




Features of drilling and improving the quality of well cementing in conditions of abnormally low reservoir pressures

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Abstract: An overview and actuality of oil and gas production are provided. The article reviews the mining and geological features of the Verkhnyomaslovske field of PJSC “Ukrnafta”. It is established that this field belongs to the category of fields with hard-to-recover hydrocarbon reserves. It is shown that the main complication in well drilling is the absorption of drilling mud. Attention is focused on the tasks and implemented solutions for well production casing. It has been established that the lack of necessary and inconsistency plugging materials to cementing conditions causes absorption of the grouting mortar, resulting in defects in the work and the need for additional time and financial costs to eliminate them. At the same time, it is difficult to estimate the extremely negative impact of grouting mortar absorption on the filtration and capacitance characteristics of the formation. The main parameters of the grouting mortar that caused its absorption are analysed. A new lightweight plugging material with a cement batter density of 1.25 g/cm³ was developed. The main parameters of the grouting mortar and stone based on the developed plugging material were investigated and tested in accordance with the thermobaric and technological conditions of cementing a typical well of the Verkhnyomaslovske field. The obtained results of research make it possible to improve the quality of casing support under abnormally low reservoir pressures (ALRP) conditions at the Verkhnyomaslovske field, as well as, in the future, at other fields with related mining and geological conditions.

Keywords: field, well, grouting mud, casing, cement stone

PARAMETRY WIERCENIA I POPRAWA JAKOŚCI CEMENTOWANIA OTWORÓW NAFTOWYCH W WARUNKACH ANORMALNIE NISKICH CIŚNIEŃ ZŁOŻOWYCH

Streszczenie: W artykule przedstawiono przegląd i aktualny stan produkcji ropy naftowej i gazu ziemnego na świecie. Omówiono cechy wiertniczo-geologiczne pola naftowego Wierchniomasłowieckiego ze względu na eksploatację. Wykazano, że główną komplikacją podczas wiercenia otworu jest ucieczka płuczki wiertniczej. Stwierdzono, że brak niezbędnych materiałów tamujących ucieczki płuczki oraz niedopasowanie tych materiałów do warunków cementowania powoduje dalsze komplikacje i awarie wiertnicze. Pociąga to za sobą konieczność poświęcenia dodatkowego czasu i kosztów finansowych na ich usunięcie. Jednocześnie trudno oszacować skrajnie negatywny wpływ kolmatacji strefy złożowej na zmianę współczynnika filtracji, a w konsekwencji na wielkość wydobywania. Analizie poddano główne parametry osadu filtracyjnego, które spowodowały jego osadzanie się na ścianie otworu. Opracowano nowy, lekki zaczyn cementowy o gęstości wynoszącej 1,25 g/cm³ możliwy do zastosowania jako dodatek tamponujący do płuczek wiertniczych. Zbadano i przetestowano go pod kątem tworzenia nieprzepuszczalnego osadu filtracyjnego i kamienia cementowego w warunkach ciśnienia i temperatury typowych dla otworów na złożu Wierchniomasłowieckim. Uzyskane wyniki badań pozwalają na poprawę jakości uszczelnienia otworów w warunkach anormalnie niskich ciśnień złożowych na złożu Wierchniomasłowieckim, a w przyszłości na innych złożach o podobnych warunkach złożowo-geologicznych.

Słowa kluczowe: złożo ropne, skała zbiornikowa, otwór wiertniczy, płuczka wiertnicza, kamień cementowy

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1. Introduction

Despite the priorities of the transition to green energy, oil and gas remain an extremely important component of the energy market on a global scale.

Long-term and active hydrocarbon production has caused the transition of a significant number of oil and gas fields to the final stage of development. As a result, hydrocarbon production in such conditions requires a review of the technological processes used at all stages of the well life cycle.

The results of research by scientists of PJSC “Ukrnafta” (Ukraine) confirm that the part of fields with hard-to-recover reserves in this company is about 70% (Doroshenko 2013). More than 72% of oil reserves and 10–15% of natural gas reserves are considered to be hard-to-recover. In addition, 45% of gas fields have initial recoverable reserves of less than 1 billion m³, 88% of oil fields have reserves of less than 1 million tons and are classified as ‘very small’ (Karpenko 2015).

However, fields with hard-to-recover reserves are a significant reserve and potential for increasing own hydrocarbon production. Thus, in 2023, PJSC “Ukrnafta”, as the largest oil producer, produced 1.41 million tons of oil with condensate and 1.09 billion m³ of gas of natural and oil. Accordingly, oil production increased by 3% and gas production by 6% (<https://biz.nv.ua...>).

In 2023, JSC “Ukrgasvydobuvannya” (Ukraine) produced more than 13.9 billion m³ of gross natural gas, up 5% year-on-year (almost 13.23 billion m³). In total, Ukraine produced over 18.7 billion m³ of gross natural gas in 2023. Compared to the previous year, gas production increased by 0.9% – from 18.54 billion m³ to 18.7 billion m³. Private companies, on the contrary, reduced natural gas production by almost 14% to 3.7 billion m³ in 2023. The decline in gas production by private companies is due to both difficulties in selling gas on the domestic market amid weak demand and a ban on gas exports, and the suspension of some special permits (primarily “Ukrnaftoburynnya” and Smart Energy) (Kosatka).

It should be noted that currently about 20% of the fields account for 80% of hydrocarbon production, and the remaining 80% account for only 20% of hydrocarbon production (Doroshenko et al. 2013).

2. Statement of the research problem

PJSC “Ukrnafta”, as the largest oil company in Ukraine, holds licences for oil and gas production at 85 fields. Among them is the Verkhnyomaslovske oil field, which discovered in 2001 and located in Lviv region, about 10 km southeast of Boryslav. At the moment, this field is classified as a hard-to-recover field due to the degree of depletion of initial recoverable oil reserves in menilite deposits, which is about 97% (much

more 80%) and the presence of low-permeability formations where hydrocarbon reserves are located (less than 0.05 km^2 for oil). In such conditions, the main risks that may arise both at the design stage of well and during construction and subsequent exploitation must be analysed.

In tectonic terms, the field is confined to two structural and tectonic units: the Skiba Zone and the Intermediate Layer. The Skiba Zone within the field is represented by the Pivdenno-Popelska and Popelska scales of the Oriv Skiba; the Intermediate Layer is represented by the Verkhnyomaslovska and Pivdenno-Maslovska anticlines.

Geomorphologically, the Verkhnyomaslovske field located in the Outer Carpathians, in around of lowland relief of the regional ridges and the Upper Dniester Beskydy. To the south-west, the field borders on the Carpathian ranges, so the elevation of this part of the field reaches 800–900 m above sea level. In the north-east, the elevation above sea level is 500–600 m.

The oil and gas content and prospects of the field were associated with the Popelska scale and Verkhnyomaslovska fold deposits. The Verkhnyomaslovska fold of the Intermediate Layer and the Oriv Skiba divided into individual blocks Boryslav, Pomiaraki and Ivanykivka by transverse tectonic faults. Within the Boryslav block, there are western, central, and eastern sections, which, in turn, divided into smaller elements – areas. The spatial location of the tectonic faults of the Oriv Skiba coincides in plan with the position of the Intermediate Layer faults.

Development of the menilite deposits began in 2002 by the drilling of exploration well 1-Verkhnyomaslovska, and of the Stryi deposits by the drilling of reconstituted well 25-Novoskhidnytsya.

It should be noted that the Verkhnyomaslovske oil field is partially located within the eastern part of the third zone of the sanitary protection district of the Skhidnytsia mineral water deposit of the Naftusia type. The construction of the project wells within the third zone of the sanitary protection district of the Skhidnytsia health resort is possible subject to compliance with the requirements of the relevant articles of the Law of Ukraine 'On Resorts'. In addition, the territory of Verkhnyomaslovske field includes a part of the territory of Skole Beskydy National Nature Park (Monchak 2005, Senyushkovych 2020). The conditions of work in an environmentally sensitive region require detailed planning of the entire process and implementation of highly efficient technological solutions at all stages of well construction as an engineering structure, including during their completion.

As a rule, in recent times, given the complex landscape in mountainous terrain, wells at the Verkhnyomaslovske field have been constructed with a J-shaped profile (Fig. 1). As an example, a typical well was constructed with a design bottom hole depth of MD – 1244 m (TVD – 1102 m) and taking into account the mining and geological conditions and the opening of the target horizons, the actual bottom hole was MD – 1235 m (TVD – 1082 m). The maximum zenith angle was 35° with a total reach of 460 m.

