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Increasing the reliability of oil and gas well fastening with polycomponent plugging systems

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Abstract

Purpose. Development of effective composite plugging systems for reliable fastening of oil and gas wells in difficult mining-geological conditions of deposits of Ukraine.

Methods. The proposed research is based on an analytical and industrial study of the problems of the well construction and fastening in the conditions of chemogenic deposit occurrence when applying the analysis of geophysical research materials. The research of tamponage solutions and buffer liquids was carried out using standard devices and methods that meet the set of requirements for testing cements and technological systems for well construction. Processing of research results was carried out in MATHSAD and EXCEL. Composite cement CEM V according to the European standard EN 197-1, tamponage cement 1-G, krents - high-basic C_2F $CaSO_4$ and low-basic 3(CF) $CaSO_4$ calcium sulfoferites were used for the research.

Findings. It was established that the basic plugging material, as well as technological solutions for fastening wells in difficult mining-geological conditions, do not ensure compliance of the well as an engineering structure with operational reliability indicators. As a result, violations in the fastening system are quite often recorded, which require significant time and financial costs for their elimination, and sometimes lead to well liquidation. In order to increase the reliability of fastening wells, it is necessary to use multi-component tamponade systems modified by krents. Calcium sulfoferrite admixtures have been proved to accelerate the kinetics of early strength and contribute to the formation of cement stone with improved characteristics. The need to use effective buffer systems to improve the quality of fastening is substantiated.

Originality. On the basis of assessment, systematization and detailed study of geophysical material and features of well fastening under the conditions of exposure to chemogenic sediments, the necessity of using composite plugging material was established. The conducted studies have proved that to ensure reliable fastening of wells in difficult mining-geological conditions, it is necessary to use multicomponent composite plugging material modified by calcium sulfoferites with accelerated kinetics of early strength, which form cement stone with a densely packed structure.

Practical implications. Based on the industrial material evaluation and detailed laboratory studies, technological solutions have been developed to increase the reliability of well fastening due to the introduction of multi-component composite plugging material modified by krents and buffer liquids.

Keywords: *well, plugging systems, mineral salts, rock, fluidity*

1. Introduction

Prospects for increasing the volume of oil and gas production on the territory of Ukraine are related to the development of productive horizons occurring at significant depths. Prospects for oil and gas bearing capacity at great (more than 4-5 km) and ultra-great (more than 6.5-7.0 km) depths deserves important attention [1]. It should be noted that the current recoverable reserves of natural gas in Ukraine, which are included in the "international categories", allow us to state that the "proven reserves" amount to about 300 billion m^3 [2]. About 70% of the predicted reserves of oil and gas are associated with the lower coal deposits of the Dnipro-Donetsk Depression (DDD) in the depth interval of 4-7 km [3]. Quite often, the construction of deep wells requires the opening of a thick mass layer of unstable chemogenic sediments, the behavior of which is quite unpredictable.

When drilling wells, the natural balance of the rock mass is disturbed, and therefore in the area near the wellbore there is a redistribution of rock stresses. Under the influence of rock pressure, the plastic rock bordering between two elastic layers acquires the ability to flow. When the rock changes from an elastic state to a plastic fluidity, there is a loss of holding capacity, and therefore the rock begins to move indefinitely in the direction of the well. Such plasticity is a prerequisite for complications in the construction of wells.

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A force field arises in the rock mass, resulting in maximum stress concentration on the well walls. When the load-bearing capacity of the rocks is less than the acting stresses, the walls collapse. A special ability to disrupt the stability and integrity of rocks is characteristic of saline sediments and sediments containing mineral salts in their structure.

According to genetic classification, mineral salts belong to marine sediments, the main components of which are ions Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-}, Br^-, $B_4O_7^{2-}$ [4]. In addition, Fe^{2+}, I^- and CO_3^{2-} ions are present. These elements are part of more than 30 soluble and a significant number of insoluble minerals. Among the soluble ones are halite (NaCl), sylvine (KCl), sylvinite (mixture of halite and sylvine), carnalite ($KMgCl_3 \cdot 6H_2O$), kainite ($KCl \cdot MgSO_4 \cdot 2{,}75H_2O$), langbeinite ($K_2Mg_2[SO_4]_3$). Moderately soluble – kieserite ($MgSO_4 \cdot H_2O$), polyhalite ($K_2Ca_2Mg[SO_4]_4$). At a temperature of 110°C and a pressure of 110 MPa, halite has conventional yield strength of 95-180 MPa, and for bischofite – 60 MPa. The stress limit of the transition from the elastic to the plastic state is 0.4-0.5 MN/m^2. At elevated temperatures from 20 to 100°C, the solubility of halite increases from 26.4 to 28.2%, and that of bischophytes – from 35.3 to 42.2% [4], [5].

The problem of flowability of chemogenic sediments is most noticeable in drilling and plugging wells in the Eastern part of the DDD in the Mashivsk, East-Poltavsk and Kobzivsk gas condensate fields JSC "Ukrgazvydobuvannia", as well as in the North-Western part of the DDD in the Yaroshivsk, Sofiivsk and Voloshkivsk deposits of PJSC "UKRNAFTA". The flow of salts is manifested in opening of salts of halite, sylvin, bischofite, sylvinite and carnalite. These mineral salts differ in the structure of the crystal lattice and the nature of the forces of interaction between the parts of the crystal [5].

One of the most promising is the large Kobzivsk gas condensate field [1] located in the Kharkiv region. An important feature of well construction at this deposit is the discovery of Lower Permian sediments in the interval 1950-3580 m, among which the most active influence on the technological process of well construction is exerted by chemogenic deposits of the Kramatorsk world, where potassium-magnesium salt rocks, as well as salt clays and clayey carbonates of the Slavic and Mykytivska world occur. However, the process of deep well construction is accompanied by a whole set of complications that can be partially avoided with sufficient geological information. For analysis in this paper are provided studies related to # A Kobzivska well.

In particular, during the construction of # A Kobzivska well, well logging (WL) of the well wall condition was conducted twice when drilling under the 194 mm diameter "tail" (Fig. 1). The WL data (Fig. 1) show the dynamics of changes in the size and shape of the cavern in the 2289-2305 m interval. Further (bottomhole 3593 m), this resulted in deformation of 193.7 mm of casing string (Fig. 2) at a depth of 2303 m and accidental drill pipe destruction.

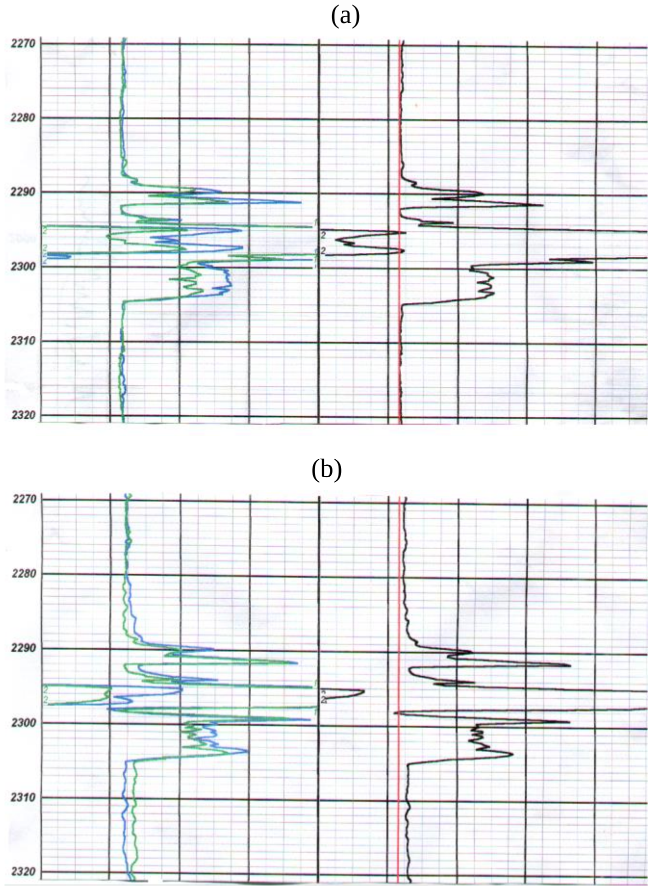

Figure 1. Results of WL (profilometry and cavernometry) in # A Kobzivska well: (a) as of 09.12 (bottomhole 2500 m); (b) as of 21.01 (bottomhole 3400 m)

