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Development and Investigation of Formulations and Technologies of Water Inflow Limitation in Oil and Gas Wells

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Abstract

In the paper the issue of development of cement composition on the basis of "Microdur" is considered. The method of mathematical planning of the experiment was used to justify the optimal formulation of the waterproofing composition, also the processing of the results of the study using the "full factorial experiment" technique, as well as the results of studies by the method of computer microtomography of the formed cement stone. Laboratory studies consisted in determining the possibility of obtaining a solid, clogging pore space of reservoir composition, both without additives, and with additives of a modifier and a plasticizer. The studies were conducted in three stages. The first stage included determining the time of formation and the quality of the insulating material. The second stage of the work was the study of kinematic viscosity and static shear stress of cement slurries. The third stage of the research was the study of the formed cement stone for compression after 2, 7, 28 days of hardening. The authors developed a technology for eliminating the inflow of bottom water using the developed waterproofing formulation and two waterproofing compositions (WPC) that differ in initial viscosity, time of hardening, strengthening properties and selectivity. The first portion of WPC is needed to cut off and precipitate the bottomhole watercone. As a cementing composition, it is recommended to use a cementing slurry on a micro-cement basis. Pumping down into the formation of the second insulating composition to create a shield in the plane of oil-water contact begins after the water cone is precipitated, the first composition hardened. As a second cementing solution, it is recommended to use a selective composition for repair and insulation works in oil and gas wells, also developed by the authors and including 10 vol. % of hydrophobizing silicone fluid (GKZh-11H), as a catalyst – 85 vol. % of ethylsilicate ETC-40, as thickener – 5 vol. % of diatomite.

Keywords: watercut, micro cement, experiment, selective composition, waterproof screen.

As the oil and gas fields of Russia (including Western Siberia) become mature, there is a progressive increase in water cut in well production, which requires the application of new methods and technologies for limiting and eliminating water inflows. The watercut of producing wells is growing everywhere, and the average Russian indicator has already reached the level of 86%, and in some fields of Western Siberia the level of watercut production reaches 95-98%. [1].

A high level of watercut leads to a decrease in the profitability of hydrocarbon production and an increase in its cost, an increasing cost of disposing of associated water, and most importantly reduces the production rate of wells for oil (gas) and the final oil recovery of productive reservoirs. A huge number of wells have to be eliminated due to premature progressive watering.

The geological and technical features of wells, such as the presence of bottom (or edge) water, high-permeability interlayers, poor-quality cementing and casing corrosion contribute to the accelerated process of watering [2].

To date, a large number of formulations and technologies for limiting water inflow have been developed and patented, but the task of isolating water inflows into oil and gas wells has not been entirely solved.

In most cases, this is due to the complexity and diversity of the geological, geophysical and thermobaric conditions of oil and gas fields, therefore, when carrying out repair and insulation works, it is important to develop and apply new backfill compositions, in particular on the basis of micro cement.

According to the European classification, cement with a particle size of less than 25 μm is considered micro cement. There are known brands like Spinor (France), Microcement ST (Finland), Intracem (RF, Mendeleyev University of Chemical Technology named after D.I. Mendeleyev). The most common brand of micro cement is Microdur (Germany, Dukkerhof). Microdur is a product of air dust separation by grinding clinker cements with grades up to "600". Microdur is distinguished by a high degree of dispersion and refers to a particularly finely dispersed binder (PFDB). There are 4 grades of Microdur: S, F, U, X, differing in particle size [3, 4, 5].

We designed and researched a backfill formulation for repair and insulation works in wells on the basis of Microdur PFDB

"R-U" grade, with the addition of a polyfunctional modifier and superplasticizer [6].

Polyfunctional modifier is a complex product based on sodium polymethylene naphthalenesulfonates, stabilizing substances with hydrophobizing components, providing increased requirements for strength and durability of the resulting microduric stone.

Superplasticizer is a product based on the condensation of naphthalenesulfonic acid and formaldehyde, has a stabilizing effect. It allows obtaining at optimal dosages highly plasticized solutions, with a minimum water / cement value, allowing retaining the mobility and uniformity of solutions for a long time.