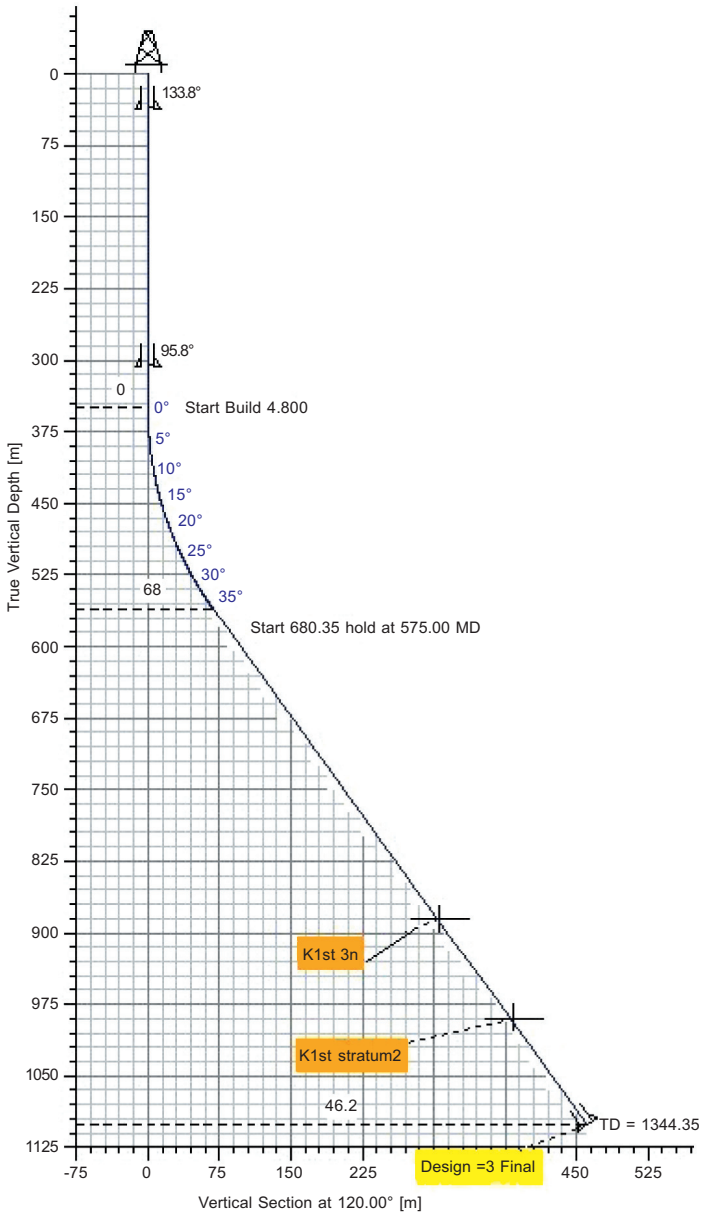


Fig. 1. Profile of well No. B Verkhnyomaslovetzka

The difficult geological conditions of well construction in fields with hard-to-recover reserves require innovative approaches to all technological processes at the well, including the well casing. For example, in the Verkhnyomaslovetzka oil field conditions, where the reservoir pressure of the menilite horizons was about 50 atm at a depth

of 1250 m, the repression on the productive horizons during drilling exceeded the reservoir pressure by 170% and during cementing by 220%. The reservoir pressure of the productive horizons of the Stryi deposits at the Verkhnyomaslovetske field is in the range of 40–45 atm.

The porosity of the Stryi deposits ranges from 9.5% to 13.5%. At the same time, permeability is characterised by a range of 1.98–9.45 mD. Repressions during drilling and cementing have a negative impact on the filtration and capacitance parameters of formation and lead to a decrease in the potential well production rate. The absorptions that occurred during drilling were eliminated by saturating the drilling mud with anti-absorption fillers.

At the well No. A Verkhnyomaslovetska, during drilling from a depth of 936 m to the bottom hole (1250 m), as well as during the logging, the drilling mud absorption was observed in the total volume of 99.5 m³. During flushing before cementing, the well absorbed another 14.5 m³. During the cementing of the production casing diameter 177.8 mm, the grouting mortar was also absorbed.

At well No. B Verkhnyomaslovetska, the absorption started at a depth of 973 m and was observed throughout the entire period of opening the productive section. The total volume of absorption during the drilling period was 62.5 m³. During the pre-cementing flushing, the well absorbed another 17 m³, and during the cementing of the production casing diameter 177.8 mm, an additional 11 m³ of grouting mortar was absorbed.

For cementing production casings for wells No. A and No. B Verkhnyomaslovetska, a backfill for low and normal temperatures with reduced water loss of the PCT-50 PV type was used. A buffer slurry based on a dry buffer mixture of type AB to separate the process fluids was used. The results of the research are shown in Table 1.

At the first stage of research (experiments 1–2), the basic formulations of TR and BS were used as a basis. During the research (experiments 3–5), the formulations of mud with the concentration of the retardant reagent NTFK equal for both portions of the TR and buffer slurry (0.455 kg/m³ of mixing water) were tested. During the tests, significant time frame of the beginning and end of the setting of the grouting mortar were noted, and therefore further research were carried out without the retardant reagent (experiments 6–8).

According to the results of research, it was found that the plugging material PCT-50 PV used in the formulation of the grouting mortar slurry lead is characterised by reduced strength characteristics. Thus, at a water-cement ratio of $W/C = 0.51$, the bending strength at the age of cement stone of 1 day at a temperature of 18°C for the forming of sample beams is 0.4 MPa, which is insufficient to ensure the required quality of casing support. Despite the absence of the retarder reagent NTFK in the formulations, the beginning and end setting times were 9-00 / 11-00 hour-min for the grouting mortar slurry tail and 15-00 / 17-00 hour-min for the slurry lead.

Table 1
Results of research the formulations of grouting mortars for cementing of the production casing diameter 177.8 mm of well No. A Verkhnyomaslovetzka in the interval 1250–0 m

Experiment number	Type cement	Formulation of grouting mortar, mass share					Density of grouting mortar [g/cm ³]	Flowability of grouting mortar [mm]	Research conditions		Time of setting, hour-min		Thickening time, hour-min	Strength of stone in bending after 24 h [MPa]	Mass fraction of additive per 1 m ³ [kg]
		quantity of cement	additive		water				temperature [°C]	pressure [MPa]	beginning	end			
			name	quantity	density [g/cm ³]	pH	quantity								
1	PCT-50 PV slurry lead	100	NTFK	0,015	1.0	7.5	51	250	22	0.1	–	–	1.4	0.294	
2	PCT-50 PV slurry tail	100	NTFK	0.03	1.0	7.5	42	250	32	0.1	–	–	3.2	0.714	
3	PCT-50 PV slurry lead	100	NTFK defoamer	0.023 0.116	1.0	7.5	51	250	32	23.0/ 0.1	15 – 00 ⁽¹⁾	17 – 00 ⁽¹⁾	2.4 ⁽¹⁾	0.455 2.27	
4	PCT-50 PV slurry tail	100	NTFK defoamer	0.02 0,1	1.0	7.5	44	250	32	23.0/ 0.1	10 – 55	12 – 10	4.0	0.455 2.27	
5	AB	100	NTFK XNT FL-CH	0.058 0.300 ⁽²⁾ 0.300 ⁽²⁾	1.0	7.5	128	250	20	0.1	–	–	–	0.455	
6	PCT-50 PV slurry tail	100	defoamer	0.1	1.0	6.6	44	250	32	0.1	9 – 00	11 – 00	3.5	2.27	
7	PCT-50 PV slurry lead	100	defoamer	0.116	1.0	6.6	51	250	32	32/0.1	15 – 20	17 – 50	0.4 ⁽³⁾	2.27	
8	AB	100	XNT FL-CH	0.30 ⁽²⁾ 0.30 ⁽²⁾	1.0	6.6	128	250	20	0.1	–	–	–	–	

⁽¹⁾ Cement stone forming conditions – first 6 hours at $t = 22^{\circ}\text{C}$, next 18 hours at $t = 32^{\circ}\text{C}$

⁽²⁾ The chemical reagent content into the amount of dry mixture to be introduced during the preparation of the buffer slurry (at the rate of 3.0 kg of reagent per 1 Mg of dry mixture)

⁽³⁾ At the temperature of forming of cement stone samples of 18–19°C for 24 hours

This indicator is significantly overestimated and adversely affects the quality of casing cementing in the cementing interval, reliable separation of productive formations and can lead to the forming of cement stone with increased permeability, reduced strength and corrosion resistance characteristics, as well as worsens the quality of cement stone adhesion to the casing, and can contribute, in some cases, to the appearance of flows and migration of reservoir fluids into overlying formations.

