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REGULARITIES OF THE PROCESS OF CRACK FORMATION IN CLAY FILTER CAKE DURING WELL CEMENTING

The object of this research is the process of crack formation in the clay filter cake upon its contact with hardening cement slurry/stone.

During well cementing, it is impossible to completely remove the clay filter cake formed on the borehole walls. This creates prerequisites for poor wellbore sealing due to the formation of channels for fluid migration at the contact boundary and directly within the clay filter cake. Studying the processes that occur during cementing makes it possible to better understand their nature and to propose technological measures to ensure the tightness of the wellbore seal.

It has been established that the process of crack formation is characterized by three periods: induction, cracking, and stabilization. The duration of each period is determined by the state of the "clay filter cake – hardening cement slurry/stone" system. The process proceeds most intensively under conditions corresponding to the near-surface (wellhead) part of the well. This is explained by the dehydration of the cement slurry during its pumping in the annular space and the loose structure of the clay filter cake. In this case, the area of the clay filter cake affected by cracks exceeds 80%, while in conditions of the bottom hole part of the borehole, it does not exceed 30%.

The effect of aqueous electrolyte solutions on the crack resistance of the clay filter cake has been investigated. It was found that with a decrease in the concentration of $CaCl_2$ and an increase in the concentration of NaCl, the area of the clay filter cake affected by cracks decreases. No crack formation was observed in the clay filter cake after its treatment with 2% and 5% solutions of Na_2CO_3.

It was established that with a decrease in the thickness of the cement sheath, the induction and cracking periods increase, while the overall area of the clay filter cake affected by cracks decreases.

The obtained results will serve as a basis for developing a comprehensive approach to ensuring high-quality wellbore sealing. This may include optimizing well design and improving the formulation of drilling fluids for specific geological and technical conditions.

Keywords: *wellbore seal tightness, cement slurry/stone, clay filter cake cracking process.*

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1. Introduction

Cementing is an important stage in well construction, and its quality affects the further operation of the wells. In the case of poor-quality cementing, wellbore sealing of the annular space is not ensured, which leads to various complications and accidents. One of these is the migration of formation fluids and drilling fluids into the inter-casing annulus. This phenomenon can occur at different stages of well drilling, as well as after its completion [1–3]. The problem of ensuring the tightness of the wellbore structure and preventing inter-casing flows has been known for many years. Despite significant attention from both researchers and field specialists, this issue has not yet been fully resolved. This is evidenced by the considerable number of published studies. Primarily, this is due to the inability to establish a single root cause of loss of tightness, although groups of factors that influence it can be identified [4, 5]. These include geological, technical-technological, mechanical, and organizational factors. To address this problem, it is necessary to constantly improve well preparation for cementing and to use advanced sealing compositions [6]. Overall, measures to ensure wellbore sealing include the analysis of issues related to:

– preparation of the wellbore for cementing;
– control of cement slurry density;
– selection of the rheological properties of drilling fluids;
– formation of bonds at the contact interface of cement slurry/stone with the formation and casing [7–11].

An important factor affecting the strength of the bond between the formation and the cement stone, as well as between the cement stone and the casing, is the presence of a filter cake and residues of drilling fluid. For the formation of a tight contact between the cement stone and the formation, the removal of the filter cake is necessary. However, its absence facilitates the saturation of the cement slurry with formation fluids. In the intervals of permeable formations cleaned of the filter cake, increased water loss occurs. This can cause dehydration of a portion of the cement slurry and its excessive thickening during pumping and displacement in the annular space. In addition to increased filtration, there is a greater possibility of contamination of the collector's channels with cement particles, and the process of initiating flow during well completion becomes more complicated [12, 13].

The filter cake consists of fine-dispersed particles, aggregates, and a dispersion medium that form its structure. The fine-dispersed particles are the primary structural elements. All structural elements that make up the filter cake are bound to each other by structural bonds. These bonds are formed as a result of complex physicochemical processes both within the cake itself and at its interface with the external environment.

Their formation occurs under the influence of crystallization, aging, condensation of compounds contained in the cake, as well as due to adsorption or crystallization of cementing substances from the surrounding medium. An example of such adsorption is the formation of calcium hydrocrystals during filtration of the dispersion medium of the cement slurry through the clay cake. Since the period of formation of structural bonds before the beginning of the study is insignificant, they can be considered primary [14].

Primary bonds formed at the moment of cake formation can be transformed (strengthened or weakened) through the use of chemical reagents or by changing external conditions of compaction or infiltration of solutions. At the same time, new secondary structural bonds may also form. In fine-grained, unconsolidated rocks, the bond between individual particles is carried out by molecular and ion-electron interactions, which are called water-colloid bonds.