In the proposed development, a set of ingredients makes it possible to obtain a composition for repair and insulation works in wells with high technological parameters. The mutual influence of the components on each other, their synergistic action in the developed formulation makes it possible to form a strong, stone-like material by means of a catalytic curing reaction under formation conditions.

The developed composition can be used to waterproof and secure reservoirs with low filtration and capacitive properties, since it is pumped into the formation in the form of a low-viscosity solution, and the formation of a backfill material takes place directly in the formation, as well as to build up the cement ring in the casing string annulus of the well, to repair production strings and others

At the current level of the development of technology and equipment for research aimed at studying complex processes, planning of experiments - one of the important sections of mathematical statistics - becomes more important. We used the method of mathematical experiment planning to justify the optimal formulation of the waterproofing composition on the basis of Microdur PFDB [4].

Methods of experiment planning are the rational organization of research, reducing costs and means for its implementation.

First, in terms of the experiment, the values of influencing factors vary within narrow limits. After conducting the experiment, the results are analyzed and a mathematical model is selected that provides the basis for a new stage of experimentation.

The use of methods of experiment planning in comparison with traditional methods makes it possible to increase the efficiency of scientific research two or more times.

The main advantage of multifactorial experiments is a higher accuracy of the results obtained. When planning experiments, one often has to deal with the interaction of several factors. The interaction between two factors means that a change in the result at different levels of one factor is not the same for all levels of the other factor, i.e. when the effect of one factor depends on the level of the other, a full factorial experiment makes it possible to quantify the interaction effect. The number of interactions depends on the number of factors.

For each combination of factors, a number of experiments are carried out in practice. After a thorough experiment and checking the homogeneity of dispersions, we proceed to construct (according to the results of the experiments) a mathematical model.

When drawing up an experiment plan, it is required to find the regression equation and check its adequacy.

If in the matrix (Table 1) for factors x_1, x_2 and x_3, instead of values +1 or -1, we put the respectively named ones, then we get a table with the resulted conditions of all the experiments.

Table 1: The resulted conditions of experiments

№ of experiment	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	y
1	2	3	4	5	6	7	8	9	10
1	+1	+1	+1	+1	-1	+1	+1	-1	y_1
2	+1	-1	+1	+1	+1	+1	-1	-1	y_2
3	+1	+1	-1	+1	+1	-1	+1	-1	y_3
4	+1	-1	-1	+1	-1	-1	-1	-1	y_4
5	+1	+1	+1	-1	-1	-1	-1	+1	y_5
6	+1	-1	+1	-1	+1	-1	+1	+1	y_6
7	+1	+1	-1	-1	+1	+1	-1	+1	y_7
8	+1	-1	-1	-1	-1	+1	+1	+1	y_8

Here the interaction effect of x_1, x_2 and x_3 is simply called the interaction effect. The total number of all possible effects and the interaction of all orders is equal to the number of experiments of the full factorial experiment.

The model of such an experiment has the form:

$$y = b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{123}x_1x_2x_3, \quad (1)$$

where b_0 – free term of the equation;

b_1, b_2, b_3 – coefficients characterizing the degree of influence of factors x_1, x_2 and x_3 on the value of y.

b_{12}, b_{13}, b_{23} – pair interaction effects;

b_{123} – triple interaction effect.

The next stage of the work calculates the coefficients of equation b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{123}.

Linear effects are calculated taking into account the data in Table 1:

$$b_1 = \frac{(+1)y_1+(-1)y_2+(+1)y_3+(-1)y_4+(+1)y_5+(-1)y_6+(+1)y_7+(-1)y_8}{8}; \quad (2)$$

$$b_2 = \frac{(+1)y_1+(+1)y_2+(-1)y_3+(-1)y_4+(+1)y_5+(+1)y_6+(-1)y_7+(-1)y_8}{8}; \quad (3)$$

$$b_3 = \frac{(+1)y_1+(+1)y_2+(+1)y_3+(+1)y_4+(-1)y_5+(-1)y_6+(-1)y_7+(-1)y_8}{8}; \quad (4)$$

Similarly, the remaining coefficients of the equation are calculated.