Researches on the compatibility of the grouting mortar and buffer slurry was conducted, which established their incompatibility in the contact zone – a decrease in flowability, deterioration of structural homogeneity, accompanied by the release of filtrate from the mixed solution, especially in a volume ratio of 1 : 9. However, after conditioning the mud using the LMR-1 device (stirring time 3 min at a speed of 1500 rpm), the fluidity was 210 mm along the AzNDI cone. At the same time, it should be noted that the use of incompatible technological mud is undesirable, as it carries risks associated with increased hydrodynamic losses during pumping of mud in the annulus, deterioration of filtration characteristics of mud in the mixing zone and contributes to a negative impact on the reservoir properties of the productive formation, increases the risks associated with loss of mud mobility in the intervals of formations with increased permeability.

Based on the results of the absorption of the grouting mortar in wells No. A and No. B Verkhnyomaslovetska were repaired and insulated with counter cementing. For example, in well No. B, due to the absence of cement stone in the interval from 0 to 608 m, we injected 17 Mg of PCT 50–100 grouting mortar in a volume of 12.5 m³ with a cement density of 1.80 g/cm³. Such works entail additional time and financial costs and may also have a negative impact on the filtration and capacitive characteristics of the formations.

3. Forming of the article objectives

Ensuring fast well construction can be achieved by implementing advanced technological solutions. At the same time, a prerequisite for high-quality well cementing in complicated mining and geological conditions of formations with ALRP is the use of sedimentation-stable plugging systems with reduced grouting mortar density and accelerated structure formation kinetics, which form cement stone with the required physical and mechanical properties.

The purpose of the article is to evaluate the implemented technological solutions for drilling and cementing wells under ALRP conditions and to design, research and justify the need use the special plugging materials.

4. Results of the research

In the period from 2005 to 2020, eight wells were drilled at the Verkhnyomaslovske field within the central section of the Boryslav block, and two wells were drilled as horizontal wells. From 2021 to the first half of 2024, an additional nine wells were drilled at the Verkhnyomaslovske field.

The typical well design (design horizon K_{2st} , zenith angle about 35°) involves a directional casing diameter 339.7 mm to a depth of 36 m, a conductor diameter 244.5 mm to a depth of 306 m and a production casing diameter 177.8 mm to a depth of approximately 1250 m (TVD – 1100 m). In case of penetration of the menilite horizon P_{3ml} , the well design envisages running a production string diameter 177.8 mm to a depth of approximately 1550 m (TVD – 1400 m). Additional exploration of well No. 105 on the Yamna deposits (P_{1jm}) is provided by casing with a production string diameter 177.8 mm (TD – 1553 m) and a production liner diameter 127 mm (TD – 1497–2067 m).

The analysis of the main technical and economic indicators of well drilling at the Verkhnyomaslovske field was carried out (Tab. 2). The wells of this field were considered. The interval of drilling wells in the approximate range of the productive thickness of 800–1455 m (considering the opening of the horizons of the Stryi and menilite deposits) was taken as a basis.

Please note that well No. 103 Verkhnyomaslovska (design horizon P_{3ml} Boryslav sandstone) was drilled in 2021, where the reservoir pressure of the project horizon was lower, approximately two times lower than the reservoir pressures for wells No. 1 and No. 10, and compared to well No. 21, which was put into production in 2012, the reservoir pressure of the horizon P_{3ml} Boryslav sandstone for well No. 103 was only 56% of the initial one. This decrease in reservoir pressure put additional requirements on PJSC “Ukrnafta” to select and optimize drilling and completion processes. A clay-free biopolymer type of drilling mud GLYDRIL was used, which ensures shielding of the low-pressure formation without adversely affecting the filtration and capacitive parameters (permeability recovery factor was 96%). Clay-free biopolymer drilling muds are being used in other wells.

Also, to minimize the impact of repressive processes on the formation with ALRP associated with the trip round, modern BHA and highly efficient rock destruction tools were used. Wells No. 1, 10, 21, 31 were drilled by drilling departments. Wells No. 102, 103, 104 have already been drilled using individual services. All wells are directional, based on a depth of 1101m and drilling with bits without coring. Modern bits and screw motors have already been used at wells No. 10, 21, 31.

As you can see, the implementation of effective technological solutions during the construction of wells at the Verkhnyomaslovske field has shown the possibility of increasing the rate of penetration from 3.9 to 6.6 times.

Table 2
Analysis of well construction at the Verkhnyomaslovetske field

Parameters	Wells				
	1	10	21	31	103
Year of well drilling	2001	2011	2012	2012	2021
Time of drilling mud impact on the formation [days]	58	46	44	45	20
Number of deepening flights	14	21	18	21	7
Number of core trip	10	9	3	4	2+ARFT
Total core sampling interval [m]	55	44	15	17	15
Drilling mud type	–	–	clay mud polymer-potassium		clayless
Core permeability recovery factor	–	27	–	75	96
Project horizon	P ₃ ml	P ₃ ml, Kliva, Boryslav sandstone	P ₃ ml Boryslav sandstone	P ₃ ml Kliva	P ₃ ml Boryslav sandstone
Reservoir pressure at the time of put on production [MPa]	10.84	9.00	8.92	7.80	4.90
Flow rate at the time of put on production [Mg]	5.0	10.40	9.09	9.73	28.78
Reservoir pressure 2021/2022 [MPa]	–	5.50	5.51	4.34	4.90

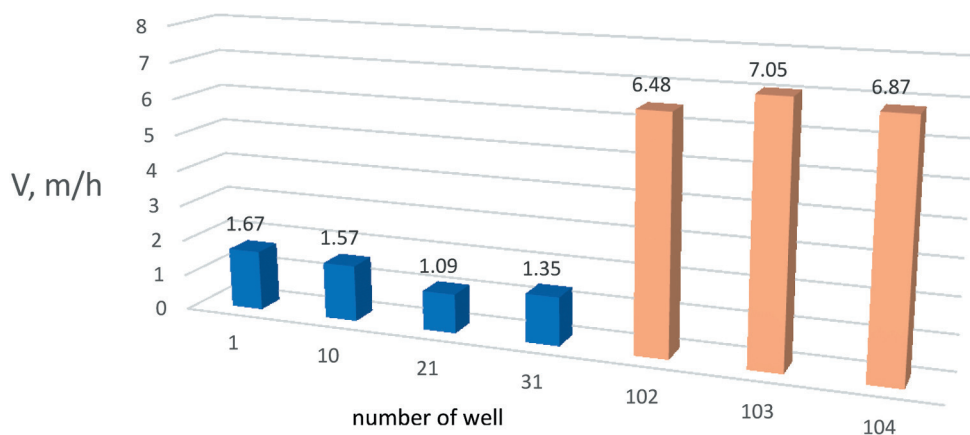


Fig. 2. Rate of penetration at the Verkhnyomaslovetske field

The increase in the rate of penetration is closely related to the monthly rig progress (Fig. 3), which is a time indicator of the efficiency of work performance.

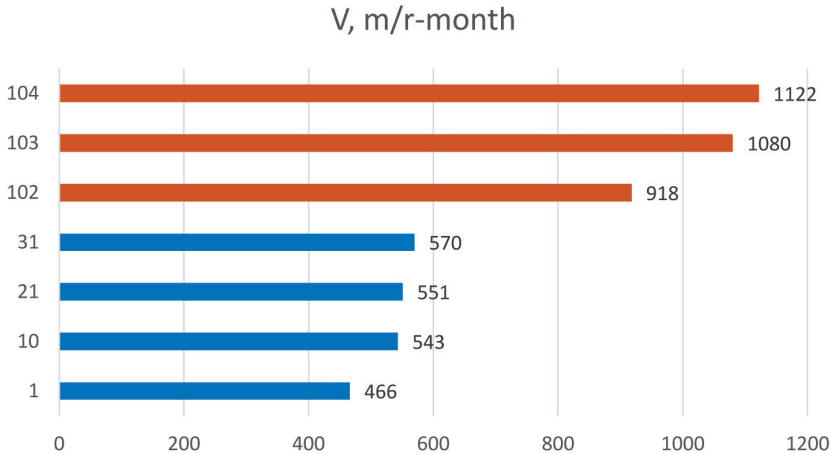


Fig. 3. Monthly rig progress at Verkhnyomaslovettske field (averaged depth of 1101 m)

The analysis of the monthly rig progress shows that the implemented efficient technological solutions allowed to increase it almost twofold compared to the most efficiently drilled well No. 31.