The chemical type of structural bond is close in nature to intracrystalline bonds of minerals. It can arise through direct contact of mineral grains with each other or by filling the space between grains with another cementing substance. Chemical bonding is the strongest type of structural bond. In the clay filter cake, such a bond may develop as a result of the infiltration of solutions and the precipitation of salts from them. Molecular bonds always exist and are manifested not only between charged ions but also between neutral atoms, molecules, and solids. For the latter, the magnitude of molecular interaction increases with an increase in the specific surface area of the system. A characteristic feature is that these forces manifest themselves over relatively long distances, reaching several thousand angstroms.

Structural bonds in moist dispersed clay filter cakes have a much more complex character. Along with molecular attraction forces, wedge-like forces of hydration shells arise, directed oppositely to the molecular forces. Also, ion-electrostatic interaction forces appear, associated with the occurrence of an electrostatic charge on the particles and the formation of a diffuse ion layer around them. Therefore, it can be considered that moist fine-grained clay cakes possess molecular-ion-electrostatic bonds.

It has been proven that the clay filter cake formed on permeable formations is heterogeneous in its composition. In particular, regardless of the conditions of its formation, larger particles of the dispersed phase are deposited on the formation side, with decreasing particle size towards the borehole axis [15]. The upper layer consists of a loose mass with relatively weak particle cohesion and a high content of the dispersion medium. The layers directly adjacent to the formation have a denser structure and possess greater strength and low permeability. Thus, the clay filter cake is a colloid-dispersed body consisting of structural elements of various orders. These elements have different types of structural bonds with different amounts of immobilized water throughout the thickness. In practice, a "clean contact" between the cement stone and the formation is impossible. There is always a layer of clay filter cake between them, resulting from the physical contact between the drilling fluid and the borehole walls [12–15].

The authors of [16] evaluated the effect of the clay cake formed by different types of drilling fluids on the shear bond strength between the formation, cement stone, and casing. A negative effect of the presence of the filter cake on the bond strength was established. The results of studies of the effect of drilling fluid contamination on the cement stone formed opposite different types of rocks, as reported in [17], indicate their varied interactions with cement slurry/stone. Overall, the results obtained in [16, 17] confirm the negative impact of drilling fluid contamination on shear bond strength.

Laboratory experiments to identify the effect of the curvature of the interface surface on the character of crack propagation in the cement stone were carried out by the authors of [18]. It was found that samples with a convex interface contained radially oriented fractures perpendicular to it. Samples with a concave interface were characterized by ruptures (cracks) along the surface. The rupture along the concave interface between the formation and cement stone was more irregular than along the concave interface between the cement stone and casing.

Experimental studies on the degree and nature of contamination of rock specimens with drilling fluid and their effect on bond strength were carried out by the authors of [19, 20]. For quantitative assessment of the contamination effect, shear bond strength tests and material characterization methods were used. It was noted that physical contamination (the presence of a filter cake) is more detrimental than chemical contamination resulting from the interaction of drilling fluid with the cement slurry.

Studies aimed at ensuring high-quality cementing through chemical treatment of the clay filter cake have also been conducted. In particular, a two-component reagent based on a diluted silicate latex solution and a mixed alkaline solution was developed. These reagents were applied in sequence just before the interaction of the clay filter cake with the cement slurry [21]. In [22, 23], treatment of the filter cake was carried out using a solution based on alkyl polyglucoside and $CaCl_2$. An increase in the cohesive strength of the modified clay filter cake compared to the untreated one was established.

Summarizing the results of the conducted analysis, it should be noted that previous studies did not pay sufficient attention to assessing the crack resistance of the clay filter cake.

The aim of this research is to identify the mechanism of crack formation in the clay filter cake that contacts hardening cement slurry/stone. Understanding the regularities of the process will make it possible to improve the quality of wellbore sealing.

2. Materials and Methods

The object of this research is the process of crack formation in the clay filter cake upon its contact with hardening cement slurry/stone. The cement slurry pumped into the annular space comes into direct contact with the clay filter cake. During the hardening of the cement slurry/stone, contraction processes at its contact surface with the clay filter cake create a vacuum, which promotes the suction of water from the clay filter cake. Under the influence of this vacuum, the clay filter cake becomes dehydrated, resulting in the formation of cracks and channels capable of conducting fluids. Cracks may also form due to the physicochemical action of the cement slurry filtrate on the clay filter cake as a result of ion exchange and changes in bond strength. At the contact between the clay filter cake and the cement stone, ion exchange occurs with the formation of calcium hydroxides. Over time, the content of silicon oxide in the clay filter cake decreases, while the content of calcium oxide increases, whereas in the cement stone, the opposite is observed.