The coefficient b_0 is calculated by the same formula, but in all cases the "+" sign is taken.

Interaction effects are determined similarly to linear effects. So, to determine the coefficient b_{12}, it is necessary to use the formula:

$$b_{12} = \frac{\sum_{i=1}^{n}(x_1x_2)_j y_i}{n}, \quad (5)$$

where y_i – optimization parameter.

The remaining coefficients are determined in a similar way.

After that, the adequacy of the model is checked, in other words, it is checked if it is possible to describe the process being studied using the obtained model, i.e., if the found regression equation (the given model) is correct with the required accuracy or it is necessary to search for an equation of a more complex kind.

To test the hypothesis of adequacy, we can use the F-criterion of Fisher, the essence of which is that it compares the error of the deviation of the model from the experimental data with the experimental error.

$$F = \frac{\sigma_{ад}^2}{\sigma_y^2}, \quad (6)$$

where $\sigma_{ад}^2$ – dispersion of adequacy (residual variance).

$$\sigma_{ад}^2 = \sum_{i=1}^{n}\frac{(y_i-y_{iT})^2}{f}, \quad (7)$$

where y_{iT} – value of the optimization parameter calculated from the regression equation;

f – difference between the number of different experiments and the number of parameters of the regression equation (mean variance of reproducibility).

$$\sigma_y^2 = \sum_{i=1}^{n}\frac{(y_i-\bar{y})^2}{n-1}, \quad (8)$$

where $\bar{y}$ – mean value of optimization parameter.

The analysis of the found equation allows estimating the degree of influence of factors on the resultant sign, since with the increase of their importance the value of the corresponding regression coefficient should increase.

Signs of coefficients indicate the nature of the influence. If the coefficient has a "+", then as the value of the factor grows, the resultant sign increases, and if "-", it decreases.

Let us consider the change in the flexural strength after two days of hardening the formed backfill stone on the basis of Microdur PFDB using a polyfunctional modifier and a superplasticizer.

The influence of these factors was considered in the following ranges: Microdur PFDB - 48.5-49.2%; modifier - 1.0-1.2%; superplasticizer - 0.9-1.3; water is the remainder.

When drawing up an experiment plan, it is required to find the regression equation and check its adequacy.

If in the matrix for factors x1, x2 and x3, instead of values +1 or -1 we put the respectively named ones, then we obtain Table 2, where the conditions of all the experiments are given.

Table 2: Conditions and results of experiments

№ of experiment	Microdur PFDB, % (x_1)	«PFM-ISO», % (x_2)	«F-10», % (x_3)	Flexural strength after two days of hardening, MPa (y)
1	2	3	4	5
1	49.2	1.2	1.3	3.81
2	48.5	1.2	1.3	4.33
3	49.2	1.0	1.3	2.81
4	48.5	1.0	1.3	2.92
5	49.2	1.2	0.9	3.59
6	48.5	1.2	0.9	3.50
7	49.2	1.0	0.9	3.03
8	48.5	1.0	0.9	3.64

Water is the remainder.

Here the interaction effect of x_1, x_2 and x_3, as already mentioned, is called the interaction effect.

The next stage of the work calculates the coefficients of equation b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{123}.

Linear effects are calculated taking into account the data in Tables 1 and 2 by formulae 2-4.

Interaction effects are determined similarly to linear effects. So, to determine the coefficient b_{12}, it is necessary to use formula (5). Similarly, the remaining coefficients of the equation are calculated.

As a result, we obtain the equation:

$$y = 3{,}45-0{,}14x_1+0{,}35x_2+0{,}01x_3+0{,}04x_1x_2-0{,}01x_1x_3+0{,}25x_2x_3-0{,}14x_1x_2x_3. \quad (9)$$

The values of optimization parameters are calculated from the regression equations.

Mean variance of reproducibility σ_y^2 = 0.1902.

Since the number of experiments is 8, and the number of evaluated parameters is 4, then f = 8-4 = 4. Then, according to formula (7), the variance of adequacy or the residual variance $\sigma_{ад}^2$ = 0.33.

