

ENHANCING PRODUCTION CASING CEMENTING QUALITY THROUGH THE APPLICATION OF EXPANDING CEMENT SYSTEMS AND POLYMERIC SPACER FLUIDS UNDER CONDITIONS OF ABNORMALLY LOW AND ABNORMALLY HIGH FORMATION PRESSURES

M. Y. Kuliye^{*1}, A. A. Seydaliyev¹, A. Y. Kuliye², R. M. Muminov³

¹Kaspiy State University of Technology and Engineering named after Sh. Yessenov, Aktau, Kazakhstan

²«NIPIneftegaz named after O.S. Gershtansky» JSC, Aktau, Kazakhstan

³«Eurasia Services company» LLP, Aktau, Kazakhstan

ABSTRACT

The article presents the results of comprehensive laboratory and field studies aimed at improving the quality of casing cementing in oil and gas wells drilled under conditions of abnormally low formation pressure (ALFP) and abnormally high formation pressure (AHFP). The main causes of cement sheath defects, including gas and water migration, interzonal fluid communication, sedimentation instability of cement slurries, and insufficient adhesion between the cement stone, casing, and formation rock, are analyzed. Particular attention is paid to the development and evaluation of expanding cement systems based on Portland cement with controlled hydration kinetics, ensuring the formation of a durable and impermeable cement sheath under challenging geological and technical conditions. Laboratory experiments showed that the continuity of the cement sheath behind the casing increased from 55–60 to 80–85 %, while adhesive strength improved significantly and the risk of microchannel formation, which can lead to interzonal fluid migration, was reduced. The practical effectiveness of the proposed technological solutions was confirmed by acoustic cement bond logging data obtained from more than 100 production wells in the oil and gas fields of Western Kazakhstan. The findings indicate the high efficiency of the developed cementing systems and demonstrate their potential for application in the design and execution of cementing operations aimed at improving long-term well integrity, ensuring zonal isolation, and reducing the likelihood of operational complications throughout the well life cycle.

Keywords: well cementing; cement slurries; expanding cements; spacer fluids; polyacrylamide; abnormally low formation pressure (ALFP); abnormally high formation pressure (AHFP); cement stone adhesion; acoustic cement bond logging.

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1. Introduction

Reliable cementing of production casings is one of the key factors ensuring the safe and long-term operation of oil and gas wells. Loss of cement sheath integrity can lead to interzonal fluid migration, water breakthrough into productive formations, and a decline in well productivity [1, 2].

Particular challenges arise under conditions of abnormally low formation pressure (ALFP) and abnormally high formation pressure (AHFP), where conventional cement slurries often fail to provide effective zonal isolation. Under these conditions, the probability of cement stone shrinkage, fluid-loss-related complications, and the formation of microannuli and channels behind the casing increases significantly [3–5].

Recent studies have demonstrated the potential of expanding cement systems and polymer-modified spacer

fluids for improving cement sheath integrity and wellbore isolation. However, issues related to the controllability of cement expansion, long-term durability, and the stability of rheological properties under varying downhole conditions remain insufficiently investigated. Therefore, the development of cementing systems with tailored physicochemical properties capable of adapting to ALFP and AHFP conditions is an important research and engineering challenge [6, 7].

The objective of this study is to improve the quality of production casing cementing through the application of expanding cement slurries and polymeric spacer fluids. The research focuses on evaluating the effect of these systems on slurry rheology, fluid loss control, adhesion characteristics, and the continuity of the cement sheath, as well as assessing their effectiveness under field conditions in oil and gas wells of Western Kazakhstan. The findings are expected to contribute to the enhancement of zonal isolation efficiency, reduction of post-cementing complications, and improvement of long-term well integrity [8, 9].

*E-mail: murad.kuliye@mail.ru

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2. Literature review and current state of the problem

The implementation of advanced cementing technologies for production casings, including the use of a 0.2% polymer-based spacer fluid and expanding cement systems adapted to conditions of abnormally low formation pressure (ALFP) and abnormally high formation pressure (AHFP), has significantly improved well integrity in the oil and gas fields of Western Kazakhstan. Field applications have demonstrated an increase in cement sheath continuity behind the casing from 55–60 to 80–85 %, indicating enhanced zonal isolation and improved cementing quality [10-12].

To improve sealing performance and formation isolation, several expanding cement formulations have been proposed. These systems incorporate calcium oxide (CaO), magnesium oxide (MgO), and hydration-control additives that regulate the expansion kinetics of the cement matrix. A cement slurry formulation based on Portland cement PCT-I-G-CC-I, modified with hydroxyethyl cellulose, defoaming agents, and plasticizers, has been developed to provide controlled linear expansion ranging from 0.2 to 22 %, depending on downhole conditions.