The "clay filter cake – cement slurry/stone" system in the wellbore is in various physicochemical states. The clay filter cake located in the lower part of the wellbore (at the shoe of the casing string) is exposed to the cement slurry for the longest time during its movement in the annular space. As a result, it becomes denser and thinner due to the partial erosional action of the cement slurry. The erosional and compacting effects of the cement slurry decrease along its flow path, and near the wellhead, the clay filter cake practically retains its initial thickness. In the lower part of the wellbore, the clay filter cake becomes enriched with polyvalent ions throughout its thickness due to filtration of the dispersion medium of the cement slurry through it. The clay filter cake located in the upper part of the wellbore becomes saturated with calcium ions only in the contact zone with the cement slurry/stone. In the middle part of the wellbore (between the bottom and the wellhead), the cement slurry is characterized by intermediate values in terms of the amount of filtered water, flow path, and contact time with the clay filter cake. Therefore, to study the process of crack formation in the clay filter cake in contact with hardening cement slurry/stone, these three characteristic states of the "clay filter cake – cement slurry/stone" system were modeled.

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The clay filter cake was obtained by filtering a clay slurry on a full-scale Ofite #140-00 filter press under a pressure differential of 100 psi (689.5 kPa) and a filtration area of 7.1 ± 0.1 in^2 (45.8 ± 0.6 cm^2). According to API-13B recommendations, Whatman No. 50 filter paper with a diameter of 3.5 inches (90 mm) was used as the filter medium. The thickness of the filter cake was measured with a depth gauge caliper to an accuracy of 0.1 mm.

To evaluate the cracking of the clay filter cake in the upper part of the annular space (near the wellhead), after filtration, it was placed in a glass beaker. Cement slurry, pre-filtered through paper to achieve minimal water content, was poured on top of the clay filter cake. To investigate the cracking under conditions corresponding to the middle part of the wellbore, additional cement slurry with a reduced water-cement ratio was filtered through the formed clay filter cake. The resulting clay filter cake was placed in a glass beaker and covered with cement slurry of reduced water-cement ratio. To study the crack formation in the clay filter cake under conditions corresponding to the lower part of the wellbore, cement slurry with a water-cement ratio of 0.5 was additionally filtered through it.

At the next stage of research, the glass beaker with the clay filter cake and cement slurry was sealed and placed in a glass desiccator with a diameter of 210 mm. Observations of the clay filter cake and control weighing of the entire system were carried out daily to prevent changes in moisture due to leakage. During the setting and hardening of the cement slurry/stone in contact with the clay filter cake, a qualitative (presence or absence) and quantitative assessment of crack formation was performed. This made it possible to observe the kinetics of the process. For quantitative assessment, a 5 mm thick organic glass disk divided into 12 equal-area sectors, with a diameter equal to that of the filter, was used. These sectors were further subdivided by concentric circles into 9 segments. When the disk was placed on the clay filter cake, the area affected by cracks was determined. It was considered that if there was at least one crack in an element of the clay filter cake, it could serve as a fluid-conducting medium. By summing the elementary areas affected by cracks $\left(\sum_{i=1}^{n} f_i\right)$ and dividing them by the total area of the clay filter cake (F), the crack formation coefficient was determined K_{cf})

$$K_{cf} = \frac{\sum_{i=1}^{n} f_i}{F}, \quad (1)$$

or the relative area of the clay filter cake affected by cracks in (%)

$$K_{cf} = \frac{\sum_{i=1}^{n} f_i}{F} \cdot 100. \quad (2)$$

One of the ways to reduce the influence of ion exchange on the crack resistance of the clay filter cake is through the targeted physicochemical action of buffer fluids on the clay filter cake. Therefore, this study investigated their impact on the crack formation process. Aqueous solutions of sodium chloride, calcium chloride, and sodium carbonate with concentrations up to 20% were used as buffer fluids. The quantitative assessment of the crack formation process in the clay filter cake was carried out according to the methodology described above.

It should also be noted that with eccentric positioning of the casing string, the thickness of the cement sheath in contact with the wellbore wall is variable [24, 25]. Taking this into account, a study was conducted on the effect of eccentric casing positioning in the wellbore on the intensity of crack formation in the clay filter cake. The clay filter cake was placed in a glass beaker and covered with normal cement slurry. To simulate different thicknesses of the cement sheath, the cement slurry was poured to heights ranging from 10 mm to 80 mm. The quantitative assessment of crack formation in the clay filter cake was carried out using the methodology described above.