Compared to other wells, for well No. 103, the time of contact between the drilling mud and the reservoir was more than halved (20 days as opposed to 44–58 days for other wells), and the number of trips round was reduced by almost three times. The production casing was cemented with expandable backfill with reduced water loss, with a grouting mortar with a density of 1.80–1.83 g/cm³ in the productive layer and a light-weight slurry with a density of 1.54–1.56 g/cm³ above it using structured buffer slurries. These technological solutions were confirmed by the well flow rate at the time of commissioning. However, given the long-term operation of the wells, the reservoir pressure has been reduced by almost half.

As each well is drilled and additional geological information is obtained, the geological model of the field and the hydrodynamic model of oil deposits are refined (Fig. 4). The design of a detailed digital geological and hydrodynamic model and its timely updating ensures that correct and efficient technological decisions are made during well deepening, during selecting new wells for drilling and field development.

Due to the complication of mining and geological conditions for drilling due to the depletion of reservoir energy, the company's geological department is tasked with finding and laying new wells in the most favorable conditions.

An important stage in well construction is their completion. In this case, close attention should be given to well casing.

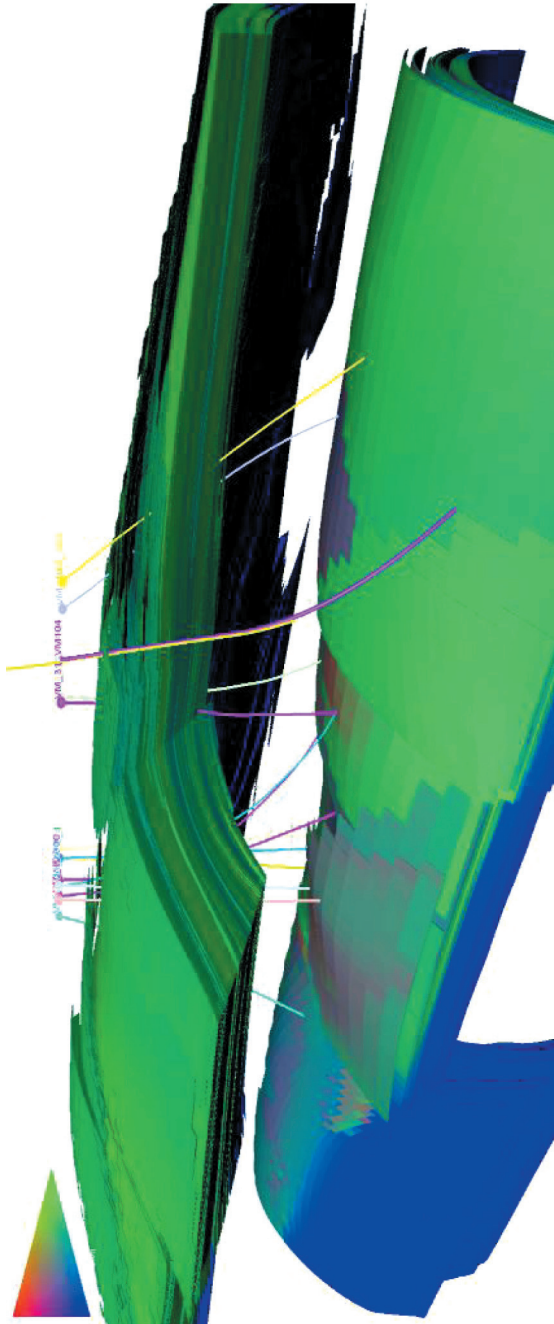


Fig. 4. Digital model of the field

Complicated mining and geological conditions require improving the quality of productive horizons delineation, which can be achieved by implementing effective technological solutions and using sedimentation-stable reinforced plugging materials (Koroviaka et al. 2024).

Violation of the support system of casing and the lack of high-quality horizon delineation can be a prerequisite for fluid flow or griffin formation, and creates additional risks to both the environment and human safety (Lutchmedial 2016).

The reports by leading hydrocarbon operators state that the lack of quality cementing is one of the main factors in accidents and uncontrolled fluid showing (British Petroleum 2010).

Reliable separation of horizons can be ensured if a high-quality insulating screen is formed in the well support system of «rock – cement stone – casing» (Heinold et al. 2002, Jadhav 2015, Ziaja et al. 2017).

It can be argued that ensuring high-quality disclosure of productive horizons and their subsequent delineation during cementing is an urgent task to minimize the negative influence of technological fluids on the filtration and capacitive properties of formations (Liu 2021).

The repression on productive intervals can be partially reduced by providing appropriate materials and cementing wells in accordance with the hydraulic program. Hydraulic modelling of the cementing process should include calculation of fluid injection modes with the show of all the main cementing parameters, dynamic modelling of the cement slurry injection process, consideration of all geometric dimensions of the annulus, rheological characteristics of technological fluids, analysis of drilling mud replacement by cement based on the initial data, calculation of dynamic and hydrostatic pressure (Hossain 2016).

However, despite the availability of significant cement production capacity in Ukraine, the market for plugging materials cannot be fully supplied with quality materials.

Portland cement production was relatively stable in 2014–2020. Production peaked in 2021 at 11 million tones. According to analysts, the expected demand for construction cement in Ukraine will be 15–16 million tons per year. In 2013–2018 only four business groups: CRH, Buzzi/Dyckerhoff, “Ivano-Frankivskcement” and “Kryvyi Rih Cement” accounted for 83% of production, and in 2019–2021, they will account for 95%. The construction of new facilities would cost approximately fi100 million to produce 1 million tons of cement (Delo).

Plugging cements, which are used for cementing of oil and gas wells, account for approximately 0.3% of building cement production in Ukraine. At the same time, the regulatory requirements for the quality of plugging cements are quite strict. Therefore, it is unprofitable to produce special plugging materials in small quantities at large cement plants.

In such conditions, plugging materials are mainly manufactured according to the technical specifications developed and approved in accordance with the established procedure. As a rule, they are based on building cements or, in some cases, special plugging cements, and fillers and modifiers are added at specialized units or enterprises. The composition of plugging materials, i.e. the components of the system, is selected depending on the requirements for mixtures, purpose and conditions of use.

The classical and proven technology for wells casing at the Verkhnyomaslovetske field involved the use of lightweight plugging materials to isolate the annular space above the productive intervals.

Lightweight plugging materials are prepared based on basic cements with the addition of various additives and fillers.

The carried-out research have highlighted the possibility of using composite cements and additives of blast furnace slag and silica fly ash, as well as limestone, to produce basic cements with regulated strength (Gursel et al. 2016, Gholampour and Ozbakkaloglu 2017, Proske et al. 2018, Król et al. 2020, Tkaczewska and Malata 2023).

Other research confirm the feasibility of using multicomponent cements (Stryczek et al. 2023) or cements with other active pozzolanic additives (Kapeluszna et al. 2020).

Fine filler such as limestone and its derivatives, based on research in the building industry, have an influence on the rheological and technological properties of grouting mortar (Tarun et al. 2003, De Schutter 2011). At the same time, calcium carbonate, the main component of limestone, reacts with calcium aluminates to form hydrated calcium carbonate. The presence of hydrated calcium carbonate inhibits the transition of ettringite to monosulfate, thus, in hydration products the amount of monosulfate decreases or disappears, and the amount of ettringite increases (Zajac et al. 2014). The reaction of calcite with C_3A to form carboaluminates suggests that limestone may to some extent play the role of a structuring regulator, which reduces the amount of gypsum as a grip regulator (Matschei et al. 2007). In addition, taking into account the nucleation effect, limestone additive grains act as crystallizing nucleus for cement hydration products (Hea et al. 2012, Zajac et al. 2014).

At the same time, research confirm that a significant part of calcite is reactive. Calcite influences on the mineralogical variant of the AFm phase(s). Calcite additives influence on the amount of free C-H, as well as on the balance between the AFm and AFt phases, although C-S-H is not affected in most of the composition range (Matschei et al. 2007).

In Ukraine, limestone is widely used in cements, its derivatives and plugging materials.

