineralization

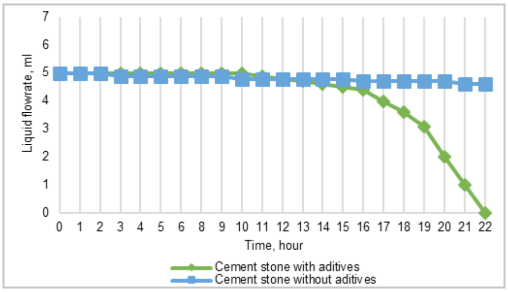

Figure 4. Study of reservoir water filtration through the cement stone samples at a temperature of 20°C and the maximum degree of mineralization

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chlorocalcium-type water; the third one from non-additive neat cement filtered fresh water.

When filtering reservoir water at a temperature of 60°C, the most rapid dissolution of the preventive sheath and the maximum activation of the water-swelling core occurred. The filtration mode was established in 6 hours, and after another 9hours there was a complete cessation of liquid filtration (fig. 3).

When filtering reservoir water at a temperature of 20°C through a sample of the "self-healing" cement, the dissolution of the preventive sheath occurred at a minimum rate. It took 10 hours to establish the liquid filtration mode. Complete termination of filtration occurred after another 12 hours (fig. 4). In the third sample, made of non-additive neat cement, no change in the nature of filtration going under the steady filtration mode observed.

In the cement stone modified with the additives, 75% of the passing through water was bound within 8 hours of the steady filtration (12 hours at ↑ mineralization and ↓ temperature), while 25% of the water has been passed through the stone for the next 7 hours (10 hours at ↑ mineralization and ↓ temperature) until the water passing complete cessation. The total time from the start of the stone hydration to the complete stop of the water filtration was equal to 15 hours (22 hours at ↑ mineralization and ↓ temperature). In the stone made of non-additive neat cement, the cracks fusion did not occur even after several days, while after the specified time, 92.5% of water turned out to be in free circulation, and only 7.5% of the water was bound by previously non-hydrated cement.

The studies of the solution temperature and the mineralization degree effect on the activator mechanisms of the modifying additive revealed, that the fastest possible water absorption with an increase in the granules by 550% from the initial volume within 1 hour is observed in hot (from 60°C) fresh water. In hot (from 60°C) mineralized water the maximum water absorption with an increase in the granule by 490% of the original volume is also observed within 1 hour.

At the same time, an attempt to estimate the size of the pore channel was made, thus the filtration of the reservoir water with a constant flow through a conditional capillary and pores of the intergranular porosity of the cement matrix were taken into account.

The permeability of the cement stone during the liquid filtration through the capillary is estimated from the ratio of the Darcy and Poiseuille equations:

$$Q = \frac{k \times F \times \Delta p}{\mu \times L} \quad (1)$$

$$Q = \frac{R^2 \times F \times \Delta p}{8\mu \times L} \quad (2)$$

from

$$k = \frac{R^2}{8}, \quad (3)$$

Where k is the permeability of the rock, m^2;
F – filtration area, m^2;
Δp – pressure drop, Pa;
μ - viscosity, Pa·s;
L – length, m;
R – radius of the capillary, m.

After converting the permeability coefficient and the capillary radius to one dimension, an empirical equation for estimating the permeability coefficient when filtering a liquid through a capillary is obtained:

$$k = 0{,}125 \times R^2 \quad (4)$$

$$F = \pi \times R^2, \quad (5)$$

Before substituting the known values of all parameters into the Darcy equation and expressing the capillary radius from it, it is necessary to convert them into the [SI] system.

$\frac{\Delta p}{L}$ = 2 MPa/m = 2×10^6 Pa/m;

$\mu_{reserv\ w}$ = 1.55×10^{-6} m^2/s = 1.8×10^{-3} Pa·s;

Q = 150 ml/min = 2500×10^{-9} m^3/s;

$$Q = \frac{0{,}125R^2 \times \pi R^2 \times \Delta p}{\mu \times L}, \quad (6)$$

$$2500 \cdot 10^{-9} = \frac{0{,}125R^2 \times \pi R^2 \times 400}{1{,}8 \cdot 10^{-3} \times 0{,}2}, \quad (7)$$

$R^4 = 5.7326 \times 10^{-15}$;
R = 0.000275 m = 0.275 mm;
D = 0.55 mm.

Having calculated the maximum diameter of the capillary (or the total size of the capillaries) involved in the filtration, it follows that the pore channel belongs to the supercapillary sizes, so that the fluid is free to move as there is no influence of capillary forces.

The volume of the water supply channel having the shape of a regular cylinder can be calculated using the following formula by substituting the known values:

$$V = F \times h = \pi \times R^2 \times h, \quad (8)$$

$V = 47.5\ mm^3$.