3. Results and Discussion

The clay filter cake can be considered a three-phase system consisting of clay particles, water, and air (gas), with coagulation-type bonds. Under loads exceeding its shape-forming stresses, the clay filter cake undergoes compression. The compaction of the clay filter cake occurs through the reduction of pore space and the compression of air/gas. As a result, its moisture content and porosity decrease. The relative deformation $\Delta h/h$ of the clay filter cake under pressure P is equal to the relative reduction of its volume

$$\frac{\Delta h}{h} = \frac{\Delta V}{V}, \quad (3)$$

where Δh – reduction in clay filter cake thickness; h – thickness of the clay filter cake after filtration of the clay slurry; ΔV – change in clay filter cake volume under pressure; V – volume of the clay filter cake after filtration of the clay slurry

$$V = V_t + V_p, \quad (4)$$

where V_t – volume of the solid phase; V_p – pore volume

$$V_p = \varepsilon_0 \cdot V = V_w + V_g, \quad (5)$$

where e_0 – initial (before compaction) porosity coefficient of the clay filter cake; V_w – volume of water; V_g – volume of gas (air).

At the same time, the clay particles move closer together, increasing the contact area and the attractive forces. All this increases the strength of the clay filter cake and its resistance to cracking during contact with the hardening cement slurry/stone.

To assess the influence of the degree of clay filter cake compaction and the water content in the cement slurry on the crack formation process in the clay filter cake, a series of experimental studies was carried out. In doing so, conditions typical for different cross-sections of the wellbore were simulated to a certain approximation (Table 1).

Table 1

Characteristics of the clay filter cake – cement slurry system

Cross-section	Average clay filter cake thickness, mm	Water-cement ratio of cement slurry	Cement slurry weight, g
Wellhead	4.5	0.265	108.6
Middle part of the borehole	3.5	0.32	108.6
Lower part of the borehole	3.0	0.5	108.6

During the course of the study, observations were made of the condition of the clay filter cake during the setting of the cement slurry and the formation of cement stone. In this way, the areas of the clay filter cake affected by cracks during contact with the hardening cement slurry/stone were determined at different stages of the process (Fig. 1).

As can be seen in Fig. 1, overall, the crack formation process is characterized by three periods: induction, cracking, and stabilization. The duration of each period is determined by the state of the "clay filter cake – hardening cement slurry/stone" system. If the cement slurry is maximally dehydrated, the induction period is the shortest and amounts to 25–30 hours (Fig. 1, curve 1). Crack formation is the most intensive and stabilizes after 180–200 hours. The total area of the clay filter cake affected by cracks exceeds 80%.

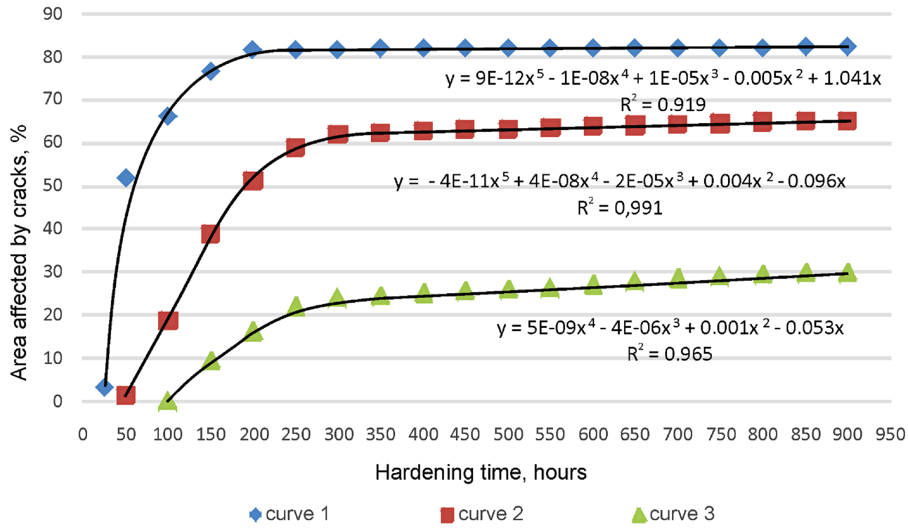

Fig. 1. Influence of formation conditions on crack development in the clay filter cake: curve 1 – clay filter cake thickness 4.5 mm, water-cement ratio 0.265; curve 2 – clay filter cake thickness 3.5 mm, water-cement ratio 0.32; curve 3 – clay filter cake thickness 3.0 mm, water-cement ratio 0.5

For the conditions corresponding to the middle and lower parts of the borehole, the crack formation process differs both in character and absolute values. For the middle part, the induction period increases to 45–50 hours (Fig. 1, curve 2), and the total affected area at the final stage does not exceed 60–65%. The induction period for conditions in the lower part of the borehole is 100–120 hours (Fig. 1, curve 3), with the total area of the clay filter cake affected by cracks amounting to 25–30%.