According to formula (6), the Fisher criterion:

$$F = \frac{0{,}33}{0{,}1902} = 1{,}7. \quad (10)$$

At α = 0.05 we have f_1= 4; f_2 = 7.

Tabular value F0.05 = 4.12 [4]. As 1.7 < 4.12, the model adequately describes the process under study in the selected intervals of variation of the factors.

The values of the Fisher criterion (F-test) for the significance level α = 0.05 [4].

For example, the equation of compressive strength after two days of hardening has the form:

$$y = 8{,}36-0{,}11x_1+0{,}43x_2+0{,}18x_3-0{,}05x_1x_2-0{,}09x_1x_3+0{,}24x_2x_3-0{,}14x_1x_2x_3. \quad (11)$$

Similarly, we consider the influence of the same components of the test backfill solutions in other parameters. All the obtained models of the equation are adequate.

The equation of flexural strength after seven days of hardening:

$$y = 7{,}15-0{,}15x_1+0{,}43x_2+0{,}01x_3+0{,}04x_1x_2-0{,}03x_1x_3+0{,}29x_2x_3-0{,}15x_1x_2x_3. \quad (12)$$

The equation of flexural strength after 28 days of hardening:

$$y = 7{,}7-0{,}16x_1+0{,}48x_2+0{,}02x_3+0{,}05x_1x_2-0{,}03x_1x_3+0{,}32x_2x_3-0{,}15x_1x_2x_3. \quad (13)$$

The equation of compressive strength after two days of hardening:

$$y = 8{,}36-0{,}11x_1+0{,}43x_2+0{,}18x3-0{,}05x_1x_2-0{,}09x_1x_3+0{,}24x_2x_3-0{,}14x_1x_2x_3. \quad (14)$$

The equation of compressive strength after seven days of hardening:

$$y = 14{,}35-0{,}2x_1+1{,}45x_2+0{,}13x_3+0{,}28x_1x_2+0{,}02x_1x_3+0{,}64x_2x_3-0{,}44x_1x_2x_3. \quad (15)$$

The equation of compressive strength after 28 days of hardening:

$$y = 16{,}36-0{,}21x_1+1{,}55x_2+0{,}1x_3+0{,}29x_1x_2+0{,}03x_1x_3+0{,}68x_2x_3-0{,}33x_1x_2x_3. \quad (16)$$

The density equation:

$$y = 1432{,}5-55x_2-2{,}5x_2x_3. \quad (17)$$

Laboratory studies consisted in determining the possibility of obtaining a hard solution, clogging pore space of a reservoir, both without additives (formulation 1), and with additives of a modifier and plasticizer (formulations 2-9).

The studies were carried out in three stages. The first stage included determining the formation time and the quality of the insulating material. The results are summarized in Table 3.

Table 3: Determining the formation time and the quality of the insulating material

Composition of working solution, mass, %	Start of hardening /End of hardening, hour	Qualitative characteristics of the formed material
1	2	3
Formulation 1 1. Microdur – 50	3.5/48	Stone-like material, medium strength

Composition of working solution, mass, %	Start of hardening /End of hardening, hour	Qualitative characteristics of the formed material
1	2	3
2. Water – 50		
Formulation 2 1. Microdur – 49.2 2. PFM-ISO – 0.8 3. F-10 – 0.8 4. Water – 49.2	3.5/48	Stone-like material, medium strength
Formulation 3 1. Microdur – 49.1 2. PFM-ISO – 0.9 3. F-10 – 0.9 4. Water – 49.1	4/48	Strong stone-like material
Formulation 4 1. Microdur – 49 2. PFM-ISO – 1 3. F-10 – 1 4. Water – 49	4/48	Strong stone-like material
Formulation 5 1. Microdur – 48.9 2. PFM-ISO – 1.1 3. F-10 – 1.1 4. Water – 48.9	4/48	Strong stone-like material
Formulation 6 1. Microdur – 48.8 2. PFM-ISO – 1.2 3. F-10 – 1.2 4. Water – 48.8	4/48	Strong stone-like material
Formulation 7 1. Microdur – 48.7 2. PFM-ISO – 1.3 3. F-10 – 1.3 4. Water – 48.7	4/48	Strong stone-like material
Formulation 8 1. Microdur – 48.6 2. PFM-ISO – 1.4 3. F-10 – 1.4 4. Water – 48.6	4/48	Strong stone-like material
Formulation 9 1. Microdur – 48.5 2. PFM-ISO – 1.5 3. F-10 – 1.5 4. Water – 48.5	4/48	Strong stone-like material

Table 3 continue

The second stage of the work was the study of kinematic viscosity and static shear stress of backfill solutions. The results of the studies are presented in Table 4.