Thereby, the modifying additive in the process of its hydration is able to block conducting channels with a cross-sectional area of up to 0.237 mm² and a diameter of up to 0.55 mm al this under the conditions of a high degree solution mineralization and a moderate temperature of the liquid. Thus, it can be argued that the elaborated modifying additive with a size in the range of clinker grain particle size has the necessary potential to block channels of 500 microns in conditions of moderate temperatures and a high degree of reservoir water mineralization.

At the beginning of 2021, a water-supply well was drilled to a depth of 300 m on a land plot allocated for a test site with a location in KhMAO-Yugra to exploit the waters of the Atlymsky aquifer complex. The design of the well and the procedure during its construction included drilling for a surface casing string, drilling for a flow string and the aquifer exposing, which were carried out according to the Certificate of Act No. 1 "Completed works on drilling a water-supply well" [11]. The surface casing string and the flow string were cemented in one-step using direct cementing technology with the rise of cement slurry with a density of 1.83 g/cm³ based on CEM-I (State Standard 1581-96 for PCT1-50 cement) up to the wellhead. According to the technical specification, the exposed interval of the water-bearing horizon was cemented with the "self-healing" cement [8] overlapping the roof of the aquifer by 6 m.

After WOC of the screen pipe, the well was deepened with the help of a chute by a churn-line method for the construction of a settling pit. To create a filtering part, an AP-6M hydroperforator equipped with hydromonitor nozzles was lowered on a stand of pipes into the production hole located opposite the aquifer. Perforation of the well walls was carried out by pumping a pressurized abrasive liquid with a pumping unit through a stand of pipes and hydromonitor nozzles of a hydroperforator. The well was tested after the completion of the perforation work. A running airlift was installed to trigger the influx of reservoir water and to flush filters from washed out and settled sludge. Drilling rods were used as water lifting pipes. Clean water was continuously poured into the well simultaneously with air being supplied to the airlift. After the water level in the well had been raised, the running airlift was removed, the water in the well was pumped out. Further, the opened aquifer hole was covered by a packer for 7 days.

The geophysical studies were carried out immediately after the cleaning and flushing of the exploratory borehole and cavernometry. The purpose of the geophysical research was a detailed dissection of the geological section, and the choice of the installation interval for the better screen operating part. This included a set of standard logging methods and radioactive logging.

To conduct geophysical research, a geophysical laboratory with an electric winch LG-500 with a logging single-core or three-core cable KGL 1–3 was used. To identify water interlayers, a standard electrical circuit was performed by the resistivity log method.

According to the technical assignment, the opened section of the aquifer +50 m were investigated using a small-sized deep flow meter (MGR-2) in order to detect the behind-the-casing flows, leakages and places of casing string violation, as well as cross-feeds. Thus, thermometry of the well was performed in a cased non-perforated well, then on the 1st day, on the 3rd day and on the 7th day after the perforation work (fig. 5).

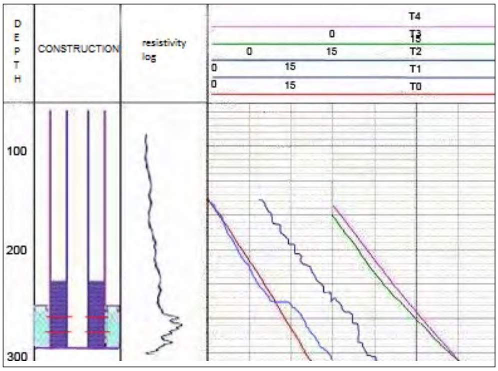

Figure 5. Thermogram of the water intake well

During the thermometric studies in the cased hole, a regular temperature increase of up to 15°C was observed at the bottom hole mark. After the perforation, a deviation of the thermogram was recorded on the 1st day in the zone of the opened aquifer, which reflected the thermal disturbance caused by the influx of water from the horizon. Carrying out a thermal logging on the 3rd day and obtaining a tortuous curve reflected the presence and intensity of water circulation in the bore hole annulus, which apparently found a breach appeared in the wall as a result of the settling pit construction. On the 7th day, thermometry demonstrated a significant decrease in intensity, and then a flattening of the values of thermal fluctuations, which was due to the absence of water influx at a fixed measurement distance from the initial thermogram taken as zero. These features of the thermographic analysis curves behavior are associated with the use of "self-healing" cement used as a plugging material for the interval of the aquifer bed overlapping.

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Discussion

The full-scale experiment with the use of the bench equipment, as well as the modeled field experiment demonstrated the actual elimination of water cross-flows and indicated the cement stone integrity restoration during the studied time.