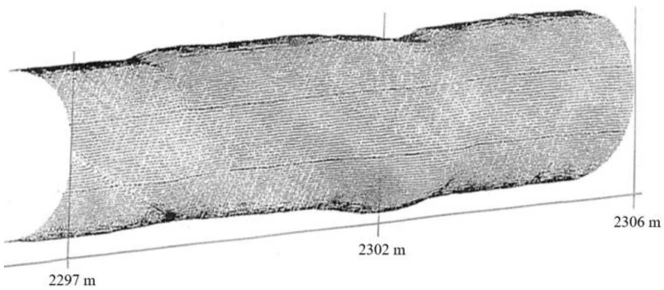

Figure 2. The nature of the deformation of the 194 mm diameter string in # A Kobzivska well in the 2297-2306 m interval according to the WL data

Typical complications during the well construction under the influence of unstable block of chemogenic sediments and time losses for their elimination are shown in Table 1. The time required to eliminate such complications can be from three days to three to five months, and sometimes lead to well losses.

Table 1. Typical complications during the construction of wells in hemogenic sediments of DDD

Well	Type of complication	Time spent on liquidation, hours	Notes
36 Yaroshivska	Casing deformation	3754	
27 Kobzivska	Casing deformation	411	Drill string fracture
69 Kobzivska	Casing Deformation	2329	
72 West-Sosnivska	Violation of the wellbore integrity	355	Drill string fracture
208 Yefremivska	Casing deformation	70.17	
517 West-Chrestyshenska	Violation of the wellbore integrity	595	
106 West-Starovirivska	Violation of the wellbore integrity	806	
40 Kopyly	Casing deformation	428.33	

The more detailed influence of unstable salt-bearing sediments prone to plastic deformation is considered on the example of # B well of the DDD field, where a 244.5 mm casing string was attached in the 0-4273 m interval. In the 2944-4273 m interval, casing pipes of strength group P-100 with a wall thickness of 13.84 mm were used to cover unstable chemogenic sediments prone to deformation processes.

On the first of June, drilling out the elements of the 244.5 mm casing string and its pressing were conducted. Drilling mud was replaced from mineralized (density 1.60 g/cm^3) to highly inhibited chlor-potassium (density 1.33 g/cm^3). Drilling of the 177.8 mm production string began. The dynamics of the rock mass influence on the well fastening system was rapid. Between the first and sixth of June, during round trip operations (various layouts – with 215.9 mm PDC bits and Ø 213 mm mandrels for resto-ring the patency in the casing), landings and tightening of the drill string in the range of 4-16 tons were obtained.

On the sixth of June, WL was conducted in the casing. According to the data of microprofilemetry in the intermediate string of 244.5 mm, its deformation was recorded, as a result of which the minimum diameter relative to the nominal one was reduced to 210 mm. The deformation of the string was recorded in the intervals 3520-3866 m, 3995-4040 m, 4090-4110 m, 4115-4125 m, 4150-4160 m, 4223-4228 m. As an example, the assessment of the string deformation in the interval of 3990-4030 m according to the data of pipe micro-profilometry is shown with a 24-lever MFC device and MTD magnetic pulse flaw detection, the results of which are shown in Figures 3-5.

As can be seen, according to the data of the multi-lever microprofilimeter (Figs. 3 and 4) in the conventional depth interval of 4009-4012 m, an S-shaped deformation of the intermediate string body is observed.

According to the electromagnetic defectoscopy data (Fig. 5), in the range of the given depths, there is a decrease in the string pipe wall metal thickness by at least 2 mm, which indicates deformation processes applied from the outside of the casing and the operation of bits, calibrators or mandrels, which resulted in the loss of string wall thickness. In addition, metal scratches and metal shavings were found on the bit and calibrator.