Thus, the degree of cracking of the clay filter cake for an isolated system depends on the condition of the clay filter cake and the cement slurry. If the cement slurry is maximally dehydrated, the crack formation process accelerates and reaches its maximum value upon contact with a normal clay filter cake. Extrapolating these results to wellbore conditions suggests that the probability of crack formation near the wellhead is significantly higher than in the lower sections.

To study the effect of buffer fluids on the crack resistance of the clay filter cake in contact with the hardening cement slurry/stone, the buffer fluid was additionally filtered through it. This caused compaction of the clay filter cake and, accordingly, a reduction in its thickness due to the removal of pore water. As a result, its moisture content and porosity decreased, and the particles moved closer together, which increased the number and area of contact points. The filtration duration corresponded to the contact time of the buffer fluid with the wellbore walls during cementing. The clay filter cake treated with the buffer fluid was placed in a glass beaker and poured over with a cement slurry containing 5% bentonite and 2.5% sodium chloride (by cement mass) with a water-cement ratio of 0.6.

At the first stage, a study was conducted on the crack resistance during the contact of untreated clay filter cake (without buffer fluid) with the hardening cement slurry/stone (Fig. 2). It was found that the induction period under these conditions is about three days (70 hours). The period of intensive cracking, during which almost 80% of the clay filter cake area is affected by cracks, lasts from 70 to 400 hours. The third period (from 400 to 1200 hours) is characterized by a monotonic increase up to 95% of the affected area.

When filtering 2%, 5%, 10%, and 20% calcium chloride solutions through the clay filter cake, cracks formed in the clay filter cake even before contact with the cement slurry. This is caused by ion exchange resulting from the replacement of sodium cations in the clay filter cake structure with calcium (Fig. 3). Increasing the concentration of calcium chloride led to an increase in the area of the clay filter cake affected by cracks. When the clay filter cake treated with calcium chloride came into contact with the cement slurry, the curve describing the crack formation process (Fig. 3) had a shape similar to that in Fig. 2. However, its intensity decreased as the calcium chloride concentration in the buffer fluid was reduced.

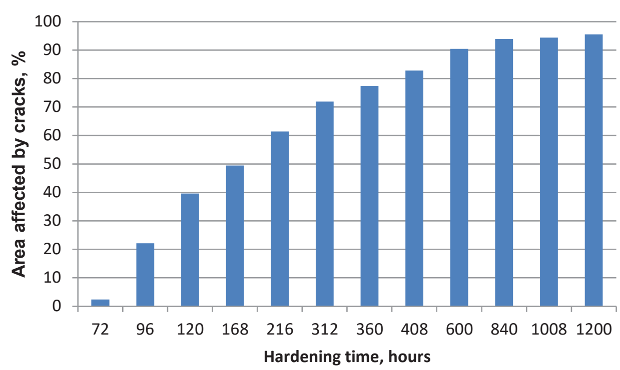

Fig. 2. Crack formation behavior in the untreated clay filter cake

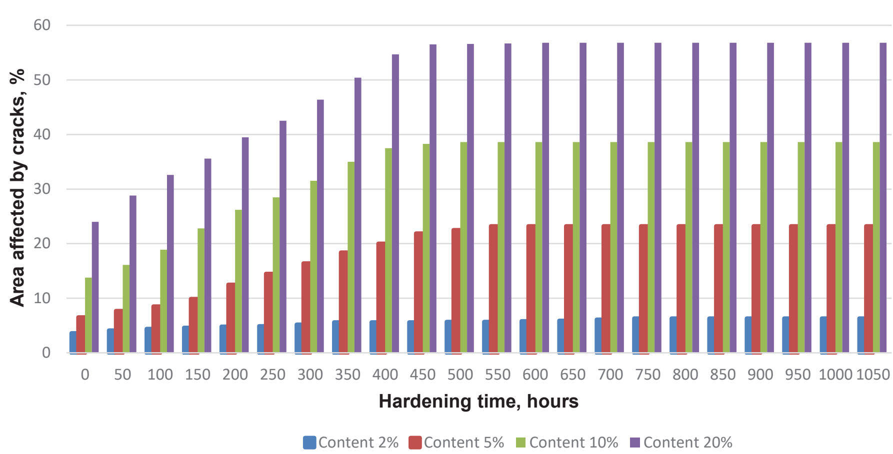

Fig. 3. Effect of aqueous calcium chloride solutions on crack formation in the clay filter cake