However, in some cases, base cements with low grinding fineness are used. As an example, we evaluated a base cement used as a basis for the preparation of lightweight plugging materials with a specific surface of $220 \text{ m}^2/\text{kg}$. Figure 5 shows research of the cement particle size and its distribution in the material.

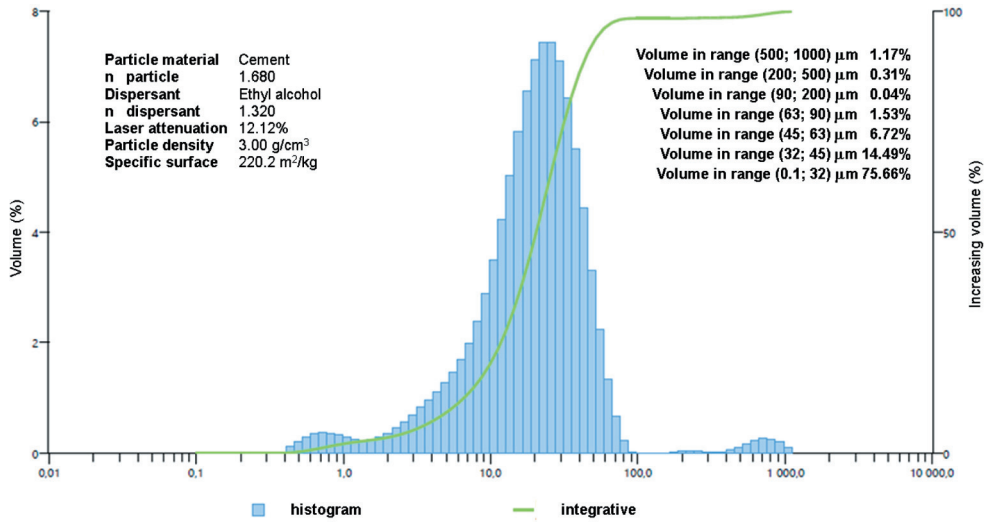


Fig. 5. Particle size of the base cement

The low specific surface of the base binder agent (Fig. 5) will have a direct influence on the prepared plugging material. As a result, the line of basic lightweight plugging cements has low sedimentation stability and reduced strength characteristics of cement stone. As a result, in most cases by the results of acoustic logging metrics, the quality of cementing with lightweight plugging material is rather poor, due to its deteriorated technological and exploitation properties. In addition, due to impaired sedimentation stability and uncontrolled water loss indicator, such materials have a negative influence on the filtration and capacitive characteristics of the reservoir.

The density of the lightweight grouting mortar will mainly depend on the density and ratio of the component materials, the water-mix ratio and the density of the dispersion medium.

The almost complete absence implementation volumes of aerated grouting mortars is due to the significantly reduced strength of cement stone based on them and the disturbance of the uniformity of the insulating ring due to the potential forming of gas belts during structuring.

The most effective method of adjusting the density of the grouting mortar is to use the optimal proportion of lightening additives in the plugging material and correction the water-mix ratio. However, it should be added that an increase in the water-mix ratio will contribute to loss of sedimentation stability, resulting in the deposition of solid particles and migration of the dispersion medium to the upper layers. In such a situation, the structuring grouting mortar may be forming with channels and water belts will form in the top part grouting mortar.

One of the ways to regulate sedimentation stability is to bind part of the free water due to the dispersion of binder agent and hydrophilic additives, stabilizer reagents, reducing the duration of structuration and the use of strengthening fillers that contribute to the forming of the structure frame. In some cases, quite often, additive of drilling clay powder is used, which has a positive effect on the stability of the grouting mortar but has an extremely negative influence on the physical and mechanical properties of cement stone and corrosion resistance.

The tightness of the insulation screen will depend on the composition of the plugging material, the properties of the grouting mortar and the features and conditions of forming its structure (Ulm and Coussy 1996, Kudapa 2023).

In Ukraine, the most widely used plugging materials are those with a grouting mortar density of 1500 kg/m^3 . However, in some cases, significant risks arise when using such materials to ensure high-quality and complete filling of the annular space, especially in the conditions of abnormally low reservoir pressures. Reducing the density of the grouting mortar by increasing the dispersion medium requires the introduction of a significant number of various stabilizers, which also leads to a significant deterioration in the physical and mechanical properties of the cement stone.

As an example, the actual use of lightweight plugging material involved the following formulation: lightweight plugging material – 100%, W/C – 0.85 and NTFK – 0.057%. The density of the grouting mortar was 1.54 g/cm^3 with a flowability of more than 250 mm. The coefficient of sedimentation resistance after 2 hours at rest was 0.93, and after 3.5 hours at rest – 0.88.

During the input control research, the water separation rate was at the lower limit of the permissible value, and the strength index exceeded the lower limit by 18%. Testing of the grouting mortar for well cementing conditions required the addition of a retarder (NTFK), which led to a significant deterioration in the properties of the grouting mortar (Fig. 6) and cement stone.

The grouting mortar based on this lightweight material is characterized by a high ratio of water separation (free water) 9 ml. At the same time, the onset of setting of the cement was 14 hours, and with modelling of downhole conditions, the ratio of water separation was 25 ml. Reducing the water-mix ratio by 14% of water leads to accelerated structuring and the onset of setting in 2 hour 45 min. In such conditions, significant risks to the success of cementing can arise and lead to a defect in the work or an emergency.

A prerequisite for ensuring high-quality horizon delineation is the use of stabilized plugging systems. The use of such materials makes it possible to obtain grouting mortar with zero ratio of water separation and a regulated water drainage value, which, in combination, ensures the forming of a non-shrinking cement stone.

Cellulose ester-based reagents are efficiently to bind free water in plugging systems (Bülichen et al. 2012). The use of stabilizer reagents must provide good retention capacity of the grouting mortar in different temperature ranges (Haichuan et al. 2015).




		
<i>WS = 9 ml (after 2 hours at 22°C)</i>	<i>WS = 20 ml (after 3.5 hours at 22°C)</i>	<i>WS = 25 ml (result) (after 2 hours at 50°C)</i>

Fig. 6. Water separation (WS) of the serial lightweight grouting mortar

The peculiarity of directional wells casing is the need to use sedimentation-stable plugging systems. Since even a slight water separation of the grouting mortar will contribute to the forming of a migration channel and a water belt (Fig. 7), which will impair the adhesion of the cement stone to the bounding surfaces and may lead to off-column flows (Ammerer and Hashemi 1983, Piatkivskyi 2024).



Fig. 7. Visualization of sedimentation stability breach of the grouting mortar

In addition, stabilized grouting mortar should be used when cementing productive reservoirs or highly permeable reservoirs. This is because it is necessary to minimize the negative influence of the grouting mortar filtrate on the filtration and capacitance characteristics of the reservoirs and prevent unexpected filtering of the dispersion medium. The loss of a part of water of the grouting mortar can lead to its premature thickening and provoke an avalanche-like grip, as a result the grouting mortar becomes non-pumpable.

To create the prerequisites for reliable horizon delineation, it is necessary to properly prepare the wellbore for cementing. Difficult dynamic loads on the casing system, in the absence of a reliable cement stone behind the casing, can cause leakage of tightness of the insulation screen (Li et al. 2023).

Another important condition for ensuring reliable horizon delineation is the forming of a strong, low-permeability and corrosion-resistant cement stone. Such pre-conditions can be achieved by reducing intergranular and capillary porosity, as well as intensification the hydration processes of the plugging material (Sanytskyi et al. 2010).

The use of plugging systems based on composite cements during hydration ensures the forming of thermodynamically stable compounds already at the first stages of the solidification process. In turn, this contributes to the forming of cement stone with high tightness and hermeticity. Such compounds with good crystal-forming properties are the basis for obtaining cement stone with low permeability and high strength in both bending and compression (Ihnatov et al. 2022, Senyushkovych et al. 2022). Research have confirmed the possibility of producing self-reinforcing composites (Taylor 1990).

It is possible to optimize hydration reactions and increase their kinetics by reducing the particle size distribution of binder particles. Figure 8 shows the particle size distribution of microcement with a specific surface of 659.6 m²/kg. For comparison, the base materials have a specific surface of 220 m²/kg to 350 m²/kg.

