



Investigation of Cement Compositions of Backfill Systems for Lining Wells with Inclined and Horizontal Sections

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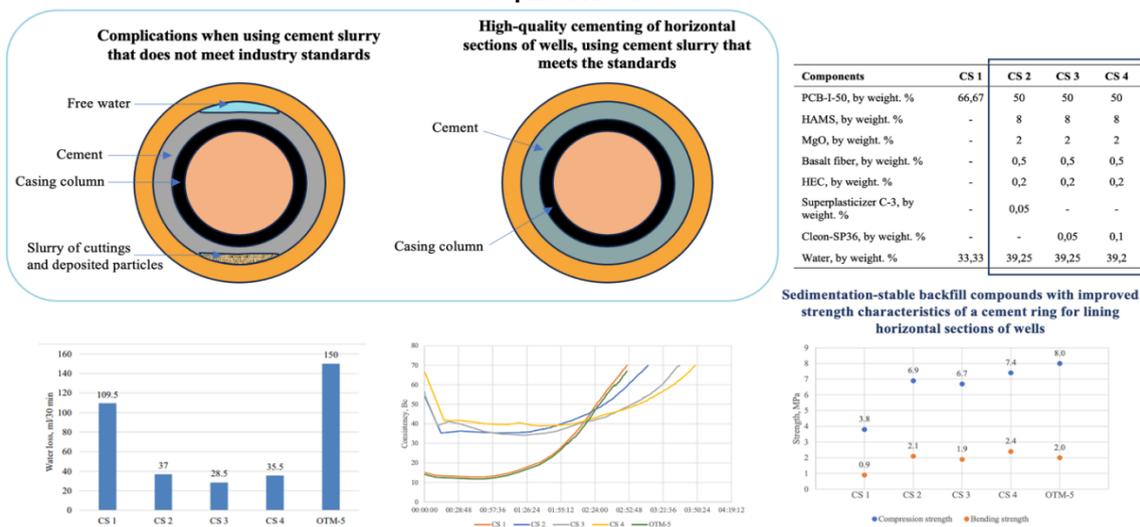
Strength of Cement Stone

ABSTRACT

In order to increase the flow rate of oil wells in oil production and gas extraction industry, there is an increase in the construction of inclined-directed and horizontal wells. Despite the experience of drilling horizontal wells, their cementing still does not have the required quality. For these areas, incomplete replacement of drilling mud with cement slurry is noted due to irregularities in the walls of the well, insufficient centering of the casing in the wells, sedimentation of process fluids. As a result, there may be no contact of the cement stone with the casing and rock in this zone, which leads to a violation of the tightness of the cement stone and the appearance of cross fluid flows. Thereby, the development of new compositions of cement slurries and well completion methods is a crucial task in the field of construction of horizontal wells for hydrocarbons. The research work presents the results of a study of the effect of various additives - hollow aluminosilicate microspheres, hydroxyethyl cellulose, magnesium oxide, polymer material "Cleon-SP36", superplasticizer C-3, basalt fiber on the structural, rheological and strength properties of cement slurry and cement stone. Sedimentation-stable compositions with improved strength characteristics of a cement ring for lining horizontal sections of wells, allowing to increase the efficiency of oil field development are proposed. The developed backfill compound based on PCB I-50 is designed for cementing oil and gas well casings at low and normal temperatures (15-50 °C), as well as taking into account the physico-mechanical characteristics of the hollow aluminosilicate microspheres (HAMS) – the recommended application depth is up to 3000 m vertically.

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Graphical Abstract



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1. INTRODUCTION

The process of oil and gas production is not getting simpler, which requires to develop technologies and introduce new methods, including horizontal drilling (1, 2). For directional and horizontal wells, the total volume is steadily increasing. The construction of horizontal wells is effective in the reservoir of small thickness, while directional wells are highly effective in formations of large thickness (3-5).