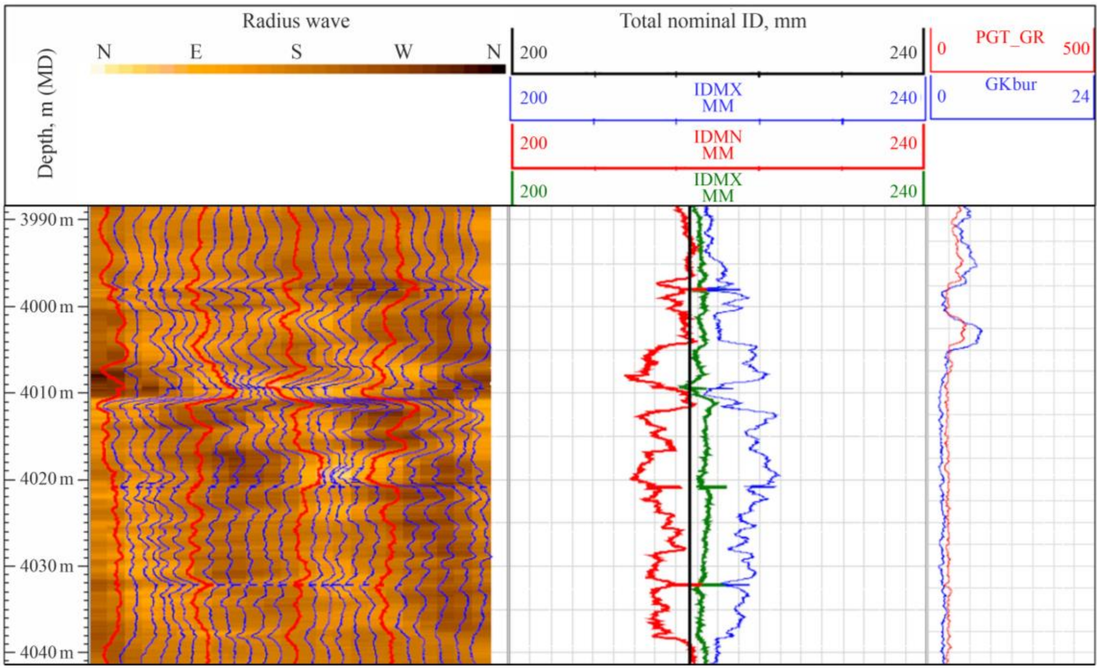

Figure 3. MFC study of the well in the sring deformation interval

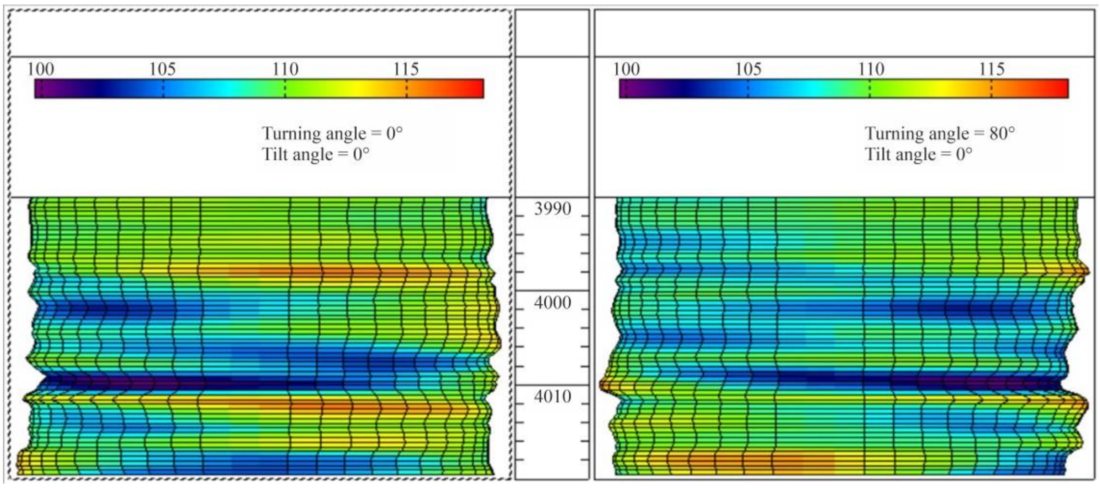

Figure 4. 3-D scan of the well survey in the deformation interval

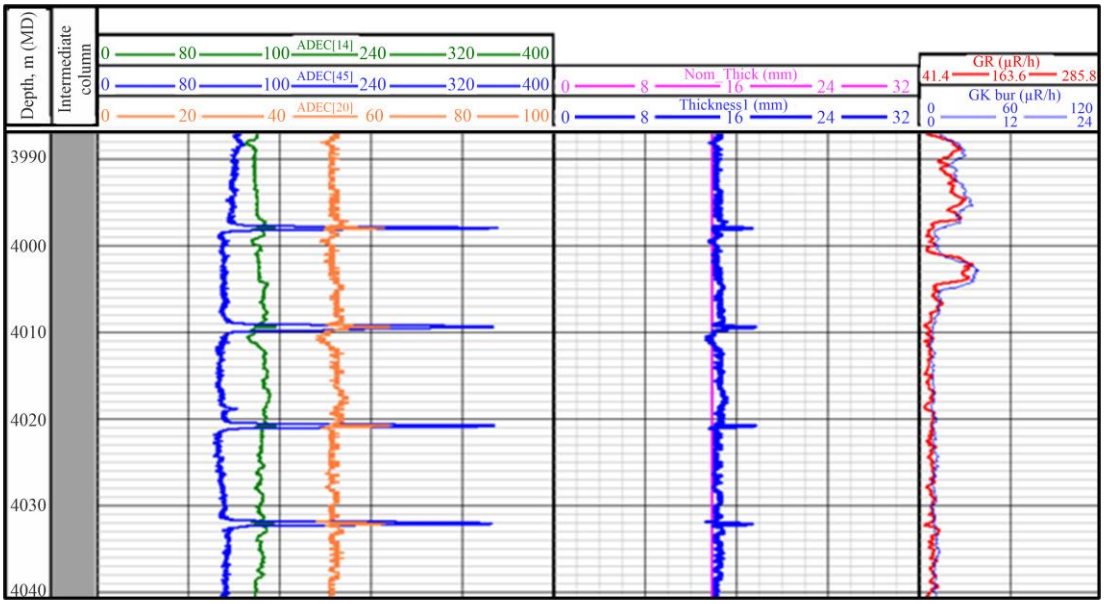

Figure 5. MTD of well research in the string deformation interval

Considering the above, changes in the geometry of the string and the presence of such (S-shaped) protrusions may further lead to a violation of the integrity and the appearance of mechanical damage to the intermediate string in the form of through cracks or rubbing of pipes, which may occur as a result of both the subsequent impact of rocks and due to carrying out technological operations in the wellbore. It should be noted that due to the complex dynamics of the drill string, dynamic loads are transferred to the fastening system. The rotational and reciprocating movement of the drill string and its oscillations lead to wear of the casing wall thickness, as a result of which its strength characteristics are significantly reduced [6]. Quite often, there are recorded cases of damage to the integrity and rubbing of the casing strings.

Therefore, despite the use of high-strength casing pipe 244.5×13.84 mm P-110 with an allowable external critical pressure of 54.7 MPa, it was damaged due to the impact of the rock mass on the fastening system in # B well of the DDD field. The main measures to prevent string violations under the influence of salt-saturated sediments is the need to use casing pipes of the higher strength group and use of special tamping cements in the interval of their location.

According to the Halliburton Company, 90% of all damage to the well fastening system is the result of poor casing cementing quality, which in turn leads to large financial and environmental losses.

The main task of well cementing is to ensure the tightness of the isolation screen and reliable demarcation of productive horizons, preventing uncontrolled migration of fluids [7].

The need to solve the problem of increasing the reliability of fastening casing strings remains relevant in connection with the growing volumes of drilling deep wells, the complication of mining-geological and technical-technological features of their construction and operation [8], as well as increasing requirements for the protection of the subsoil and the environment and the safety of people [9].

The quality of fastening the well and its durability is determined by the condition of the cement stone that forms the insulating screen. At the same time, the condition of the insulating screen determines the prerequisite for the reliability of demarcation of fluid-saturated horizons and protection of the casing string from the aggressive influence of fluids [10], [11], which will have a direct impact on further hydrocarbon production [12].

The composition of the backfill cement, the properties of the backfill solution and the conditions of structure formation will have a direct impact on the quality of the insulating screen [13]-[15]. An important factor for improving the quality of fastening is the preparation of the wellbore and the adhesion of the cement stone to the surrounding surfaces [16].

It was established that the casing pipe is subjected to significant compressive loads when the rock mass is shifted, as a result of which the loads are subjected to the critical value of the yield point, which causes the loss of stability of the casing pipe [17]. Studies have confirmed the uneven distribution of critical external loads on the casing due to the influence of the salt-bearing rock mass [18]. Quite often, the directed flow vector of individual salt-bearing sediments can cause destructive loads on the fastening system. In addition, the influence of chemogenic sediments is also reflected in the technological processes of mining, where it is also necessary to take into account the potential risks of exposure and implement effective methods to prevent them or minimize their destructive impact [19].

Important factors in the successful well construction are the correct design of its structure and the thorough criteria determined for their application during design and implementation [20]. Compliance and implementation of the established technological regulations for fastening wells is a prerequisite for further effective well operation [21].

A number of studies on the influence of loads on "casing pipe – cement stone – rock" fastenings have been carried out. The physical-mechanical properties of cement stone, the dependence and influence of the geometric dimensions of the stone and the pipe on the strength of such a fixture have been analyzed [22]-[24]. Other studies have confirmed that the presence of high-quality cement stone in the "casing pipe – cement stone – rock" system provides the possibility of strengthening the bearing capacity of fasteners by 20-28% compared to uncemented pipes [25].

Despite significant progress in the direction of securing wells in complicated mining and geological conditions, quite often there are cases of the loss of a well as a whole or the need to change its design. At the same time, there is a need to lower an additional string for fastening the deformed mass, which provokes a decrease in the diameter of the operational column and causes a significant deviation from the drilling project and worsens the operational characteristics of the well. Therefore, research on creation of methods and means providing reliable fastening of deep oil and gas wells in difficult mining-geological conditions is relevant.

2. Methods

The study of the peculiarities of well fastening in complex mining-geological conditions under the influence of chemogenic deposits and their fastening was carried out using modern methods of analytical analysis and experimental research with the approbation of mathematical modelling methods, devices and materials and research methods.