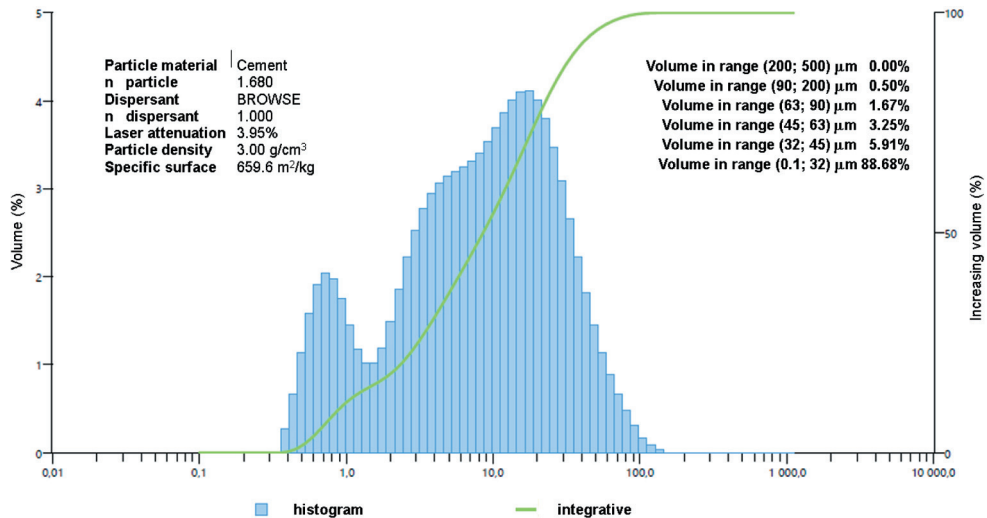


Fig. 8. Integral distribution of the fractional composition of microcement

With an increase in the specific surface of the plugging material, the constant of reaction rate increases inversely with the square of the particle radius. The increase in the dispersion of plugging mixtures helps to increase the chemically active surface of the material and this allows to release part of the internal energy of the substance, which is then realized in physical and chemical transformations (Sanytskyi et al. 2010).

The thermobaric conditions of the well will have a direct influence on the structuring process and its kinetics, which must be considered when designing the plugging material. At the same time, the components of the plugging material, in particular, their content and quantity, as well as the fractional composition, must be selected individually for each well.

Effective materials for the development of lightweight plugging materials and providing at least non-shrinking plugging materials or slightly expanding are coal ash or shale additives. Ash or variety of fly ash flotation product is a finely dispersed material with the inclusion of microspheres. The bulk density is 300–500 kg/m³. The size of microspheres is in the range of 10–400 microns. The presence in the chemical composition of SiO₂ and Al₂O₃ oxides contributes to the forming of corrosion-resistant stone, and the presence of free CaO and MgO contributes to the forming of cement stone with an expansion effect.

The combined use of ash additives and Portland cement ensures the interaction of calcium hydroxide with active silica sol and aluminosilicates, forming complex hardening compounds.

However, a significant content of fly ash in the cement composition leads to a delay in the dynamics of strength gain and, as a result, cement stone has lower values of early strength (Stryczek et al. 2023).

Compared to other lightening additives, the presence of glass spheres in the ash provides an effective reduction in the density of the plugging material. However, one of the disadvantages is the ability of spherical balls to fracture under a certain differential pressure. Nevertheless, there is a wide range of hollow spheres on the market that can withstand differential pressure of up to 700 atm. The only question will be the cost of these additives and the price competitiveness of the resulting lightweight plugging material.

To ensure the expansion effect of cement stone in a larger percentage equivalent, quicklime can be added to the composition of the plugging material, for example. However, the thermobaric conditions of the well require additional technological solutions in the calcination of lime burning as an expansion agent.

The results of the quantitative analysis of the elemental composition of lightening additives BS and TR are shown in Table 3.

Based on a summary of the results of X-ray fluorescence spectroscopy and X-ray diffraction analysis, it was found that the research material of TR has a qualitative composition, is very identical to the material of BS and differs from it primarily by a relatively higher content of the amorphous component. Like the sample of BS, the material of TR is a mixture of X-ray crystalline phases of mullite aluminosilicate

$3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$, silimanite aluminosilicate Al_2SiO_5 , and calcium carbonate CaCO_3 . In addition, the material contains a relatively higher content of iron oxide, which, however, is not detectable by X-ray diffraction. The X-ray amorphous part of the material probably includes potassium aluminosilicate.

Table 3
Quantitative analysis of the elemental composition of lightening additives

Composition (in terms of oxides) [wt.%]	Analysis number BS			Average value BS	Analysis number TR			Average value TR
	1	2	3		1	2	3	
Al_2O_3	30.92	30.46	31.25	30.88	26.38	26.14	26.58	26.37
MgO	0.80	0.86	0.75	0.80	1.65	1.58	1.54	1.59
SiO_2	58.63	57.73	58.67	58.34	53.86	53.27	53.82	53.65
P_2O_5	0.26	0.23	0.26	0.25	0.23	0.22	0.22	0.22
SO_3	0.17	0.19	0.16	0.17	0.23	0.41	0.23	0.29
K_2O	2.52	2.73	2.32	2.52	6.26	6.33	6.28	6.29
CaO	2.29	2.69	2.24	2.40	2.05	2.55	2.05	2.22
Fe_2O_3	2.86	2.71	2.81	2.79	7.68	7.84	7.63	7.71
TiO_2	1.41	1.45	1.40	1.42	1.38	1.38	1.38	1.38
V_2O_5	–	–	–	–	0.06	0.06	0.05	0.06

The composition of the plugging material, which includes a basic composite cement, microcement with a specific surface of $6596 \text{ cm}^2/\text{g}$, and a lightening additive based on ash of TR and BS, was designed. To ensure the required structural and rheological properties of the grouting mortar, for example, cellulose esters such as methylhydroxyethylcellulose or other type of stabilizer and plasticizer of polycarboxylate type or other type are used, for example, for deaeration – a silicone type defoamer or other type. Reinforcing additives, such as polypropylene or polyamide fibers, were used to increase the elastic and deformation properties of the cement stone. The formulation of the first portion of the designed plugging material is given in Table 4.

The obtained results indicate that the grouting mortar with a density of 1.25 g/cm^3 based on the developed plugging materials has satisfactory rheology (flowability index) and zero water separation. The strength of the cement stone based on C-HLW2- BS at the age of one day is 0.4 MN/m^2 , and at the age of two days – 1.1 MN/m^2 , which exceeds by 22% the strength of the base material PCT Pol 50–100 (density 1.52 g/cm^3) at the age of two days. At the same time, the base material of PCT Pol 50–100 did not reach sufficient strength of cement stone at the age of one day (samples were destroyed when disassembling the molds).

Table 4
Results of research the formulations of the first portion of the lightweight grouting mortar for cementing of the production casing $\varnothing 178$ mm in the wells of the Verkhnyomaslovetske field

Type cement	Formulation of grouting mortar, mass share				Density of grouting mortar [g/cm ³]	Flowability of grouting mortar [mm]	Water separation rate [ml]	Research conditions		Time of setting, hour-min		Thickening time to 30 Bc, hour-min	Strength of stone in bending after 24/48 hour [MPa]		
	quantity of cement	additive		water				temperature [°C]	pressure [MPa]	beginning	end				
		name	quantity	density [g/cm ³]										pH	quantity
PCT Pol 50-100	100	PCT Pol 50-100 defoamer	100 0.25	1.0	7.5	85	1.52	245	0.2	22	0.1	9-40	17-00	4-50	-/0.9
C-HLW2-TR	100	cement microcement additive TR defoamer stabilizer plasticizer reinforcing adm.	45 25 30 0.2 0.2 0.1 0.02	1.0	7.5	75	1.26	205	0	22	0.1	13-45	15-45	4-20	0.3/0.9
C-HLW2-BS	100	cement microcement additive BS defoamer stabilizer plasticizer reinforcing adm.	45 25 30 0.2 0.2 0.1 0.02	1.0	7.5	75	1.25	200	0	22	0.1	13-10	15-35	4-30	0.4/1.1

The evaluation of the rheological characteristics of the grouting mortar based on C-HLW2-BS is shown in Figure 9 using the device FANN 35SA, which characterizes the change in the twist angle at different speeds. In this case, the plastic viscosity is 90 mPa·s, and the dynamic shear stress is 350.4 dPa.