The quality of well cementing depends on effectiveness of oil and gas fields and the use of modern methods to increase reservoir recovery (6, 7). In cementing deviated and horizontal wells compared to vertical ones, the pumping time for cement slurry increases. To reduce near-wellbore formation contamination by cement filtrate, it is necessary to decrease wellbore hydrostatic pressure using lightweight additives. During cementing of deviated and horizontal wells, standard cement slurry is prone to sedimentation and stratification under gravity. Additionally, incomplete displacement of drilling fluid by cement slurry is observed. This issue is controlled by adding a viscosifier, which enhances stability and creates an optimal rheological profile for the displacement process. However, the viscosifier increases slurry viscosity, requiring the introduction of dispersant additives. Another critical factor is cement shrinkage during curing, compensated by expansive additives. The quality of set cement is determined by high strength characteristics, ensuring reliable zonal isolation, especially across productive formations. This is achieved by incorporating reinforcing additives. Presently, regulating the properties of cement slurries, the most common way is to improve the quality of well cementing. Addition of additives to cement various geological factors of wells makes it possible to regulate their basic properties and select the necessary compositions (8). The change in the strength characteristics of cement stone is based on the changes in the physico-chemical processes occurring during the hardening of cement slurry.

Despite the experience of building horizontal wells, their cementing still does not have the required quality. On the inclined upper and horizontal surfaces, the casing tends to foot on the low wall of the well, which prevents its proper centering and has a negative effect on the formation of cement stone. A channel of deposited solid particles (Boycott effect) is observed on the underside of the annular space, and the filtration crust and thickened drilling mud are located around the circumference. The removal of solid particles, filtration crust and thickened drilling mud from these two problem areas is crucial to ensure proper cementing results. However, in conditions of horizontal wells, the completeness of the replacement of drilling mud with cement is difficult (9, 10). When cementing horizontal walls of wells, the process of

settling of dispersed phase particles and delamination of cement slurry is accelerated under the influence of gravitational convection and a channel with liquid is formed at the upper wall of the well. In this layer, the continuity of the cement stone is disrupted and there is no contact between the cement stone and the rock, which can lead to cross flow behind casing. "On an inclined section of the well, the separated water can be displaced by a heavier and more mobile cement slurry, however, on an extended horizontal section, this water remains at the upper wall of the well" (11).

Despite the advantages of Portland cement as the main component of the backfill compound over other materials, filling the space between the well walls with a free cement slurry reduces the quality of wall reinforcement – the insulating characteristics of cement stone deteriorate during deformation processes. Therefore, to increase the lifetime of the well, it is necessary to use additional additives in the backfill compound (12).

Improving the quality of cementing horizontal sections of wells is achieved by using backfill materials with the following properties:

- high sedimentation stability and low water loss;
- high degree of pumpability;
- tight contact of the cement stone with the casing wall and rock formations;
- high strength characteristics of cement stone (11).

2. MATERIALS AND METHOD

The properties of the developed backfill compounds were determined according to API 10B-2, ISO 10426-2 and API 10B-6 standards and recommendations on well cementing at Gazprom Neft fields:

- the density of cement slurry;
- mobility of the mortar on the AzNII cone;
- thickening time (consistency) per ZM1002 consistency meter;
- water loss on the FANN filter press;
- viscosity of the slurry, shear stress values on the FANN 35 rotary viscometer;
- setting time of the solution on the «Vika» device;
- compressive and bending strength of the stone on the test press Controls Digimax3.

The studies were carried out with the following backfill compounds:

CS 1 - Base cement slurry consisting of PCB-I-50 Portland cement and water at water-cement ratio = 0,5;

CS 2 - Cement slurry with the addition of hollow aluminosilicate microspheres (HAMS), hydroxyethyl cellulose (HEC), magnesium oxide, superplasticizer C-3, basalt fiber;

CS 3 (CS 4) - Cement slurry with the addition of hollow aluminosilicate microspheres (HAMS), hydroxyethyl

cellulose (HEC), magnesium oxide, polymer material "Cleon-SP36", basalt fiber;

OTM-5 is a lightweight backfill material containing easily dispersed and finely dispersed lightening additives with a density from 300 to 2600 kg/m³.

The ratio of the components of cement slurries is summarized in Table 1.

Functions of the reagents used:

- hollow aluminosilicate microspheres - a lightweight supplement;
- hydroxyethyl cellulose - stabilizer;
- superplasticizer C-3 – plasticizer;
- Cleon-SP36 – plasticizer;
- magnesium oxide - expansion supplement;
- basalt fiber - providing high strength characteristics of cement stone.

3. RESULT AND DISCUSSION

3. 1. Studies of Rheological Characteristics, Sedimentation Stability and Water Loss of Cement Slurry

Hollow aluminosilicate microspheres are used to develop a lightweight cement slurry. Microspheres as a by-product are formed in the process of high-temperature coal combustion in Power plants as a result of granulation of the melt of the mineral part of the coals and the blowing of crushed small droplets by internal gases. Their distinctive feature is their low price, low density, thermal stability, significant strength and crack resistance (13). Adding of HAMS into the backfill compound increases the setting time of the cement slurry, its water retention capacity and accelerates the process of structure formation due to the formation of crystallization centers, which improves the pumpability of the mortar and the tightness of the structure. HAMS is characterized by high compressive strength: the ultimate strength is 15-30 MPa, which allows microspheres to maintain their structure even in aggressive highly viscous media. The physical properties of HAMS are presented in Table 2.