The properties of tamponage solution and cement stone were determined in accordance with DSTU B V.2.7-88-99 "Portland cements for tamponage. Technical conditions" valid in Ukraine and DSTU B V.2.7-86-99 "Tamponage cements". Test methods – thermobaric autoclaving conditions at temperature 75°C and pressure 30.0 MPa. The structure of cement stone was studied by electron microscopy, X-ray phase analysis, and mercury porometry.

The cement stone structure formation processes under thermobaric conditions were studied according to the API standard using an ultrasonic cement analyzer (UCA) from OFI Testing Equipment Inc. Company (# 120-50).

In accordance with modern world trends, composite cements are becoming more and more important, which initially harden more slowly, but later have increased durability, especially in corrosive-active environments [26]. According to the European standard (European Norm, EN), such materials must contain at least two types of mineral additives of different types of activity (hydraulic and pozzolanic action). Many studies have been conducted in the direction of using mineral additives to cement for various purposes, which confirm their effectiveness in using such materials [27]-[30].

Hardening of composite cement occurs as a result of hydration of the clinker component and reactions of the chemical interaction of hydrated neoplasms with active components. These processes are more complex compared to the hardening of traditional portland cements, since several components with different hydraulic activities are involved in the reactions. According to [31], during the formation of composite cement, the stone goes through several structural states in its development, and the hydration process can be conditionally divided into several periods, which are characterized by different kinetics and reflect the change in the properties of the formed cement stone. First of all, the formation of a coagulation structure in the system due to neoplasms at the initial stage of cement hydration is observed. Next, the destruction of the coagulation structure occurs as a result of intensive cement hydration, an increase in the volume of the hardening system, the number of hydrate neoplasms, and the formation of a transitional coagulation-crystallization structure. The third stage is characterized by an increase in the degree of completeness of structure formation, which is associated with the cement stone crystallization framework formation. Therefore, the hydration of composite cement can be considered as a set of processes that occur during the interaction of cement components with hydraulic and pozzolanic additives in the presence of water.

It is possible to control the processes of structure formation of composite systems by using modern materials of modifiers, in particular additives that accelerate crystallization (krents), the use of which is potentially able to ensure the controlled growth of strengthening crystals, providing a kind of synthesis of the stone during its hardening and creating the prerequisites for "self-healing" of the broken structure. At the same time in [32] it was shown that due to the controlled crystal growth, it is possible to obtain self-strengthening composites, where the role of matrix is performed by gel-like, sub-microcrystalline and isometric crystalline hydration products, and thread-like ($l / d > 100$) or needle-like crystals of neoplasms act as strengthening agents.

It is impossible to apply protective coating of cement shell in wells. Formation fluids under elevated thermobaric conditions are more aggressive than the natural environment at the surface, and the thin cement ring of the well is more vulnerable than elements of other hydraulic structures. Therefore, the only method of preventing corrosive destruction of tamponage stone is to replace traditional Portland cement with binders of a new generation, which include hydraulically active mineral additives with increased corrosion resistance.

These additives bind calcium hydroxide released during hydrolysis of cement minerals, reduce its balanced concentration, and thus prevent the formation of calcium hydrosulfoaluminate, which cause plugging stone destruction.

During their hydration, lower heat release is observed, which is especially important for the formation of insulating screens against chemogenic deposits.

The strengthening effect of the cement ring helps increase the resistance of the string attachment to external crushing pressure. The amount of crushing pressure in the "pipe – pipe" system mostly depends on the condition of the cement shell in the inter-pipe space. If the cement ring is not characterized by satisfactory properties, it is deformed due to the deformation of the outer pipe, the strengthening effect of the cement stone is disturbed, and the "pipe – pipe" system becomes unstable. In another case, if the cement stone has increased elastic-deformation properties, despite the significant deformation of the outer pipe, the "pipe – pipe" system is characterized by much greater stability. That is, if the cement stone has sufficient strength and increased elastic-deformation properties, then the inter-tube space remains unchanged, and the overall strength limit increases due to the strength of the cement shell. The next step, when the crumpling resistance value of the outer pipe is reached – the crumpling strength limit of the "pipe – pipe" system will depend on the residual strength of the outer pipe and the strength of the inner pipe. It is this mechanism that indicates damage to the integrity of the "intermediate – operational string" system.

3. Results and discussion

The problem of cement stone stability in various aggressive environments is important in the process of operation of engineering structures. One of the most aggressive is magnesium-sulfate corrosion, since in this case both cationic and anionic components of salts are subject to corrosion. Magnesium salt solutions are aggressive if they contain more than 500 mg/l of Mg^{2+} ions. During magnesium sulfate corrosion, $MgSO_4$ reacts not only with $Ca(OH)_2$, but also with hydroaluminates and calcium hydrosilicates. The reason for this is the very low solubility of $Mg(OH)_2$ and therefore a lower pH (10.5) than that of $Ca(OH)_2$. At this pH, hydroaluminates and hydrosilicates begin to decompose with the formation of $Ca(OH)_2$, which interacts with $MgSO_4$ to form $Mg(OH)_2$ and gypsum. An example of a cement stone sample based on PCT I-100 aged in a 5% $MgSO_4$ environment at the age of 10 years is shown in Figure 6. The visual dimensions of the sample deformed by corrosion processes are (mm): 22×23×57 (height × width × length). The sample is destroyed without effort in the hands. The basic dimensions, until the moment of storage in an aggressive environment, were 20×20.5×52.

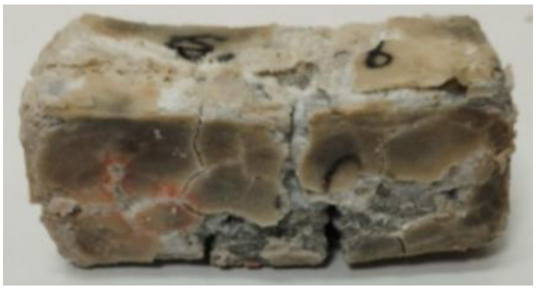

Figure 6. A sample of cement stone under the influence of sulfate-magnesium corrosion

At the same time, gypsum, interacting with calcium aluminates, ensures the formation of additional ettringite, during the crystallization of which the volume increases from 2.2 to 2.8 times, as a result of which the destruction of the stone is accelerated. In addition, the effect of magnesium sulfate corrosion causes the decomposition of calcium hydrosilicate. These corrosion processes are confirmed by X-ray fluorescence spectroscopy and X-ray structural analysis (Fig. 7).

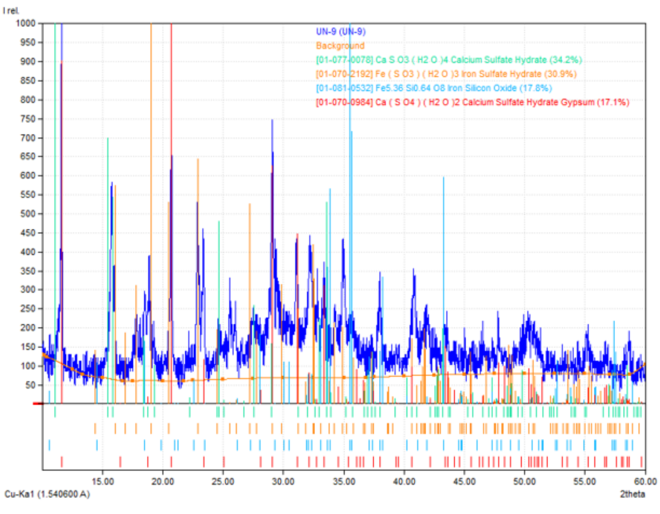

Figure 7. X-ray phase analysis of corroded cement stone

Based on the generalization of the X-ray fluorescence spectroscopy and X-ray structural analysis results, it has been found that for the studied sample of corroded cement stone based on PCT I-100, the sulfur content in terms of oxide is 9-11 wt. %. The sample is characterized by a complex phase composition with the presence of an amorphous component. The main phases are gypsum $CaSO_4(H_2O)_2$ at different degrees of dehydration (multiple phases), iron sulfate and its hydrated form, as well as calcium carbonate $CaCO_3$. The presence of dispersed quartz is highly probable. Magnesium in the composition of X-ray crystalline phases is not recorded, since it is not identified by X-ray fluorescence analysis. Quantitative Rietveld analysis of the phase composition of the samples is fundamentally impossible due to the presence of a significant content of X-ray amorphous phase. Estimated values of the X-ray amorphous phase content are at least 40-43 mol. %. The X-ray crystal phase of portlantite lacks $Ca(OH)_2$, the X-ray crystal phase of alite $SiCa_3O_5$ is not identified.