For AHFP environments, the most effective formulations include CaO combined with lignosulfonates or sodium silicate, while for ALFP conditions, CaO–ferrite systems have shown superior performance. These additives contribute to reduced fluid loss, improved slurry stability, and enhanced adhesion between the cement stone, casing, and formation rock.

The efficiency of borehole cleaning prior to cementing has also been improved through the development of a spacer fluid containing aluminum sulfate, a polymeric reagent, and the bridging material IKKARB-75. The interaction of these components promotes the formation of a carbonate film on the borehole wall, facilitating drilling fluid displacement and improving cement bonding [13, 14].

For wells drilled under ALFP conditions, a lightweight polymer-based cement system containing vermiculite has been proposed. With a density of 1.1–1.2 g/cm³, the system provides flexural strength values of 7.2–8.7 MPa while minimizing hydrostatic pressure on weak formations. The formulation includes urea-formaldehyde resin, a curing agent, and wood-based fillers.

In practical cementing operations, a conventional Portland cement slurry (PCT1-G) with a density of 1.85 g/cm³ is commonly used across productive intervals, whereas a lightweight cement–bentonite slurry with a density of 1.55 g/cm³ is placed above the reservoir section. This approach reduces the risk of formation fracturing and helps maintain wellbore stability during cement placement.

The effectiveness of the proposed technologies has been verified experimentally and confirmed through field implementation at the Uzen, Shagyrly-Shomyshte, and several other oil and gas fields in Western Kazakhstan [15]. A particularly important contribution reported in previous studies is the development of an expanding additive that significantly improves the bonding strength between cement stone and casing. The formulation demonstrated high performance during laboratory adhesion testing and is considered especially suitable for cementing upper well sections, including conductor casings. Furthermore, an empirical relationship describing the dependence of cement slurry consistency on

expanding additive concentration and thickening time was established, providing a basis for optimizing cementing operations under varying well conditions.

A number of studies have focused on the composition and performance characteristics of fiber-reinforced cement slurries, with particular emphasis on fluid loss, rheology, sedimentation stability, and static gel strength development [16, 17]. In study, experimental investigations based on the design of experiments (DOE) methodology were conducted to establish empirical relationships between cement slurry properties, water-to-cement ratio, and fiber concentration using probabilistic and statistical analysis. Standard laboratory techniques were employed to evaluate the structural and mechanical properties of the slurries, while analytical approximations were developed to describe slurry behavior under different formulation conditions. The dimensions of cracks formed in disk-shaped specimens were also incorporated into the assessment of water separation characteristics. Furthermore, a novel multi-criteria decision-making approach based on fuzzy logic was proposed, enabling the determination of optimal slurry formulations through the calculation of membership functions. The obtained results demonstrated that fiber reinforcement significantly improves the physical and mechanical properties of cementitious systems. Practical recommendations were provided for the modification and optimization of cementing materials intended for both construction applications and oil-well cementing operations.

Several studies have also addressed the problem of risk assessment in well cementing operations. An important aspect of risk evaluation is the practical applicability of the obtained results for developing recommendations aimed at mitigating potential operational hazards. According to this approach, decisions regarding risk acceptability should be based on the extent to which the assessment reflects actual well cementing conditions and operational constraints [18].

To reduce formation overbalance pressures during well construction, two-stage cementing techniques employing stage cementing collars (SCCs) have been widely adopted. This technology enables the distribution of hydrostatic pressure along the wellbore and minimizes the risk of formation fracturing and lost circulation during cement placement.

Table 1 presents data on the quality of production well cementing achieved using various plasticizing additives, including S-3, KSSB, and WellFix P-130. Figures 1 and 2 illustrate the cementing quality and well integrity performance at several oil and gas fields where these plasticizers were incorporated into the cement slurry formulations. Comparative results obtained without the use of plasticizing additives are also presented to demonstrate their effectiveness in improving cement sheath quality and zonal isolation.