TABLE 1. Compositions of cement slurries

Components	CS 1	CS 2	CS 3	CS 4
PCB-I-50, by weight. %	66,67	50	50	50
HAMS, by weight. %	-	8	8	8
MgO, by weight. %	-	2	2	2
Basalt fiber, by weight. %	-	0,5	0,5	0,5
HEC, by weight. %	-	0,2	0,2	0,2
Superplasticizer C-3, by weight. %	-	0,05	-	-
Cleon-SP36, by weight. %	-	-	0,05	0,1
Water, by weight. %	33,33	39,25	39,25	39,2

TABLE 2. Physical properties of HAMS (17)

Fractional composition	Percentage content
< 100 microns	10 - 16%
100 - 160 microns	35 - 41%
160 - 250 microns	38 - 44%
250 - 400 microns	7 - 11%
400 - 500 microns	< 2%

The sedimentation stability of cement slurry is determined by the high strength of its thixotropic structure (14) and ensures the uniformity of the cement ring obtained during hardening (15). The water loss of the cement slurry leads to the formation of channels with the tempering fluid in the well, for example, with a water loss of up to 4%, channels up to 7 mm thick are formed. In this regard, a polymer-based structure-forming component, hydroxyethylcellulose (HEC), is added to the cement slurry. The introduction of a thickener (polymer) into the system affects an increase in the viscosity of the tempering fluid and, according to Stokes' law, leads to a decrease in the rate of precipitation of solid particles, which increases the sedimentation stability of the mortar.

HEC is also used to reduce the filtration of the dispersion medium from the cement slurry in the intervals of permeable formations. When pumping cement slurry into the well, filtering free water from the mortar contributes to its thickening, premature setting, and contamination with the filtrate of the mortar of the bottom-hole zone, which affects the productivity of the well. Addition of HEC to mortar increases its viscosity and binds some of the free water due to its structure, in which the molecules adsorbed on cement particles and create protective shells.

The mechanism of action of HEC against sedimentation:

a) Polymer mesh formation

- Adsorption on cement particles: HEC molecules are adsorbed on the surface of cement grains through hydrogen bonds and electrostatic interactions. They create "bridges" between the particles, preventing them from settling.
- Forming a 3D structure:

Long chains of HEC intertwine to form a three-dimensional grid that:

- increases the structural viscosity (the solution behaves like a gel at rest);
- captures and holds solid particles and air bubbles in suspension.

b) Viscosity increase

Deceleration of gravity deposition: The HEC dramatically increases the shear stress limit. It takes more energy than gravity to start moving the particles.

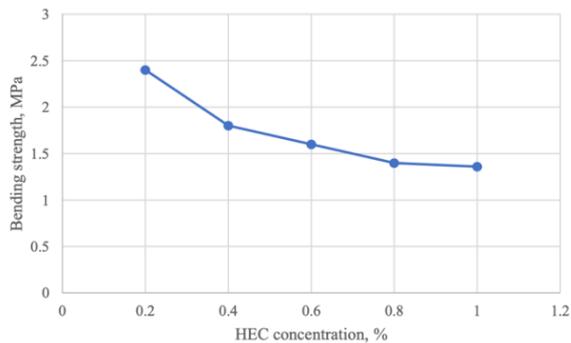


Figure 1. Effect of the HEC on the bending strength of cement stone

- Thixotropic behavior: at rest, the solution thickens, and when stirred, it liquefies. This prevents stratification during transportation.
- c) Water retention
- Hydrogel formation: HEC binds free water in its structure, reducing its migration to the surface. There is no "watery" stratification.

With an increase in the concentration of HEC in the backfill system, the water loss of the cement slurry decreases, however, at a concentration of HEC of more than 0.2%, a decrease in the strength of cement stone is observed due to a slowdown in hydration (HEC forms films on cement particles) and an increase in porosity due to air entrainment. Figure 1 shows the effect of the HEC concentration in the backfill compound on the bending strength of cement stone.