Today, several hundred different types of plugging material are known for the construction of wells with certain conditions. Usually, known binding materials, mineral or organic additives are included in their component composition, and special technological properties are ensured by the use of various modifiers.

Taking into account the peculiarities of the use of plugging material, such as great depths, complex spatial architecture of the wellbore, abnormal thermobaric conditions, the presence of chemogenic deposits and rocks prone to plastic deformation, the authors of the paper study the possibility of replacing traditional materials with plugging systems of a new generation on a composite basis.

The authors of this research have revealed that the addition of calcium sulfoferites to the basic composite cement as a krents improves the properties of cement stone (Table 2 and 3).

At the same time, low- and high-base calcium sulfoferite additives behave somewhat differently under the thermobaric conditions of the study. As can be seen, the fragility cement stone coefficient with the addition of 3% high-basic calcium sulfoferite after 1 and 7 days is lower by 6.9 and 28.1%, and with the addition of 3% low-basic calcium – by 1.0 and 23.5%, respectively, also it is lower for a stone made of CEM V cement. On the 7^{th} day, a significant increase in the fragility of additive-free tamponage stone is observed, which is explained by a strong slowdown in the growth of its strength during bending and preservation of the strength growth under compression. In the seven-day period of formation, there is also a decrease in total porosity with a more intense increase in the share of micro- and gel pores up to 94-97%.

Increasing the calcium sphalerite additive up to 5% results in deterioration of the cement stone pore structure, especially if the additive is high-basic calcium sphalerite. This is caused by excessive tension during the crystallization $C_3F \cdot 3CaSO_4 \cdot 31H_2O$. Strength gain kinetics of such samples coincides with their total porosity and the cement stone porometry results. Higher cement stone strength is observed for samples with 1 and 3% calcium sulphoferrite after 24 hours in comparison with control sample. At the same time, the addition of 5% high-basic calcium sulphoferrite results in a slight drop of strength, but no such process was observed when low-basic calcium sulphoferrite was added.

The character of formation of composite material crystallization structure modified by krents differs slightly from that of CEM V Portland cement and begins when the size of solid phase nuclei, arising at the coagulation stage of hardening, exceeds the critical one and depends directly on the chemical nature of the phases of the hardening system, the rate of supersaturation of solutions by hydration new formations and surface tension coefficient at the interphase boundary. Rate of crystallization structure formation is regulated by diffusion coefficient of colloidal particles from supersaturated solutions of hydration new formations to solid phase nuclei.

Table 2. Influence of high-basic calcium sphalerite $2CaO·Fe_2O_3·CaSO_4$ on the cement stone properties

Item	Binder composition, %							
	CEM V		CEM V + 1% $C_2F·CaSO_4$		CEM V + 3% $C_2F·CaSO_4$		CEM V + 5% $C_2F·CaSO_4$	
Formation time, days	1	7	1	7	1	7	1	7
Ultimate bending strength, MPa	7.5	7.8	8.2	8.8	8.7	9.2	7.7	7.4
Ultimate compressive strength, MPa	22.1	29.9	22.8	25.5	24.0	27.5	26.3	24.3
Fragility coefficient	2.94	3.83	2.78	2.89	2.75	2.99	3.41	3.28
Total porosity, %	27.73	26.52	28.13	23.78	28.42	24.72	30.30	29.80
Pore distribution by radius, %								
0.47-0.30 µm	–	–	1.05	–	2.81	–	8.26	5.35
0.29-0.15 µm	11.18	7.52	0.4	–	1.62	–	7.4	5.82
0.14-0.10 µm	1.27	1.46	0.5	–	0.19	1.19	9.4	6.32
0.10-0.074 µm	1.21	1.29	3.2	2.72	1.00	0.94	7.3	5.39
less 0.074 µm	86.34	89.73	94.85	97.28	94.38	94.92	67.65	81.98

Table 3. Influence of low-basic calcium sulphoferrite $2CaOFe_2O_3·CaSO_4$ on the cement stone properties

Item	Binder composition, %							
	CEM V		CEM V + 1% 3(CF)·$CaSO_4$		CEM V + 3% 3(CF)·$CaSO_4$		CEM V + 5% 3(CF)·$CaSO_4$	
Formation time, days	1	7	1	7	1	7	1	7
Ultimate bending strength, MPa	7.5	7.8	7.6	8.4	8.0	8.6	8.4	8.7
Ultimate compressive strength, MPa	22.1	29.9	22.7	25.8	23.3	26.7	24.9	27.3
Fragility coefficient	2.94	3.83	2.98	3.07	2.91	3.10	2.96	3.13
Total porosity, %	27.73	26.52	27.91	22.14	28.12	24.58	28.25	24.92
Pore distribution by radius, %								
0.47-0.30 µm	–	–	–	–	2.73	–	4.31	–
0.29-0.15 µm	11.18	7.52	2.36	–	2.58	–	5.32	2.85
0.14-0.10 µm	1.27	1.46	0.39	–	0.14	1.74	2.74	3.21
0.10-0.074 µm	1.21	1.29	0.71	2.81	0.36	1.91	1.45	2.48
less 0.074 µm	86.34	89.73	96.54	97.19	94.19	96.35	86.19	89.14

As the crystals of composite minerals differ in shapes and sizes of unit cells, then, during the period of their growth, linear defects of structure develop intensively, namely misfit dislocations and point defects-vacancies. The crystals are located perpendicularly to the matrix surface in the direction to the nearest hydrated particles of the binder and serve as centers of nucleation and crystallization on which further sedimentation of hydration products occurs (Fig. 8).

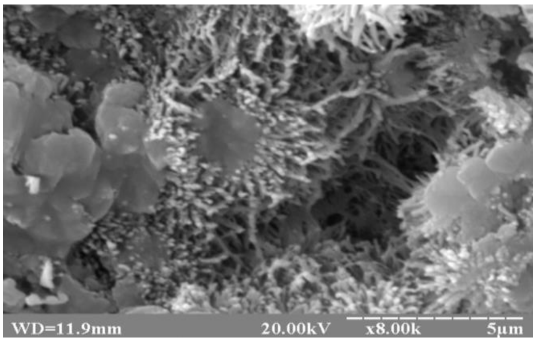

Figure 8. Cement stone structure modified by additives

The composite is characterized by a more even distribution of hydrates in the gel mass of hydrosilicates, a better orderliness of the contact growth zones and an increase in the number of fused fibers in the hydrosilicate blocks. Thus, the use of $C_2F·CaSO_4$ and 3(CF)·$CaSO_4$ as krents ensures the formation of a denser stone structure and the closure of a greater number of active hydrate surface centers during contact interactions compared to the control sample, which ensures the controlled cement stone structure formation (Fig. 9).