Crack formation almost completely stopped after 400–500 hours of contact with the cement slurry/stone, depending on the $CaCl_2$ concentration. When filtering an aqueous solution with a $CaCl_2$ concentration of 20%, the maximum affected area reached 56%. The mechanism of this phenomenon can be explained by the presence of 14.2 mmol/L of calcium ions in the cement slurry filtrate, which corresponds to 0.56 g/L. Converted to $CaCl_2$, this is equivalent to a 0.15% solution. Therefore, with a calcium chloride buffer fluid concentration of 2%, the clay filter cake becomes saturated with Ca^{2+} ions, and upon further contact with the cement slurry filtrate, the total area of the clay filter cake affected by cracks increases only slightly. When using a buffer fluid with a higher concentration of calcium chloride (5%, 10%, and 20%), the cracking of the clay filter cake increases.

The obtained results indicate a positive effect of treating the clay filter cake with a buffer fluid containing 2% calcium chloride, which is consistent with the findings reported in [22, 23]. This confirms the possibility of achieving not only a strong but also a tight contact between the cement stone and the formation. At the same time, the cost of treatment with the proposed buffer fluid is significantly lower than when using the solutions proposed by the authors of [22, 23].

Fig. 4, 5 shows the results of studies on the effect of aqueous sodium chloride (NaCl) and sodium carbonate (Na_2CO_3) solutions on the crack formation process in the clay filter cake during contact with the hardening cement slurry/stone.

As seen in Fig. 4, with an increase in the sodium chloride content, the crack resistance increases. This is due to an increase in sodium ions in the adsorption and diffuse layers of the clay micelles, as well as in the intermicellar liquid. As a result, the influence of calcium ions from the cement slurry is screened, maintaining the clay filter cake in a plastic state.

The effect of treating the clay filter cake with an aqueous sodium carbonate solution (Fig. 5) on crack resistance is somewhat different. When treated with 2% and 5% sodium carbonate solutions, no cracks were observed in the clay filter cake for 1400 hours. Sodium carbonate converts potassium bentonites to sodium bentonites more readily than other reagents. The replacement of calcium ions with sodium ions improves the quality of the solution. Soda ash enhances stability by binding calcium ions into calcium carbonate. Another positive property of soda ash is converting polyvalent metal cations into an inactive form. Therefore, soda ash neutralizes the influence of calcium ions. At concentrations of 10% and 15%, the crack formation period begins 650–700 hours after the start of contact with the cement slurry/stone (Fig. 5). The period of intensive cracking lasts 400–500 hours, after which the process stabilizes.

The summarized results of the studies described above are presented in Table 2.

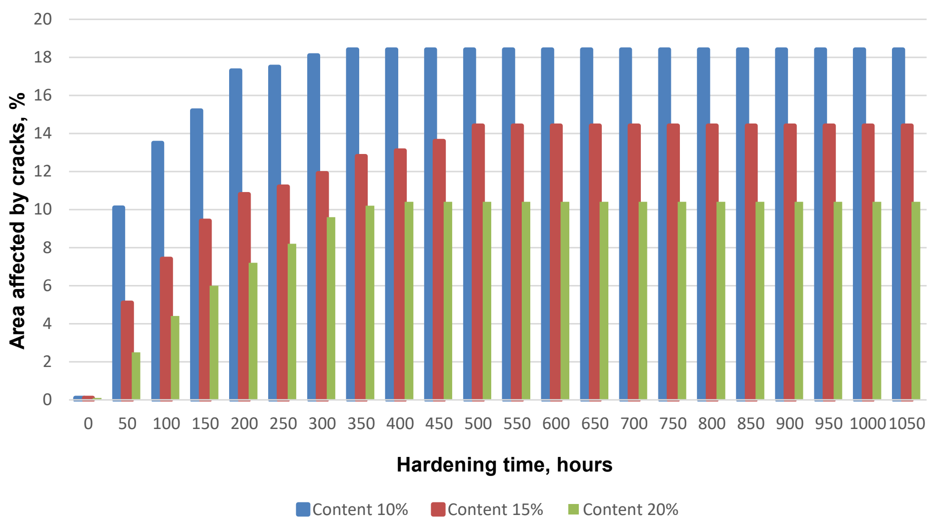

Fig. 4. Effect of aqueous sodium chloride solutions on crack formation in the clay filter cake