When preparing the cement slurry in the laboratory, the HEC was dissolved in advance in water at a temperature of 45 °C with stirring for 3 hours to form a solution exhibiting pseudoplastic properties. Due to its non-ionic nature, HEC is characterized by high compatibility with various reagents. Another significant advantage of HEC is that it is environmentally friendly, as it is capable of biodegradation without forming harmful substances.

According to the results of the experiments, it was noted that cementing slurries of CS 2-4 with a concentration of 0.2% hydroxyethylcellulose polymer have zero water loss (Table 3).

The results of a study of the filtration index of cement slurries at an excess pressure of 690 kPa on a FANN filter press are shown in Figure 2.

For cementing shanks, the water loss value according to the Requirements of PJSC Gazprom Neft should not exceed 50 ml/30 min. Based on Figure 2, the water loss rates of CS 2-4 mortars meet the requirements, which will allow pumping the maximum amount of cement slurry into the well, obtaining the necessary compressive strength and good adhesion between cement stone, rock and casing, and the water loss rate of cement slurry without special additives (CS-1) is unsatisfactory and

TABLE 3. The effect of reagents on the density and sedimentation stability of cement slurry

Composition number	Density, kg/m ³	Presence of water loss in the vertical cylinder	Presence of water loss in the horizontal cylinder
CS 1	1890	yes	yes
CS 2	1460	no	no
CS 3	1460	no	no
CS 4	1500	no	no
OTM-5	1000	yes	yes

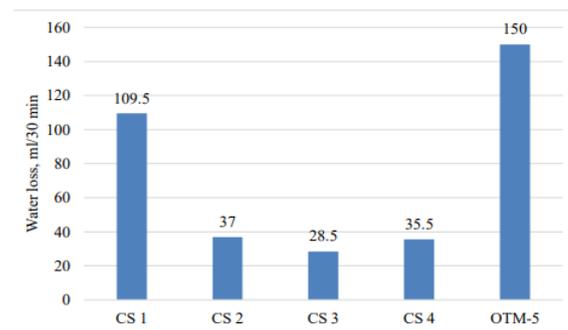


Figure 2. Water loss of backfill compounds

exceeds the required value. Cement slurries containing the polymer additive "Cleon-SP36" have the best rheological properties.

The disadvantage of the stabilizing additive in the form of HEC in the backfill compounds is a decrease in the spreadability of the slurry. Superplasticizer C-3 and polymer material "Cleon-SP36" were used to increase the mobility of the cement slurry. Superplasticizer C-3 is a product of condensation of naphthalene sulfonic acid with formaldehyde, the degree of polymerization is 2-10. It has no inhibitory effect on hydration processes. The main component of the C-3 superplasticizer is sulfonated naphthalene-formaldehyde polycondensates (82-84%). These organic compounds belong to surfactants that affect the structure of the mixture, reducing the need for water and increasing the strength of the cement stone. They are supplemented with 8-10% sodium sulfate and up to 10% water. Polymer material "Cleon SP36" manufactured by «Orgpolymersynthesis SPb» LLC is an aqueous polymer system based on acrylic and vinylsulfonic acids and their salts. The presence of several types of functional groups in the polymer provides a high affinity for cement, and its branched structure leads to the fact that cement particles repel each other not only due to electrostatics, but also due to steric difficulties. The use "Cleon SP36" improved the rheological characteristics of backfill compounds, an increase in strength, a decrease in porosity, and a reduction in the water-cement ratio. It has thermal stability and belongs to a non-toxic substance.

Figure 3 shows the results of measurements of the spreadability of cement slurries. The change in the consistency of the compounds was studied at a temperature of 50 °C and a rotation speed of the consistency mixer at 150 rpm, the results are illustrated in Figure 4.

The thickening time is considered to be the time that has elapsed from the moment of initial application of pressure and temperature to the moment when the cement slurry reaches a consistency of 70 Bc – the generally accepted consistency value at which the cement slurry is considered not to be pumped. CS-4 has the longest thickening time at a temperature of 50 °C.

The measurement results of the setting time of cement slurries are shown in Figure 5.

When choosing cementing modes, the rheological parameters of the mortar are important for predicting the magnitude of the hydraulic resistances of the cement slurry that occur during the initiation of its flow, and the completeness of the replacement of drilling mud with cement slurry (16). Figure 6 shows the results of research on the FANN 35 rotary viscometer device.

3. 2. Investigation of the Physico-mechanical Characteristics of Cement Stone After the cement slurry hardens, the cement stone must have significant strength characteristics, low permeability, and good adhesion to the casing and rock formations (17, 18).