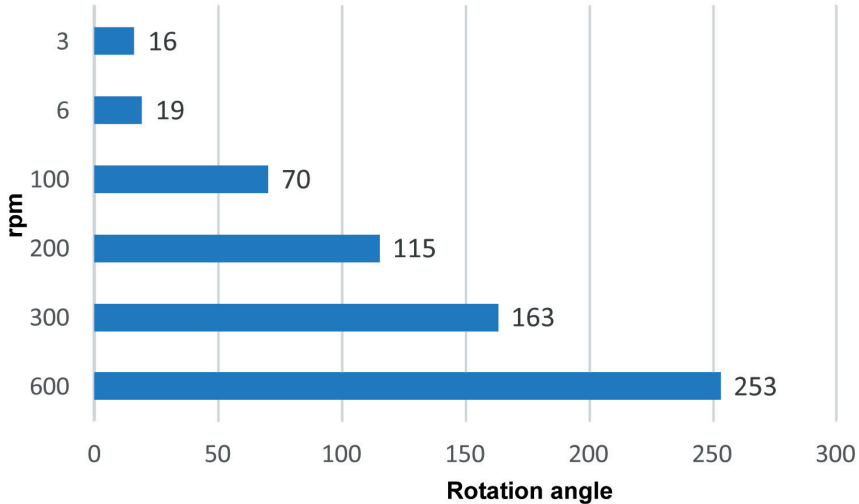


Fig. 9. Changes in the twisting angle at different rotational speeds

In addition, the first portion of the grouting mortar was tested on the consistometer KC-3 according to the schedules reflecting the technical, technological and thermobaric conditions of cementing with a research duration of $T_c = 2$ hours 40 minutes (Fig. 10).

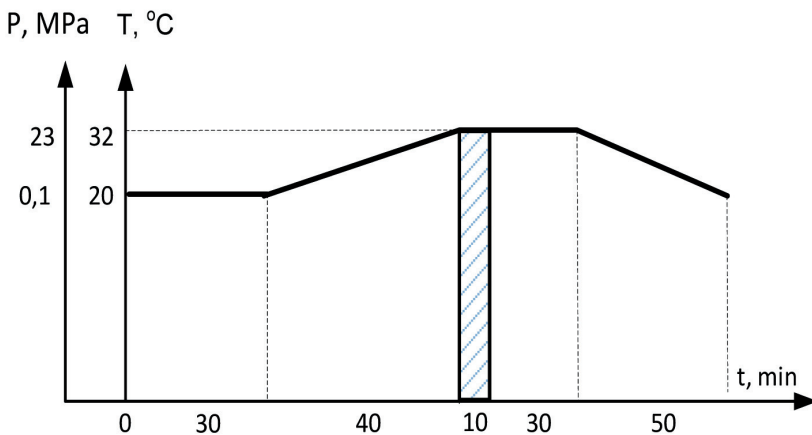


Fig. 10. Research schedule for the first portion of the grouting mortar of the typical well No. C Verkhnyomaslovetska (interval 1250–0 m)

Based on the results of modelling the thermobaric and technological procedures for cementing a production casing for a typical well in the Verkhnyomaslovetske field, it can be stated that the research materials C-HLW2-TR and C-HLW2-BS meet the established conditions of use.

For the well conditions, we tested and evaluated the dynamics of strength gain by the non-destructive method using OFITE UCA (Fig. 11).

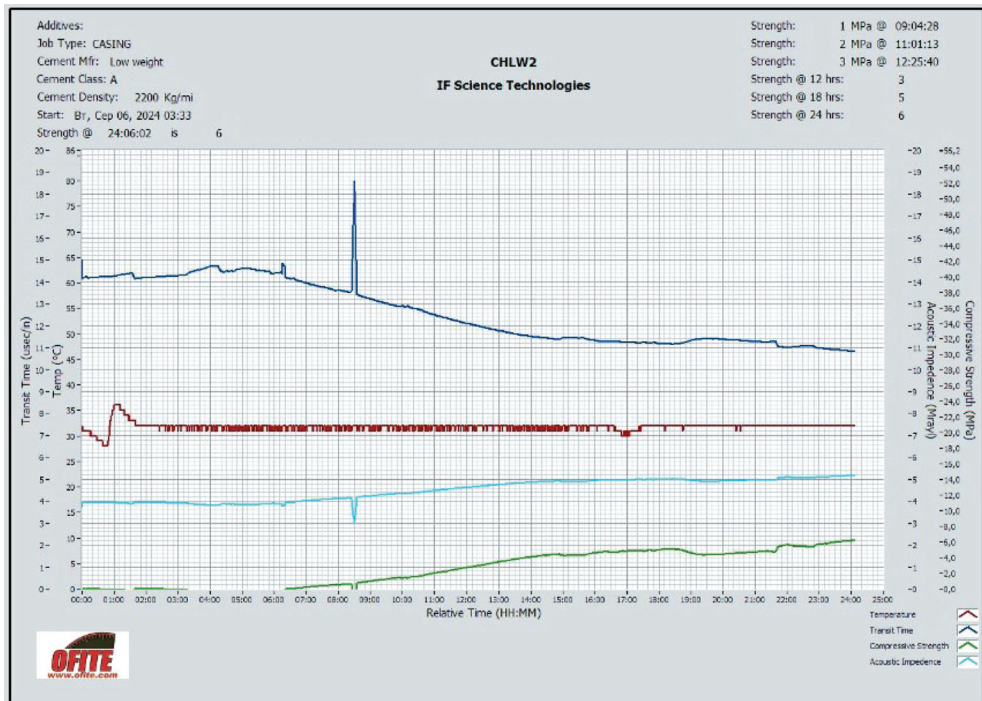


Fig. 11. Dynamics of the strength gain of the C-HLW2-BS plugging material for the conditions of well No. C Verkhnyomaslovetske field

According to the test results, it was found that the research material C-HLW2-BS is characterized by rapid structuring (6 hour – 30 min beginning of strength gain). The compressive strength at the age of one day is 6 MPa.

In addition, a quantitative analysis of the elemental composition of cement stone samples C-HLW2-TR and C-HLW2-BS was also carried out. The results of the quantitative analysis of the elemental composition of the research cement stone samples are given in Table 5.

As we can see, the cement stone research samples of plugging materials are close in elemental composition in terms of oxides.

It is known that C_3S plays a key role in providing strength among the main phases of cement clinker. At the same time, cement stone which made of C_3S monocrystals

has a compressive strength of 68 MPa, which made of C_3S – 63 MPa, of C_3A – 8 MPa, and of C_3AF – 17 MPa (Runova et al. 2008). However, the polycomponency of the cement material and its multiphase composition can introduce complex changes that affect the hardening mechanism of the constituent minerals.

Table 5
Quantitative analysis of the elemental composition of cement stone samples

Composition (in terms of oxides) [wt.%]	Number of research C-HLW2-TR			Average value	Number of research C-HLW2-BS			Average value
	1	2	3	C-HLW2-TR	1	2	3	C-HLW2-BS
Al_2O_3	6.09	7.46	8.07	7.21	8.22	7.94	8.00	8.05
SiO_2	23.24	18.03	17.29	19.52	16.97	17.07	16.93	16.99
SO_3	1.92	1.99	2.00	1.97	2.78	2.63	2.62	2.67
K_2O	1.80	2.03	1.97	1.93	1.17	1.29	1.17	1.21
CaO	60.32	63.31	63.09	62.24	63.60	63.77	63.93	63.76
MnO_2	0.40	0.44	0.45	0.43	0.44	0.46	0.45	0.45
Fe_2O_3	5.40	5.84	6.21	5.82	5.55	5.59	5.65	5.59
SrO	0.11	0.12	0.13	0.12	0.16	0.16	0.16	0,16
TiO_2	0.59	0.64	0.69	0.64	0.97	0.94	0.99	0.97

The study and comparison of the X-ray phase analysis (Fig. 12) of the lightweight plugging material used in well No. 150 (obtained as a result drilling a cement cup in the casing at a depth of 1500 m), as well as the designed lightweight material C-HLW2-TR (BS) and the mass-produced lightweight cement plugging material PTC-Pol (PTC-P) were carried out.

Based on the X-ray phase analysis, it was found that the lightweight cement stone from well No. 150 Verkhnyomaslovetzke field (density of the grouting mortar before injection into the well was 1500 kg/m^3) has a slightly lower quantity of C_3S and other basic phases that take an active role in the early strength of the stone.

The researches plugging material C-HLW2-TR is a complex mixture of calcium hydroxide phases of portlandite $Ca(OH)_2$, calcite $CaCO_3$ with the presence of hydrated calcium silicate, aluminosilicate silimanite $Al_2O_3 \cdot SiO_4$ and probably hematite Fe_2O_3 . The data obtained by X-ray diffractometry are consistent with the results of X-ray fluorescence analysis. The material contains an X-ray amorphous component, the relative content of which (estimated using Match! software) is at least 50–55 mol.%. The amorphous phase is probably formed not by a single phase, but by a few phases, as evidenced by a wide halo in the range of counter angles of 12–40°. The sulphur content

is up to 2 wt.% in terms of oxide. Potassium is present, probably part of the aluminosilicates, but no X-ray crystalline mica was detected.