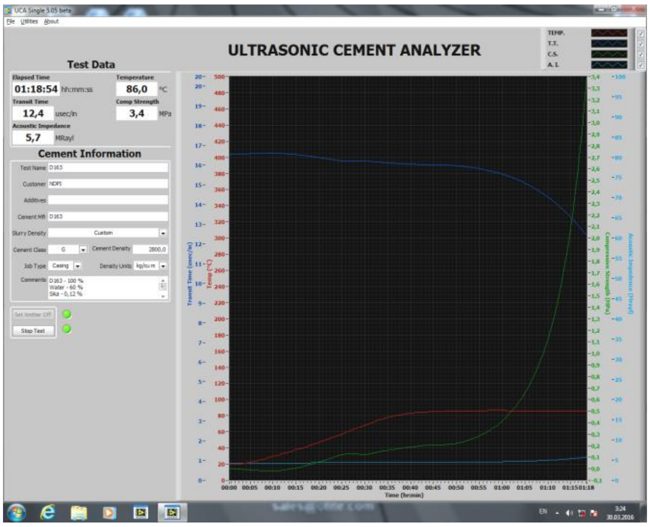

Figure 9. Course of the structure formation process of the modified composite under thermobaric conditions

In this case, the result of the system component interaction is the formation of the AF_t – phase of ettringite, the AF_m – phase of calcium monohydrosulfoaluminate (CMHSA), hydrogelenite. It is characteristic that calcium monohydrosulfoaluminate $3CaO·Al_2O_3·CaSO_4·12H_2O$ in this case is the main sulfoaluminate phase, which stably exists at a temperature of 75°C and provides the hardening system with constancy of properties without recrystallization and strength declines.

At the same time, the densely packed structure of the stone is ensured by the growth and stable existence of calcium hydrosilicates and hexagonal AF_m – phases and calcium hydroxide, which clog micropores.

Polyfunctional chemical additives (stabilizer, plasticizer, adhesive, microfiber) are used to ensure the controllability of the hydration and hardening processes of the polymineral composite. The hydration process peculiarities of the multi-component plugging system with the specified additives have been studied by means of differential thermal analysis. Figure 10 shows the derivative diagram of the studied composition hydration for 2 days.

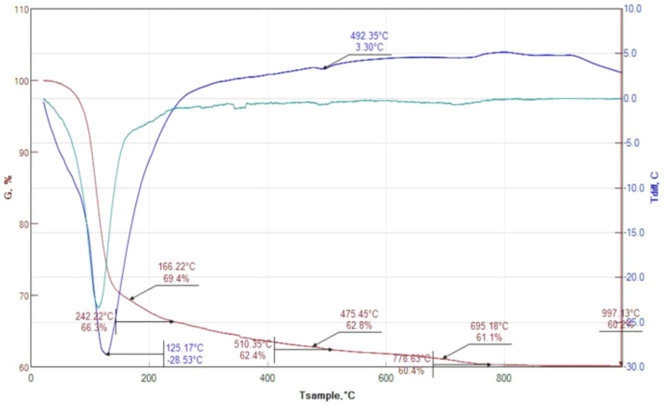

Figure 10. Derivatograms of the modified plugging composite, hydrated for 2 days at a temperature of +75°C

According to the data of thermal analysis (Fig. 10), intensive endo-effects were recorded in the region of 166 and 242°C, corresponding to the release of water from hydrosilicates and hydrosulfoaluminates of calcium. The displacement of endo-effects to a higher temperature region indicates a gradual dehydration of the CMHSA. The derivatogram also shows low-intensity endo-effects of $Ca(OH)_2$ at 492°C.

It should be noted that the introduction of polyfunctional additives into the cement composition, without changing the phase composition of hydration products, leads to a decrease in the degree of crystallization of the system.

The physico-chemical features of hydration of plugging composite with polyfunctional additives are determined by processes of competitive adsorption modification of primarily aluminum-containing hydrated phases and stabilization of structurally active ones. The kinetics of early structure formation of composite cements modified by krents is mainly determined by the peculiarities of the formation of AF_t and AF_m phases. At the same time, the kinetics of strength gain is due to hydration of the alite phase and reactions with the adhesive in the non-clinker part of the binder. The introduction of multifunctional additives ensures both the proper plasticity of the cement system and the better realization of the potential properties of the composite. Also, if necessary, plasticizer reagents can be introduced to optimize the structural and rheological characteristics of the tamponage suspension [33]-[35]. It should be noted that an important prerequisite for cementing of strings or liners in conditions of small annular gaps when drilling branch holes is the mandatory use of stabilized sedimentation-resistant dispersed-strengthened plugging systems [36].

It should be noted that fine-crystalline ettringite, which is formed during the hydration of modified composite cement, does not cause dangerous internal stresses, which in turn contributes to the formation of a higher-quality stone. A characteristic feature of the microstructure of the stone with polyfunctional additives is a significant increase in the metamix component, which confirms the effectiveness of the the binder system adsorption modification.

In this way, the optimal combination of polymineral components of different genesis provides controlled synthesis of cement stone with improved operational properties under elevated thermobaric conditions.

It is known that high-quality cementing of the well is impossible without ensuring the effective displacement and replacement of the drilling fluid in the annular space by tamponage. Because the mixing of technological fluids during cementing and the placement of this mix in the annular space makes it impossible to form a high-quality insulating screen and violates the reliability of the delimitation of productive horizons. Certain chemical reagents or materials of the drilling fluid or a certain percentage of it cause a negative impact, as does the backfill solution and cement stone based on it [37]. At the same time, the rheological properties of the tamping solution deteriorate, the time of thickening changes uncontrollably, the binder hydration kinetics is disturbed, and the dynamics of stone strength decrease.

The study of phase composition and structure of cement stone samples taken from # 55 Yaroshivska, # 52 Rosilnianska, # 122 Leliakivska, and # 4 Lysovytska wells unequivocally indicate the presence of introduced drilling fluid in the latter (Table 4).

Table 4. Comparative composition of materials

Well / type of sample	Material composition										
	CaO	BaO	SiO_2	SO_3	Fe_2O_3	Al_2O_3	MgO	TiO_2	K_2O	P_2O_5	Other
#55 Yaroshivska	30.05	30.70	14.95	15.40	3.04	3.35	0.43	0.19	0.21	0.18	1.50
#52 Rosilnianska	32.27	28.10	14.36	15.93	2.94	3.12	0.33	0.17	0.19	0.18	2.41
#122 Leliakivska	31.32	28.80	14.20	16.50	3.01	3.10	0.30	0.21	0.19	0.17	2.20
#4 Lysovytska	44.60	16.80	16.21	13.20	3.12	3.74	0.42	0.32	0.19	0.16	1.23
1-G	64.39	–	20.46	3.62	4.45	3.78	2.01	–	0.86	–	0.43
Barytic weighting agent	0.17	56.90	4.04	35.80	0.698	0.825	0.314	–	–	0.171	1.082

Compared to the control sample (1-G), cement stone from # 55 Yaroshivska and # 52 Rosilnianska wells contains a smaller amount of CaO (instead of 64.39%, only 30.05 and 32.27%, respectively), SiO_2 (instead of 20.46%, only 14.95 and 14.36%), and Al_2O_3 content is approximate. At the same time, additional BaO appeared in the stone (30.7 and 28.1%) and the SO_3 content increased from 3.62 to 15.4% and 15.93%, which indicates the presence of a significant amount of barite thickener. A similar trend was recorded for cement stone from wells # 4 Lysovytska and # 122 Lelyakivska. The increasing concentration of BaO (16.8 and 28.8%) and SO_3 (13.2 and 14.2%) indicates the presence of 40 to 60% drilling mud impurities in the rock samples. The content of the drilling mud admixture in the cement stone is also confirmed by the study of its microstructure, where the barite admixture was recorded in the cement stone (Fig. 11).