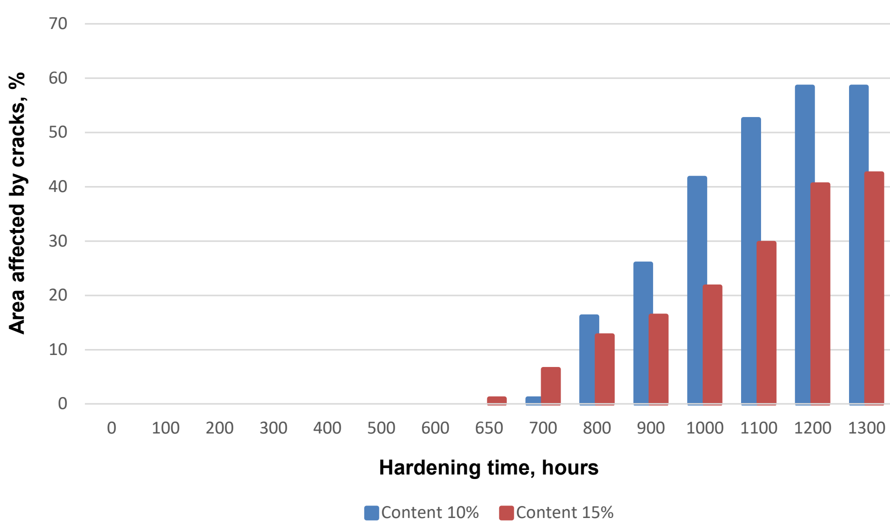

Fig. 5. Effect of aqueous sodium carbonate solutions on crack formation in the clay filter cake

Table 2

Results of the study on the effect of buffer fluids on the crack formation process in the clay filter cake

Aqueous solution	Concentration n, %				
	2	5	10	15	20
	Total area affected by cracks S, %				
$CaCl_2$	6	23	39	–	56
NaCl	–	–	18	14	10
Na_2CO_3	0	0	59	43	–

Approximation of the experimental data made it possible to obtain analytical expressions describing the dependence of the total area affected by cracks on the concentration of aqueous $CaCl_2$ solutions

$$S(n) = -1410.5 \cdot n^2 + 582.62 \cdot n - 4.2375, \qquad (6)$$

and NaCl solutions

$$S(n) = -80 \cdot n + 26, \qquad (7)$$

where $S(n)$ – total area affected by cracks, %; n – concentration of the aqueous solution, %.

In this case, the approximation reliability levels were 0.997 and 1.00, respectively. Regarding aqueous sodium carbonate solutions, it should be noted that concentrations up to 5% are effective for increasing the crack resistance of the clay filter cake.

At the final stage, a study was carried out to investigate the effect of eccentric positioning of the casing string in the wellbore on the intensity of crack formation in the clay filter cake. The results of studying the influence of the cement sheath thickness on the crack resistance of the clay filter cake are shown in Fig. 6.

The nature of the obtained dependencies indicates that the thickness of the cement sheath significantly affects the duration of the induction and cracking periods, as well as the area of the clay filter cake affected by cracks. In particular, with a cement slurry height of 80 mm, the induction period is approximately 24 hours, with a height of 20 mm – 75 hours, and with a height of 10 mm – nearly 500 hours. The cracking period for a cement slurry height of 80 mm is 80–100 hours, for a height of 20 mm – 200–220 hours, and for a height of 10 mm – 250 hours. The total area of the clay filters cake affected by cracks decreases with a decrease in the cement slurry height. Specifically, it is approximately 80% for 80 mm, 71% for 20 mm, and 47% for 10 mm.