Table 4: The results of studying kinematic viscosity and static shear stress of backfill solutions

Composition of working solution, mass, %	Viscosity, sP							SSS	
	Rotational speed, rpm							10 sec	10 min
	300.0	200.0	100.0	60.0	30.0	6.0	3.0		
Formulation 1 1. Microdur – 50 2. Water – 50	181.0	174.0	162.0	117.0	91.0	45.0	29.0	18.1	32.6
Formulation 2 1. Microdur – 49,2 2. PFM-ISO – 0,8 3. F-10 – 0,8 4. Water – 49,2	63.0	55.0	44.0	39.0	40.0	22.7	16.8	11.2	13.4
Formulation 3 1. Microdur – 49,1 2. PFM-ISO – 0,9 3. F-10 – 0,9 4. Water – 49,1	64.0	55.0	44.0	38.0	34.0	21.5	16.6	9.8	12.1
Formulation 4 1. Microdur – 49 2. PFM-ISO – 1 3. F-10 – 1 4. Water – 49	66.0	56.0	44.0	38.0	33.0	21.2	16.4	8.3	11.0
Formulation 5 1. Microdur – 48,9 2. PFM-ISO – 1,1 3. F-10 – 1,1 4. Water – 48,9	59.0	51.0	40.0	35.0	30.0	20.2	16.3	7.4	11.6
Formulation 6 1. Microdur – 48,8 2. PFM-ISO – 1,2 3. F-10 – 1,2 4. Water – 48,8	54.0	47.0	37.0	34.0	29.0	19.0	15.0	6.8	8.2
Formulation 7 1. Microdur – 48,7 2. PFM-ISO – 1,3 3. F-10 – 1,3 4. Water – 48,7	53.0	45.0	36.0	31.0	28.0	18.4	13.9	6.4	9.6
Formulation 8 1. Microdur – 48,6 2. PFM-ISO – 1,4 3. F-10 – 1,4 4. Water – 48,6	50.0	42.0	33.0	29.0	24.0	16.5	12.6	6.5	9.5
Formulation 9 1. Microdur – 48,5 2. PFM-ISO – 1,5 3. F-10 – 1,5 4. Water – 48,5	63.0	54.0	44.0	38.0	34.0	22.5	16.4	7.3	12.5

The third stage of the work was the study of the formed cement stone for compression after 2, 7, 28 days of hardening. The results of the studies are presented in Figures 1 and 2.

We have developed a technology for eliminating the inflow of bottom water using the developed waterproofing formulation with the use of two waterproofing compositions that differ in composition due to their initial viscosity, hardening time, stiffening properties and selectivity.