The result of testing the mixture containing 50% of plugging cement and 50% of drilling fluid in thermobaric conditions using the ultrasonic analyzer of the cement (UCA) confirmed the unsatisfactory quality of the structure formation (Fig. 12). The increase in strength begins four hours later, and the compressive strength (after 24 hours of waiting for the cement to harden) is only 5 MPa instead of 22 MPa. Such cement stone does not meet the modern requirements to plugging materials and does not ensure reliable fastening of the well as an engineering structure.

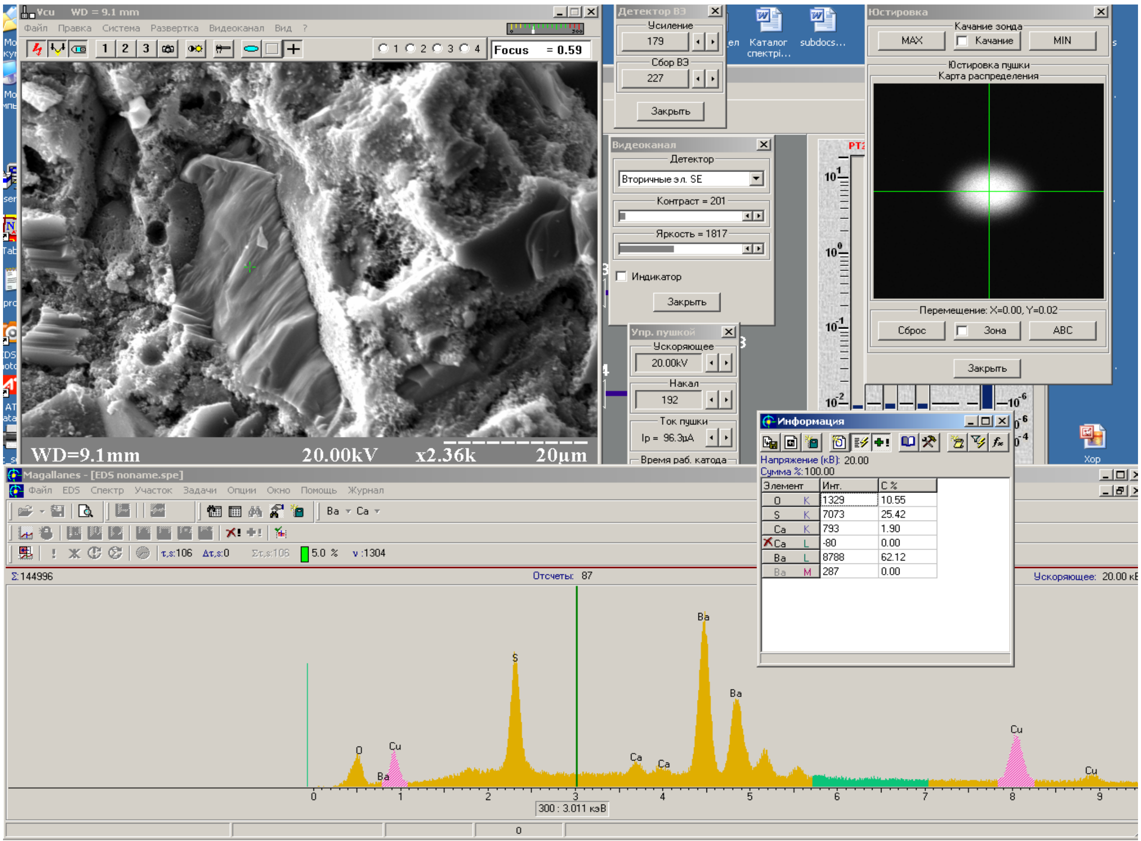

Figure 11. Microstructure of cement stone sampled from No.# 52 Rosilna well

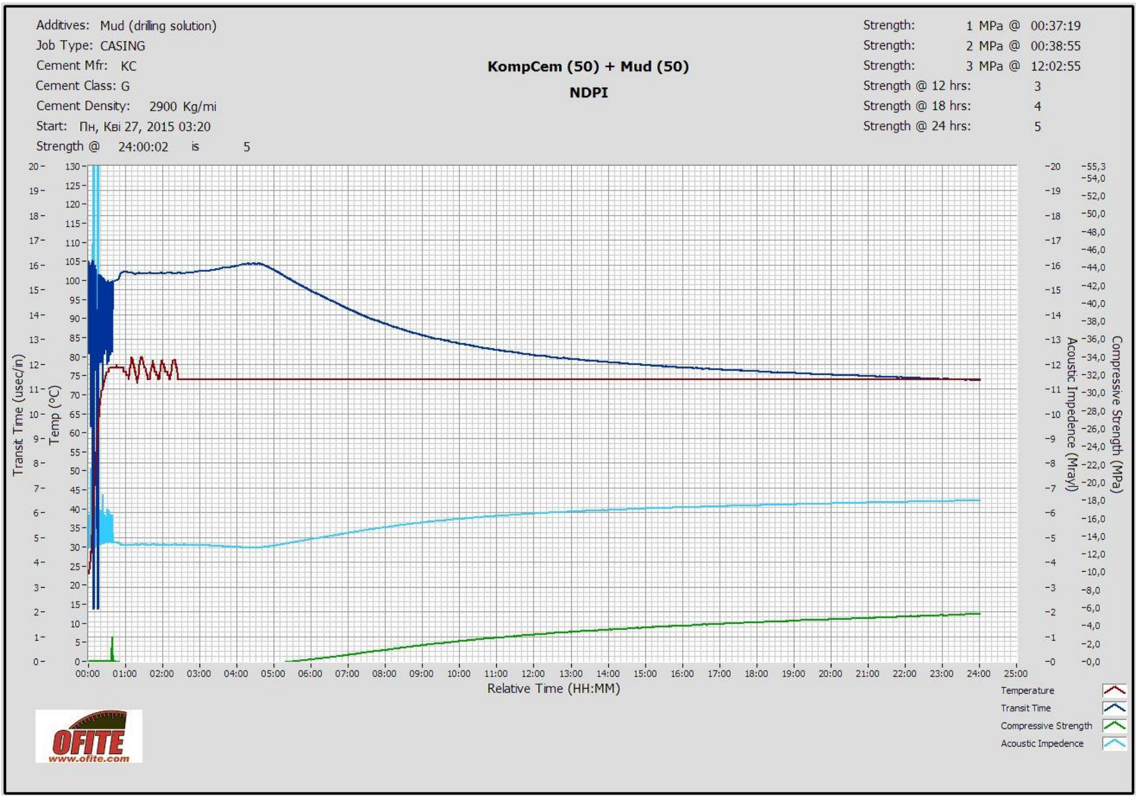

Figure 12. Dynamics of structure formation of the mixture that contain 50% of cement and 50% of drilling fluid

In order to improve the quality of well fastening, buffer systems are used in industrial practice, which are pumped into the well to separate the drilling and plugging solutions.

Given the low efficiency of known buffer fluids, a structured buffer system (SBS) has been developed, in accordance with modern world trends in well construction and compliance with "tandem technology" principle requirements (Table 5).