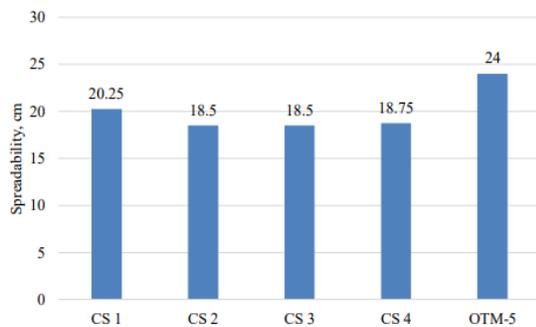


Figure 3. Spread ability of cement slurries

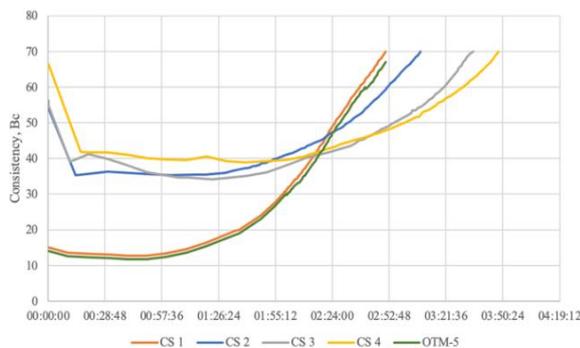


Figure 4. Changes in the consistency of cement slurries

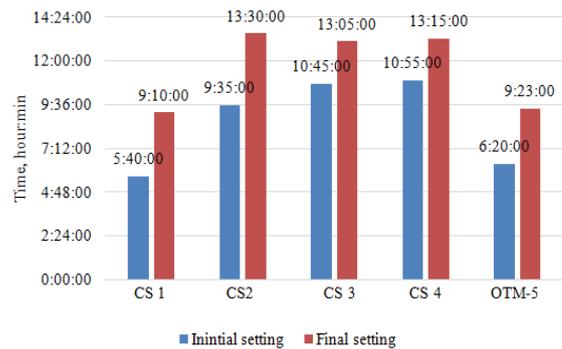


Figure 5. Setting time of cement slurries

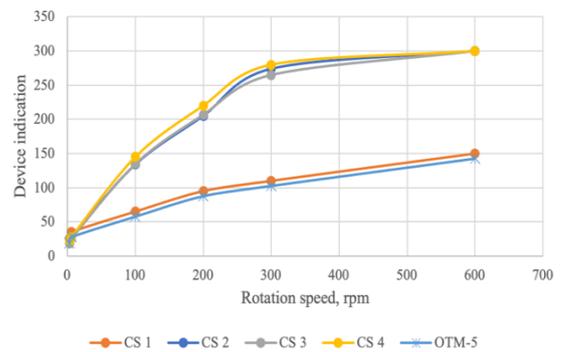


Figure 6. Research results on the FANN 35 rotary viscometer

Inappropriate contact between rock formation – cement stone – casing prevents their strong adhesion and the formation of reliable tightness of casing string annulus, and therefore an expansion additive is introduced into the backfill compound. Expansion of the oxide type is considered the most effective, providing maximum linear expansion with a minimum amount of a component – magnesium oxide or calcium oxide. This expansion is caused by the formation of corresponding metal hydroxides the oxides of which occupy a smaller volume than the hydration products (19-21).

Volumetric reinforcement is used to increase the strength and increase the ability of cement stone to withstand dynamic loads (6, 22). Reinforcing fibers as a short lengths of basalt fiber are used. The fiber hardening may occur due to the transfer of the applied load caused by the cement matrix to the fibers by means of tangential forces acting along the interface. If the modulus of elasticity of the fibers exceeds the modulus of elasticity of the cement matrix, then the fibers perceive the main part of the acting stresses. Then, total strength of the cement stone is proportional to their volume content (23). The cement matrix provides resistance to compressive stresses, the basalt fiber provides resistance to tensile and bending stresses.

Besides, adding basalt fiber into the backfill compound increases the expansion of the cement slurry-

stone by transferring the crystallization pressure of the expanding additive to the frame formed by the fiber (23).

The study conducted by Rozhkova et al. investigated the effect of cement reinforcement to the coefficient of linear stone expansion which has revealed that the fiber concentration of more than 0.5% reduces the expansion values of cement, and also leads to fiber supersaturation in the cementing slurry and the formation of lump. The results of studies of backfill compound for strength characteristics are shown in Figure 7.