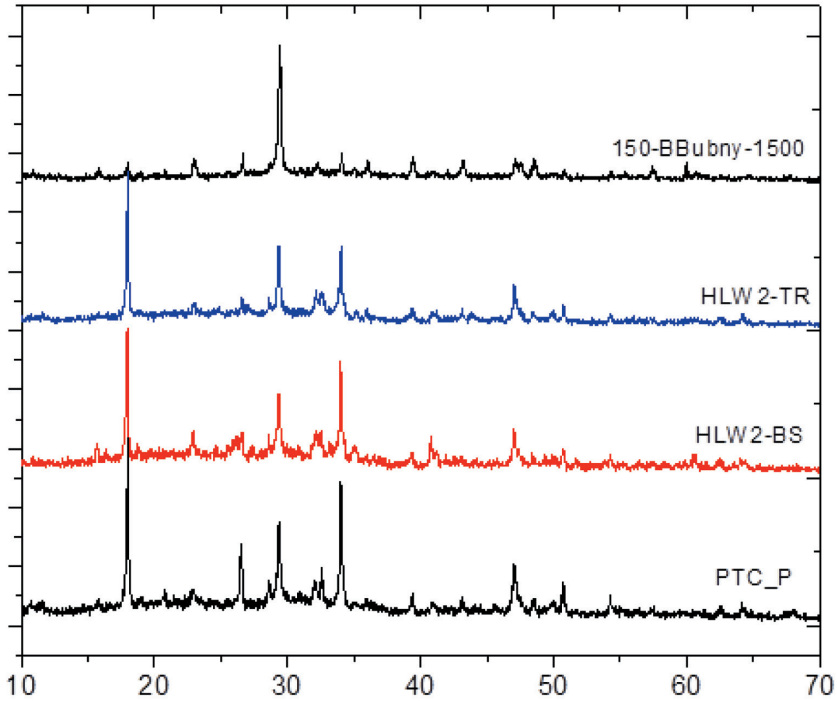


Fig. 12. X-ray diffraction analysis and comparison

For the lightweight material C-HLW2-BS, a mixture of phases of portlandite $\text{Ca}(\text{OH})_2$, calcium carbonate calcite CaCO_3 , and calcium silicate Ca_3SiO_5 was found. In addition, the X-ray crystalline phase of hydrated calcium silicate is likely presence. The diffractogram shows a halo in the region of the counter angles $13\text{--}40^\circ$. The material contains an X-ray amorphous component, the relative content of which, according to the estimation using the Match! software, is up to 75 mol.%; in general, at least 70 mol.% of the sample is in the X-ray amorphous state. The X-ray amorphous component is probably formed by calcium silicates. The sulfur content is 2.5–3.0 wt.%. Iron-containing phases are not recorded, but the iron content in terms of oxide is 5–6 wt.%.

In contrast to the lightweight cement stone from well No. 150 Verkhnyomaslovske field, the C_3S content in the proposed plugging systems (C-HLW2-TR and C-HLW2-BS) and the C-H content indicate a tendency of high kinetics of early strength gain. The C_2S content in the designed plugging systems indicates a potential reserve for strength gain at the age of 28 days and later. The base lightweight material PCT-Pol (PCT-P) (grouting mortar density 1530 kg/m^3) has a relatively satisfactory

early strength trend, taking into account the C_3S content, but due to the low quantity of C_2S , the reserve for stone strength in the long term is reduced.

It should be noted that the research of compositions which containing quartz and the results of these tests suggest that X-ray phases analysis for the research of hydrated composite systems with a SiO_2 content of more than 15 wt.% is not effective enough due to the significant background intensity of reflective SiO_2 . Such a quartz content facilitates to a decrease the ratio of 'passing signal/background', weak intensity of C-S-H reflections and other hydrate phases and neoplasms. Therefore, the hydrate phases of calcium hydrosilicate are difficult to assess due to their X-ray amorphous state.

A more detailed evaluation of the C-H, C_3S , and C_2S content is shown, as an example, for the cement stone of the lightweight material C-HLW2-BS.

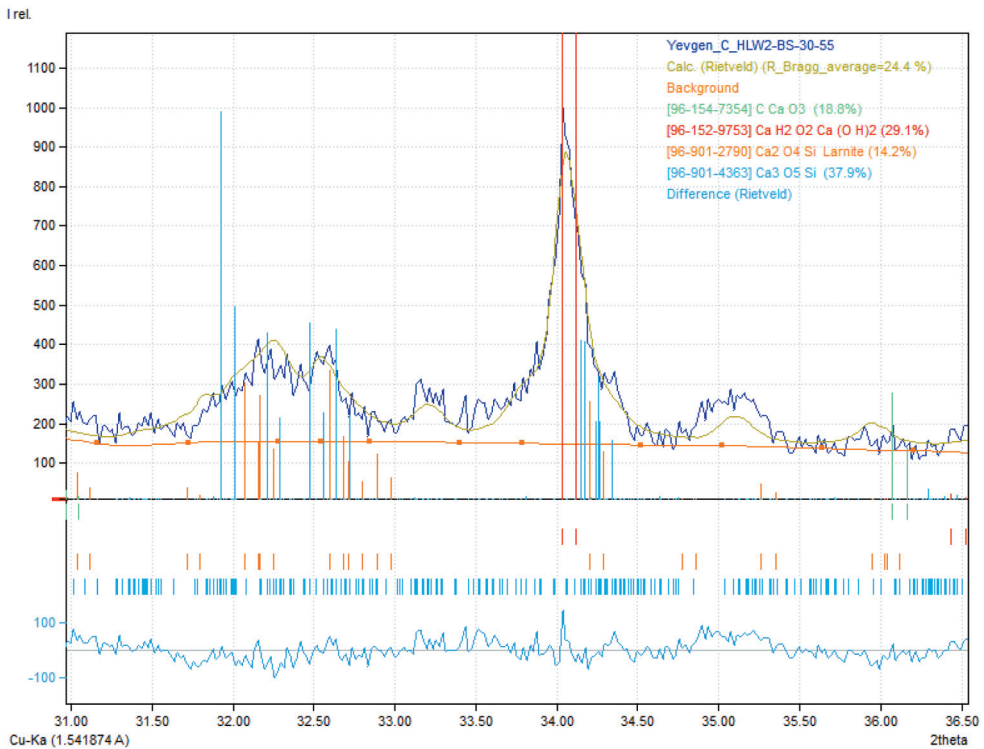


Fig. 13. X-ray phases analysis of the cement stone sample of the material C-HLW2-BS

As can be seen from Figure 13, the X-ray phases analysis in the range of counter angles 31.0–36.5° makes it possible to establish the content of C-H at approximately 29% of C_3S – 38% of C_2S – 14%, $CaCO_3$ – 19%. Such distribution of hydrate phases in this range of research mainly indicates rapid kinetics of early strength and sufficient potential for the forming of a strong and dense structure at a later age.

The analytical and laboratory research carried out and the results obtained suggest that it is possible to improve the quality of casing under ALRP conditions at the Verkhnyomaslovske field, as well as at other fields with related mining and geological conditions.

5. Conclusion

Based on the analysis and research conducted, the following conclusions can be drawn:

1. Long-term exploitation and peculiarities of the geological structure of the Verkhnyomaslovske field confirm the need to implement modern technical and technological solutions at all stages of well construction.
2. The basic technological solutions for cementing production casings do not respond the conditions for the qualitative delineation of productive horizons and ensuring reliable well casing, as evidenced by the absorption of the grouting mortar.
3. The developed composition of the lightweight plugging material can be the basis for grouting mortar with density of 1.25 g/cm^3 and a guarantee of filling the annular space with grouting mortar to the wellhead under conditions of potential absorption.
4. The structural and rheological parameters of the grouting mortar based on the developed lightweight material and the physical and mechanical properties of cement stone allow us to assert the prerequisites for ensuring high-quality well casing of the Verkhnyomaslovske field in the conditions of ALRP.
5. Strength studies and X-ray phase analysis confirm the high kinetics of structure forming of the designed compositions and the potential for further growth of strength characteristics. As a result, it can be argued that a cement stone with improved exploitation characteristics has been formed.

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