With a density from 1190 to 1790 kg/m³ (Table 6) SBS has zero water gain, low filtration properties, good pumpability (flowability is not less than 195 mm), necessary structural and rheological properties, and according to its consumer properties, it meets the requirements for ensuring reliable well casing.

Table 5. Main technological properties of SBS

Indexes	Type of buffer system			
	SBS ultra light	SBS half	SBS	SBS full
Density, kg/m^3	1190	1470	1640	1790
Flowability, mm	220	200	210	195
Water gain, ml	0.5	0	0	0
Filtration index, cm^3 in 30 min	12	8	8	9
Plastic viscosity, mPa·s	36	65	68	85
Dynamic shear stress, dPa	164	288	259.2	211.2
Detergent capacity (one cycle), %	48	49	55	43

Table 6. Results of testing the compatibility of SBS and typical plugging solutions

#	Cement slurry (composition, density)	The ratio of plugging solution to stabilized buffer mixture	Conditions of the experiment		Thickening time of the mixture (*Cement slurry + buffer liquid*), h-min
			Temperature, °C	Pressure, MPa	
1	CS – 100 LWG – 100% NTPA – 0.03% *W/C – 0.5 ρ = 1820 kg/m^3	–	75	45	2-55
		1:9	75	45	3-50
		1:1	75	45	3-20
		9:1	75	45	3-10
2	CS – 50 – 100% NTPA – 0.03% *W/C – 0.5 ρ = 1820 kg/m^3	–	50	30	4-00
		1:9	50	30	4-40
		1:1	50	30	4-20
		9:1	50	30	3-50
3	CRCS – LWG – 100% NTPA – 0.05% *W/C – 0.54 (density of mixing water 1.12 g/cm^3) ρ = 1800 kg/m^3	–	75	45	5-00
		1:9	75	45	5-40
		1:1	75	45	5-20
		9:1	75	45	5-15
4	ECS – 150 LWG – 100% plasticizer – 0.2%; NTPA – 0.08% *W/C – 0.48 ρ = 1810 kg/m^3	–	90	82	5-15
		1:9	90	82	6-15
		1:1	90	82	6-00
		9:1	90	82	5-40

*W/C – water-cement ratio; CS – cement slurry; LWG – lowered water gain; NTPA – nitrilotrimethylphosphonic acid; CRCS – corrosion-resistant cement slurry; ECS – expanding cementing slurry

Industrial production of modified composite plugging systems has been established by "Energo Kompozit" Ltd (Lviv). In total, since 2010, more than 20000 tons of dry plugging mixtures and 1000 tons of structured buffer systems have been produced for the needs of oil and gas companies of Ukraine. With their use, more than 200 oil and gas wells have been cemented and successfully put into operation.

4. Conclusions

Violation of the technological process of well fastening in conditions of salt-bearing sediments is a fairly common phenomenon, which primarily depends on the quality of well cementing.

Traditional plugging materials do not meet modern requirements for the quality of oil and gas well construction, protection of mineral resources and the environment in the fields of Ukraine. Cement stone formed under such conditions does not provide the necessary operational level of reliability of the well casing as an engineering structure.

The use of basic composite cement $C_2F \cdot CaSO_4$ and 3(CF) $CaSO_4$ as krents ensures the formation of a denser stone structure and the closure of a larger number of active hydrate surface centers during contact interactions compared to the control sample, which ensures controlled structuring of cement stone.

Modified multi-component plugging systems can be considered as a promising direction of increasing the reliability of fastening casing strings of oil and gas wells.

As a result of the synergistic effect of complex multifunctional additives, it is possible to control the modification of the plugging composite, achieving increased operational characteristics of the stone. In the composite cement stone modified by krents, stabilization and modification of AF_m phases and AF_t phases, which are structurally active components of cement stone, take place due to the establishment of the optimal ratio of active mineral and polyfunctional chemical additives. Therefore, destructive processes associated with the decomposition and recrystallization of hexagonal calcium hydroaluminates take place to a much lesser extent, and the stone based on the modified multicomponent composite is characterized by better operational characteristics.

The development and introduction of structured buffer mixtures during cementing allows for improved quality of fastening due to improved washing properties, satisfactory separating, retaining and carrying properties and sufficiently high identifiability to typical tamponage solutions and drilling flushing fluids.

Industrial tests and implementation have shown the effectiveness of using composite plugging systems during well cementing in oil and gas fields of Ukraine.

Author contributions

Conceptualization: OV, JZ; Data curation: OC, RM; Formal analysis: OC; Funding acquisition: OV; Investigation: OC, YS, JZ; Methodology: OC, YS; Project administration: OV, RM; Resources: RM; Supervision: OV; Validation: OV, JZ; Visualization: OC, YS; Writing – original draft: OC, YS, JZ; Writing – review & editing: OV, RM. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Підвищення надійності кріплення нафтогазових свердловин полікомпонентними тампонажними системами

О. Витязь, О. Чернова, Є. Ставичний, Р.Мартинюк, Я. Зяя

Мета. Розроблення ефективних композиційних тампонажних систем для надійного кріплення нафтогазових свердловин у складних гірничо-геологічних умовах родовищ України.

Методика. Пропонована робота побудована на основі аналітично-промислового дослідження проблематики споруджування та кріплення свердловин в умовах залягання хемогенних відкладів при застосуванні аналізу матеріалів геофізичних досліджень. Дослідження тампонажних розчинів і буферних рідин проведено із застосуванням стандартних приладів та методів, що відповідають встановленим вимогам до тестування цементів та технологічних систем для спорудження свердловин. Обробку результатів досліджень проведено у середовищі MATHCAD та EXCEL. Для досліджень використано композиційний цемент CEM V за європейським стандартом EN 197-1, тампонажний цемент 1-G, кренти – високоосновний C_2F $CaSO_4$ та низькоосновний 3(CF) $CaSO_4$ сульфоферит кальцію.

Результати. Встановлено, що базові тампонажні матеріали, а також технологічні рішення для кріплення свердловин в складних гірничо-геологічних умовах, не забезпечують відповідність свердловини як інженерної споруди експлуатаційним показникам надійності. Як наслідок, доволі часто фіксують порушення системи кріплення, що потребують значних часових та фінансових затрат на їх усунення, а інколи призводять до ліквідації свердловини. Для підвищення надійності кріплення свердловин необхідно застосовувати полікомпонентні тампонажні системи модифіковані крентами. Доведено, що домішки сульфоферитів кальцію прискорюють кінетику ранньої міцності та сприяють формуванню цементного каменю з покращеними характеристиками. Обґрунтовано необхідність застосування ефективних буферних систем для підвищення якості кріплення.

Наукова новизна. На основі оцінки, систематизації та детального вивчення геофізичного матеріалу й особливостей кріплення свердловин в умовах впливу хемогенних відкладів встановлено необхідність застосування композиційних тампонажних матеріалів. Проведеними дослідженнями доведено, що для забезпечення надійного кріплення свердловин в складних гірничо-геологічних умовах необхідно використовувати полікомпонентні композиційні тампонажні матеріали, модифіковані сульфоферитами кальцію, з прискореною кінетикою ранньої міцності, що формують цементний камінь з щільно-упакованою структурою.

Практична значимість. Проведеною оцінкою промислового матеріалу та детальними лабораторними дослідженнями розроблено технологічні рішення для підвищення надійності кріплення свердловин за рахунок впровадження полікомпонентних композиційних тампонажних матеріалів, модифікованих крентами, та буферних рідин.

Ключові слова: *свердловина, тампонажні системи, мінеральні солі, гірська порода, текучість*

Publisher's note