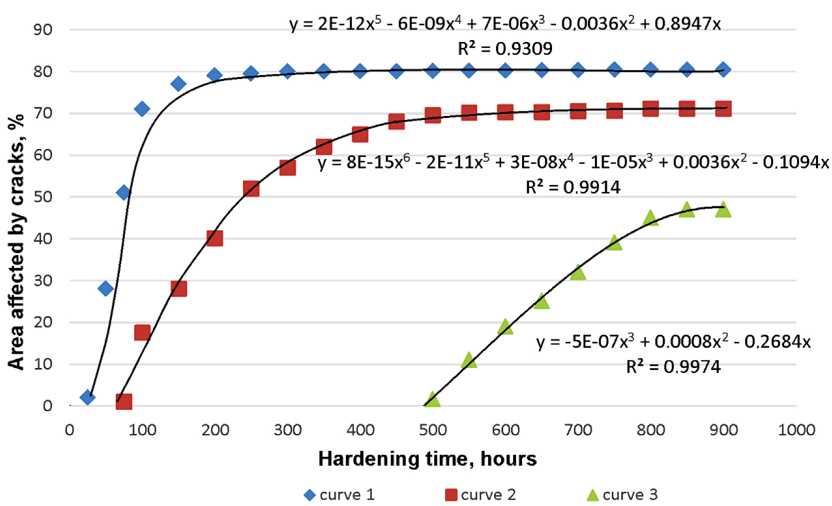

Fig. 6. Influence of cement slurry height on crack formation in the clay filter cake: curve 1 – cement slurry height 80 mm; curve 2 – cement slurry height 20 mm; curve 3 – cement slurry height 10 mm

Thus, with an increase in cement sheath thickness, the number of cracks and channels increases, and consequently, the probability of inter-casing fluid migration also rises. Therefore, to improve the tightness of the wellbore annulus, it is advisable to reduce the thickness of the cement sheath while ensuring concentric positioning of the casing strings in the wellbore by means of centralization.

Summarizing the conducted research, it should be noted that similar results regarding the influence of adding fiber-reinforcing additives to the drilling fluid on the crack resistance of the clay filter cake have been reported in [26]. An increase in the concentration of chrysotile asbestos fiber in the drilling fluid reduces the crack resistance of the filter cake. This phenomenon is explained by the additional water absorption of the clay filter cake both due to the hardening process of the cement stone and as a result of water adsorption by chrysotile asbestos, which is itself a hydrophilic material. For polypropylene fibers, the opposite effect is observed. Due to their chemical inertness to the external environment and their ability to inhibit the migration of the dispersed phase of the drilling fluid, the crack resistance of the filter cake increases. Thus, our results are consistent with those reported above.

In view of this, a comprehensive approach to solving the problem of ensuring high-quality wellbore sealing should be adopted. This should include measures to optimize the design of wells by rationally reducing the radial clearances between casing strings. In terms of the technological implementation of the cementing process, the design of the compositions and parameters of the drilling fluids should be carried out with regard to the specific geological and technical conditions and the minimization of their cost.

Regarding the compositions of buffer fluids, the obtained results indicate the promising application of aqueous sodium carbonate solutions. Taking this into account, further research will focus on an in-depth study of their influence on the crack formation process in the clay filter cake. Studies on the crack formation process in the filter cake during well washing with low-clay and polymer-based drilling fluids under high-pressure and high-temperature conditions are also promising.

4. Conclusions

Based on the results of experimental studies, it was established that the process of crack formation in the clay filter cake is influenced by ion exchange and contraction. The crack formation process is characterized by three periods: induction, cracking, and stabilization. The duration and intensity of each period are determined by the state of the "clay filter cake – hardening cement slurry/stone" system. The most intensive course of the process is characteristic of conditions corresponding to the wellhead section of the borehole. In this case, the process stabilizes after 180–200 hours, and more than 80% of the clay filter cake area is affected by cracks. For the middle section of the borehole, the induction period increases to 45–50 hours, and the total area affected by cracks at the final stage does not exceed 60–65%. The induction period for the lower section of the borehole is 100–120 hours, with the total area of the clay filter cake affected by cracks amounting to 25–30%.

The influence of buffer fluids (aqueous electrolyte solutions) on the crack resistance of the clay filter cake in contact with hardening cement slurry/stone was studied. It was found that when using an aqueous solution with a 2% concentration of calcium chloride, the clay filter cake becomes saturated with Ca^{2+} ions, and upon further contact with the cement slurry filtrate, the

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total affected area increases only slightly. For buffer fluids with higher concentrations of calcium chloride (5%, 10%, and 20%), cracking of the clay filter cake increases and reaches up to 56%. When using aqueous sodium chloride (NaCl) solutions with concentrations of 10–20%, the affected area ranges from 18% to 10%, respectively. When treating the clay filter cake with 2% and 5% sodium carbonate solutions, no crack formation was observed for 1400 hours.

It was experimentally confirmed that the process of crack formation in the clay filter cake is also influenced by the thickness of the cement sheath, which is determined by the eccentric positioning of the casing string in the wellbore. For a thickness of 80 mm, almost 81% of the area is affected by cracks, while for a thickness of 10 mm, this figure is 47%. Therefore, it is advisable to adhere to the principle of minimizing the thickness of the cement sheath when designing the well structure.

Conflict of interest

The authors declare that they have no conflicts of interest regarding this study, including of a financial, personal, authorship, or other nature that could have influenced the research and its results presented in this article.

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Data availability

This manuscript has no associated data.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in creating this work.

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