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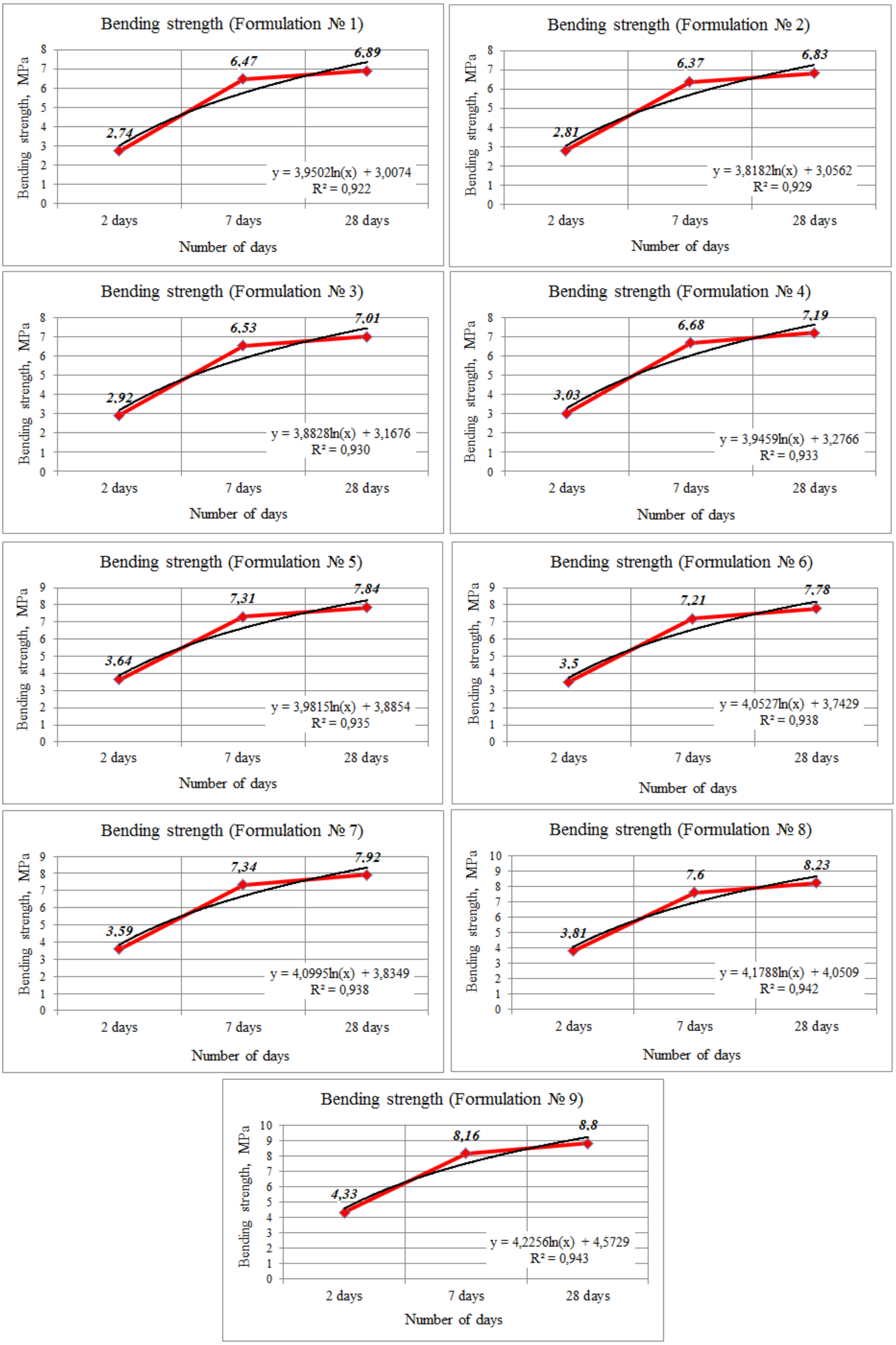