According to the requirements of PJSC Gazprom, the recommended minimum value of compressive strength of cement stone after 2 days is 3.4 MPa. Compressive strength testing of each of the cement stones showed sufficient values, the cement stone formed from CS-4 exceeds the required compression strength by 118%.

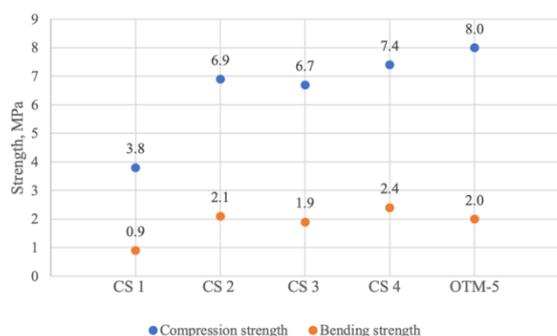


Figure 7. Strength characteristics of cement stone (Compiled by the authors)

4. CONCLUSION

The research results show that a non-additive cement slurry consisting of PCB 1-50 and process water, as well as lightweight backfill material OTM-5, do not meet the requirements of high-quality cementing of horizontal sections of wells and, therefore, it is necessary to use various reagents that improve the properties of the cement slurry. The use of hydroxyethyl cellulose has a positive effect on the filtration characteristics and sedimentation stability of the cement slurry. The water loss decreased by 74% with a concentration of 0.2% HEC, in comparison with CS-1. To increase the mobility of cement slurries, sulfonated naphthalene-formaldehyde polymers such as Superplasticizer C-3 are mainly used. However, in conditions of increased requirements for the quality of cementing horizontal sections of wells and environmental safety, the polymer material Cleon-SP36 is more effective in influencing the rheological and physico-mechanical characteristics of cement slurry - stone. The addition of basalt fiber to the backfill systems has a positive effect on the strength of cement stone. With a fiber concentration of 0.5%, the increase in compression and bending strength

was 49% and 63%, respectively. The developed backfill compound based on PCB I-50 is designed for cementing oil and gas well casings at low and normal temperatures (15-50 °C), as well as taking into account the physico-mechanical characteristics of the HAMS – the recommended application depth is up to 3000 m vertically. Further detailed studies are planned for high-depth conditions and elevated bottomhole temperatures.

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**Persian Abstract****چکیده**

به منظور افزایش سرعت جریان چاههای نفتی در صنعت تولید نفت و استخراج گاز، افزایش ساخت چاههای شیبدار و افقی وجود دارد. با وجود تجربه حفاری چاه های افقی، سیمان آنها هنوز کیفیت مورد نیاز را ندارد. برای این مناطق، جایگزینی ناقص گل حفاری با دوغاب سیمان به دلیل بی نظمی در دیواره های چاه، مرکز ناکافی پوشش در چاه ها، رسوب مایعات فرآیند، که در نتیجه ممکن است هیچ ارتباطی از سنگ سیمان با پوشش و سنگ در این منطقه وجود نداشته باشد، که منجر به نقض سفتی سنگ سیمان و ظاهر جریان مایع متقاطع می شود. در نتیجه، توسعه ترکیبات جدید دوغاب سیمان و روش های تکمیل چاه یک کار مهم در زمینه ساخت چاه های افقی برای هیدروکربن ها است. این کار تحقیقاتی نتایج یک مطالعه در مورد اثر مواد افزودنی مختلف - میکروسفرهای آلومینوسیلیکات توخالی، هیدروکسی اتیل سلولوز، اکسید منیزیم، مواد پلیمری "Cleon-SP36"، سوپراپلاستیزر C-3، فیبر بازالت بر خواص ساختاری، رئولوژیکی و استحکام دوغاب سیمان و سنگ سیمان را ارائه می دهد. رسوب-ترکیبات پایدار با ویژگی های قدرت بهبود یافته یک حلقه سیمان برای پوشش بخش های افقی چاه ها، اجازه می دهد تا بهره وری توسعه میدان نفتی را افزایش دهد. ترکیب پستی توسعه یافته بر اساس pcb I-50 برای سیمان پوشش های چاه نفت و گاز در دمای پایین و عادی (50-15) درجه سانتیگراد و همچنین با در نظر گرفتن ویژگی های فیزیکی-مکانیکی ژامبون ها طراحی شده است - عمق کاربرد توصیه شده تا 3000 متر عمودی است.