1. Composition of lightweight cement slurry:

Cement class G	100%	by cement weight
Defoamer HX	0.06%	by water weight
FL core – 500	0.2%	by cement weight
Light core	1%	by cement weight

2. Composition of heavy cement slurry:

Cement class G	100%	by cement weight
Defoamer HX	0.06%	by water weight
FL core – 500	0.15%	by cement weight
Light core	0.08%	by cement weight

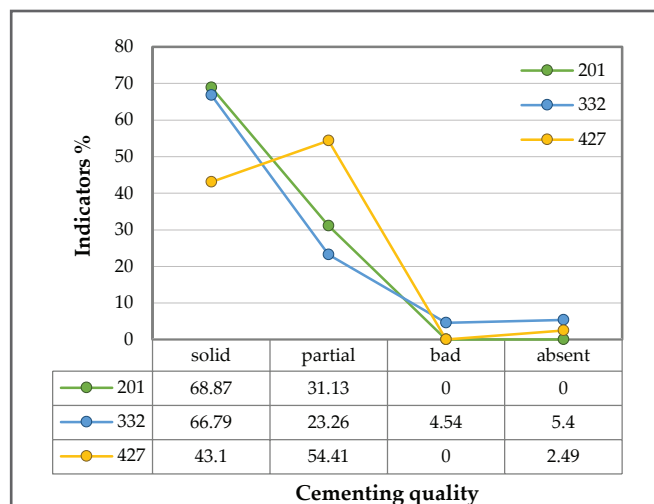


Fig. 1. Cementing quality of production casing using plasticizers at the Arystanovskoye field

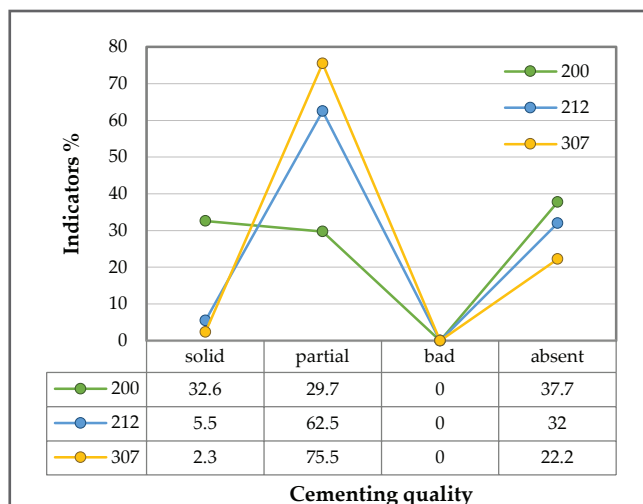


Fig. 2. Cementing quality of production casing without the use of plasticizers at the Arystanovskoye field

Quality of production casing cementing using plasticizers											Table 1
Well numbers	Casing diameter (mm) and investigation interval (m)	Cement–casing bond quality								Cementing Quality Coefficient	
		Solid		Partial		Bad		Absent			
		M	%	M	%	M	%	M	%		
1	4	5	6	7	8	9	10	11	12	13	
Kara – Arna field											
166	168.3 (12.7-540.7)	413.5	78.32	57.5	10.89	43.4	8.22	13.6	2.58	0.78	
167 H	168.3 (10-748)	586.6	86.6	66.4	9.8	12	1.8	12	1.8	0.87	
472	41.0-532.6	430	87.4	24.1	4.9	34.4	7.0	0	0	0.87	
473	11.0-534	438.3	83.8	62.65	11.98	11.2	2.15	11.03	2.11	0.84	
Arystanovskoye field											
201	177.8 (550-3115)	1766.6	68.87	798.6	31.13	0	0	0	0	0.69	
332	168.3 (500-3130)	1756.5	66.79	611.6	23.26	119.5	4.54	142.1	5.4	0.67	
427	168.3 (550-3006)	1058.4	43.1	1336	54.41	-	-	61.1	2.49	0.43	
Kul – Bas field											
КБД-03	17.7-2451.3	1625.2	66.8	503.2	20.7	169.1	6.9	136.1	5.6	0.67	
КБД-04	5.2-2540.5	1813.8	71.53	686.3	27.07	0	0	35.4	1.4	0.72	
КБД-07	156.6-2504.5	1506.9	64.2	113.1	4.8	106.3	4.5	621.4	26.5	0.64	
КБД-08	9.3-2502.3	1448.5	58.1	839.7	33.7	163	6.5	41.8	1.7	0.58	
Shagirly – Shomishty field											
268	177.8 (4.8-413.0)	259.9	63.7	119.1	29.2	25.3	6.2	3.7	0.9	0.64	
269	177.8 (4.8-416.0)	170.1	41.2	117.5	28.6	76.4	18.6	47.7	11.6	0.41	
270	177.8 (6.2-415.0)	214.3	52.4	161.1	39.4	33.5	8.2	0	0	0.52	
P-24	177.8 (6.2-433.5)	204.1	47.8	205	48.0	17.9	4.2	0	0	0.48	