Figure 1: Results of studies of the formed backfill formulations for flexure

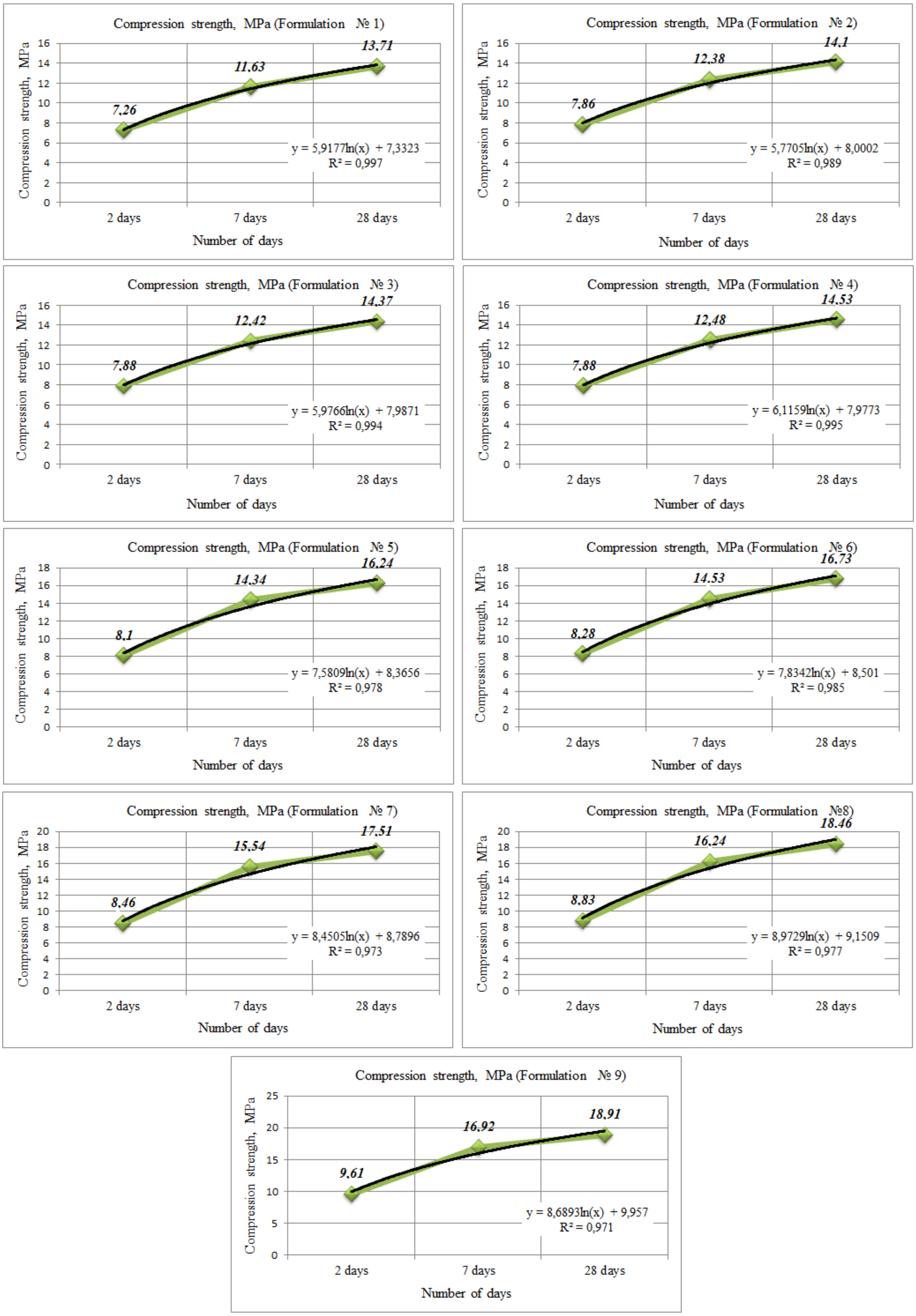

Figure 2: Results of studies of the formed backfill formulations for compression

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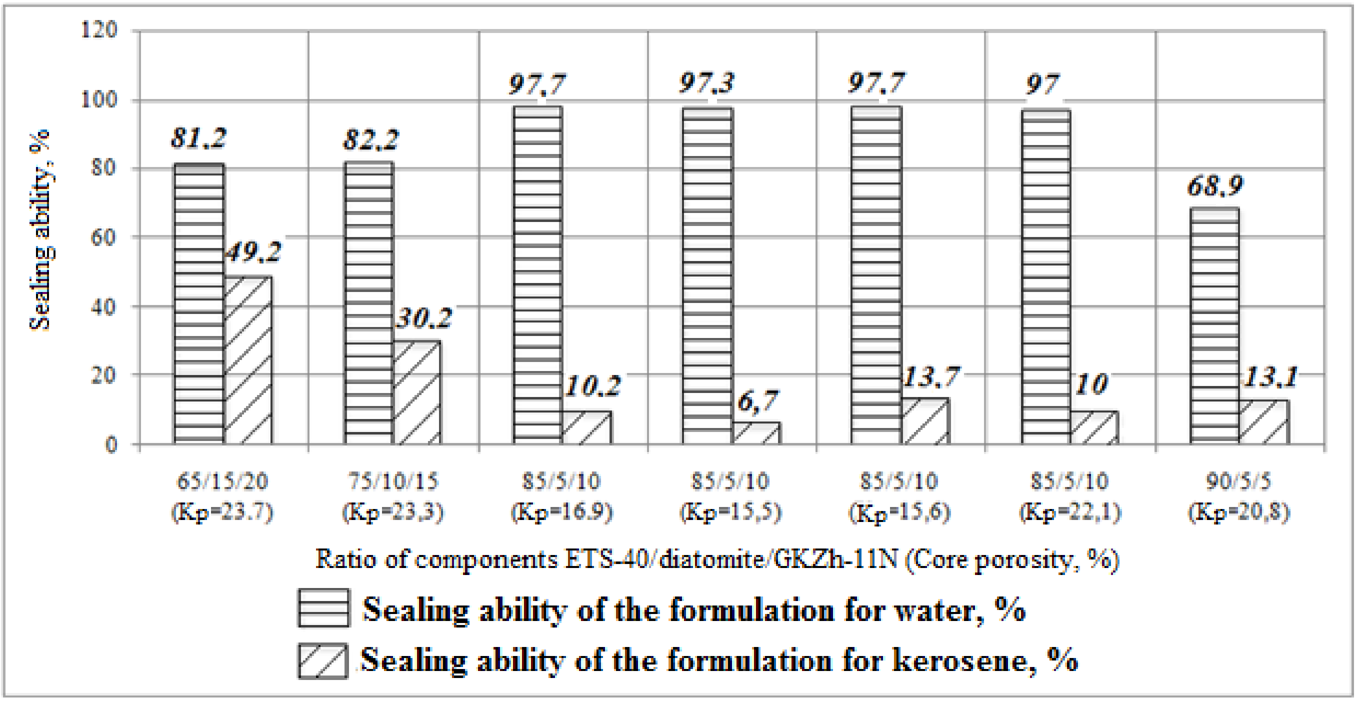

Figure 3: Graphic representation of the sealing capacity of pumped formulations

The first portion of WPC is required for cutting off and settling of the cone of bottom water. As a backfill composition it is necessary to apply backfill solution based on micro cement.

The second insulating composition is pushed down into the formation with the creation of a screen in the OWC plane, after the water cone is deposited, the first composition is hardened and the screen is formed 1.0-1.5 m below the OWC.

As a second backfill composition, it is recommended to use a selective composition for repair and insulation works in oil and gas wells, also developed by the authors and including 10 vol. % hydrophobizing silicone fluid (GKZh-11N), as a catalyst 85 vol. % ethylsilicate ETS-40, as a thickener 5 vol. % diatomite [7].

The sealing capacity (in percent) of the test compositions for water and kerosene is shown in Figure 3.

The second insulating screen from the composition of selective action with diatomite is set higher than the first screen cutting off the water cone in the water-oil contact plane (OWC).

The technology is implemented as follows [8].

A well in which the level of the bottom water blocked the lower openings of the perforation interval is stopped.

A cement bridge is installed overlapping the productive formation at 5 m from the roof of the productive formation. After WOC, the bridge is drilled and 1.0 m of the formation is perforated 1.5-2.0 m below the OWC with the perforation interval fixed in the RK and the first microdur-based waterproof screen with the calculated radius of the screen is established.

After holding the well on the hardening reaction of the backfill cementing composition based on microdur, 1-2 m of the formation is perforated in the OWC plane. A selective waterproofing composition ETS-40 with diatomite is pumped through the perforations with a waterproofing composition based on microdur that has higher strength characteristics compared to the ETS-40-based backfill composition with diatomite with follow-up hardening at the borehole wall (in a radius of 1-2 m).

After hardening the composition for the second waterproofing screen installed in the OWC plane, perforation of the productive formation is repeated, the inflow is initiated, the well is completed and put into operation.

Waterproofing screens formed in the productive layer prevent the inflow of bottom water in the non-watered part of the productive formation, preserving and prolonging the waterless period of operation.

The proposed method of isolating the inflow of bottom water in the wells makes it possible to increase the strength and radius of the waterproofing screen and thereby increase the waterless (or optimal water content in the production) period of the well operation.

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