Eco-orientation of the applied technology is in the use of environmentally friendly materials, as well as in ensuring a technological process that excludes any negative impact on the environment. Thus, the elimination of heavy repair equipment from the repair process prevents the release of pollutants into the atmosphere - combustion products during the combustion of fuel and lubricants. The absence of a working crew, the exclusion of equipment transportation and materials do not allow the risk of spontaneous harmful effects on the local area with characteristic plant and animal species. It also includes the prevention of noise and vibration pollution during downhole operations that carry the risk of negative effects on biota.

The environmental safety of the used materials, and in particular the additive, which is a synthetic flocculant obtained as a result of the synthesis of nitrile acrylic acid saponified in the presence of sulfuric acid, is mainly confirmed by its time-regulated chemical inertia due to confinement in a preventive inactive sheath that excludes the corrosive activity of the additive.

The experimental work was carried out to identify destructive reactions of the polymers, factors leading to undesirable changes in the structure of the polymers during their operation in downhole conditions were considered. Thus, the effects of elevated temperatures, pressure, mechanical load, humidity, salinity, as well as possible ionic reactions were studied.

Regarding temperature limitations, the gradual destruction of the polymer core granules occurs at temperatures of more than 100°C, as well as with direct and prolonged exposure to sunlight, which is not provided by the conditions of its operation.

Discussing the topic of all-round compression acting on the additive, so it can be assumed that the pressure will be minimal, since during the hardening of the cement stone, the hydrostatic pressure on the formation will decrease due to the suspension of the solution and contraction of the volume of actively hydrating cement material.

Experiments to determine the kinetics of the polymer swelling included preliminary immersion of the additive in a mineralized medium using a paddle mechanical agitator operating at maximum speeds. This demonstrated the additive coated with a multilayer shell has a high mechanical strength, which is sufficient to withstand the mechanical load that occurs during mixing and pumping cement slurry into the well.

The deterioration of the absorbent properties of the additive is facilitated by high water mineralization, which makes it impossible to achieve the maximum possible size of the granule, but this does not affect the service life of the material. Speaking of syneresis, the drying and water loss of the selected water-swellable polymer is possible under the condition of an increase in temperature, an increase in the electrolyte concentration in the system, the introduction of desolvating agents into the system, and an increase in the mobility of the elements of the coagulation structure. Due to the fact, that the cement stone works in a closed system, while maintaining the conditions of hygrometric equilibrium, the phenomenon of syneresis with the subsequent resumption of water flow is excluded.

Further, it is necessary to mention the presence of salt ions present in natural waters. Thus, Cl- is a corrosion activator anion of concern in this case. However, the selected flocculant does not enter into a corrosive reaction when in contact with calcium chloride water, moreover, it perfectly absorbs organic impurities, in particular humic substances, while the polymer does not affect the pH of the water.

Based on the field test of the presented technology of "self-healing" cement, an attempt was made to conduct an elementary comparative analysis of the economic efficiency of the most popular technologies for restricting water influx to the well [11]. For comparison, water-proofing activity and the cost of repair and insulation works were analyzed, data on the most successful technologies were used [1]. The main idea of cost reduction was to thin the number of interventions, the number of which, under the combination of fortunate circumstances, reaches at least five during the depreciation period of an oil well. It should be noted that during the operation of the water supply well, which participated in the model field experiment, there was no need to carry out water shut-off works due to the non-detection of behind-the-casing flows.

Speaking about the economic costs, in order to minimize the expenses for the "self-healing" cement manufacturing and the usage it is proposed to take a rational approach by using the “self-healing” cement only for bandaging intervals overlapping the contact area of oil-bearing and water-bearing formations [12]. In addition, the use of the "self-healing" cements will increase profits by eliminating well downtime during workovers and insure additional oil production by limiting water cut due to behind-the-casing flows elimination. All these will eventually reduce the cost of oil produced and achieve a significant economic effect [13].

Conclusion

The results of physical experiments and auxiliary methods show the viability of the approach in achieving the goal of restoring the integrity of the well support using the "self-healing cement".

In the present research, the intrinsic autogenous healing of cement matrix is realised by embedding superabsorbent polymer at batching, thus appearing one of the most promising sustainable material in cracks repair mechanisms [14].

The elaborated plugging material for improving the quality of well casing based on Portland cement and modifying additives introduced into its composition is promising as "self-healing" technology aimed at selective cementing of the most dangerous well support sections, which may overlap the contact intervals of oil-bearing formation and aquifer. Providing local placement of the "self-healing" cement in the areas of probable existence of through-open cracks, leading to behind-the-casing circulation, the cement sheath is being strengthened with a special plugging material, which is ready to begin autonomous restoration of the well support integrity when free water appears.

Thus, it can be argued that "self-healing" cement is not only restoration but also prophylactic technology aimed at well cement support self-maintenance, what was confirmed by the results of the research, including the test bench experiment and modeled field test, which proved the ability of the devised technique to prevent loss of the cement sheath [15].

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