Stringent requirements are imposed on oil-well cement slurries with respect to both mechanical strength and setting characteristics. The compressive strength of cement stone after 7 days of curing (for Class I cement) should not be lower than the strength achieved during the first 24 hours of hydration. Setting time is determined considering the safe execution of cementing operations and includes an additional safety margin of 25%. For Class G and Class H oil-well cements, the minimum initial setting time should be at least

2 hours. Laboratory testing is conducted under pressure conditions corresponding to the hydrostatic pressure exerted by a cement slurry column of the specified density.

Specialized cement systems are commonly employed under challenging geological and technical conditions. These include lightweight cement formulations based on pozzolanic, fly-ash, and lime-pozzolan systems, as well as ultra-lightweight slurries with densities below 1250 kg/m³. Such systems are typically produced through the incorporation of

hollow microspheres or by nitrogen foaming in combination with surfactants [5, 19, 20]. Conversely, heavyweight cement slurries are formulated by adding weighting materials such as barite, hematite, quartz sand, and other high-density agents, or by reducing the water-to-cement ratio through the use of plasticizing additives.

Improvement of production casing cementing quality is achieved through a combination of technical and technological measures. These include optimization of drilling fluid properties prior to cementing, application of effective spacer fluids, reciprocation or rotation of the casing string during cement placement, and the use of cement slurries with different densities along the wellbore interval to ensure effective zonal isolation and pressure management.

To enhance sealing efficiency in perforated intervals, mechanical cleaning and flow-conditioning devices such as casing scrapers and centralizers and turbulators are installed. Cement slurry formulations are further modified with additives that reduce fluid loss and friction coefficients, thereby improving displacement efficiency and cement sheath integrity. During conductor casing cementing, calcium chloride is frequently added to accelerate strength development and reduce waiting-on-cement time. Drilling operations are conducted under controlled overbalance conditions maintained by the hydrostatic pressure of the drilling fluid column to prevent formation fluid influx and ensure well control throughout the construction process.

Overall, the analysis of existing technologies indicates that achieving reliable long-term zonal isolation requires an integrated approach that combines optimized cement formulations, effective spacer systems, and appropriate operational practices. These considerations form the basis for the development of the expanding cement systems and polymer-based spacer fluids investigated in the present study [21-23].

3. Materials and methods

Portland cement PCT-I-G was used as the primary binding material in the preparation of the cement slurry systems. To impart controlled expansion properties and compensate for cement stone shrinkage during hydration, calcium oxide (CaO) and magnesium oxide (MgO) were incorporated into the formulations together with stabilizing additives designed to regulate the hydration kinetics of the expansive components.

To reduce fluid loss and improve rheological performance, several chemical additives were employed, including hydroxyethyl cellulose (HEC), lignosulfonates, plasticizers (S-3, KSSB, and WellFix P-130), and defoaming agents. These additives were selected to enhance slurry stability, improve pumpability, and ensure effective displacement of drilling fluids from the annular space.

Spacer fluids were prepared using a 0.2 wt.% aqueous polyacrylamide solution supplemented with the bridging material IKKARB-75. The spacer system was designed to improve borehole cleaning efficiency, facilitate drilling fluid removal, and promote the formation of a low-permeability filter cake on the borehole wall, thereby minimizing fluid losses and improving cement-to-formation bonding.

Laboratory investigations included the determination of slurry density, rheological parameters, fluid loss characteristics, thickening time, and mechanical properties of the hardened cement stone. Particular attention was given

to evaluating the effects of expanding additives and polymer-based spacer fluids on cement sheath integrity and adhesion characteristics.

The quality of well cementing was assessed using acoustic cement bond logging (CBL) techniques. Acoustic measurements were used to evaluate the continuity of the cement sheath, identify potential channeling zones, and characterize the quality of bonding between the cement stone, casing, and surrounding formation. The effectiveness of the proposed cementing systems was further validated through field applications in production wells located in Western Kazakhstan under conditions of abnormally low and abnormally high formation pressures.

4. Research methodology

The research methodology combined laboratory investigations and field-scale validation of the proposed cementing systems. The study included:

- laboratory testing of the physical, mechanical, and rheological properties of cement slurries;
- determination of the linear expansion characteristics of hardened cement stone;
- analysis of the hydration kinetics of expansive additives;
- field implementation and evaluation of the developed cementing formulations;
- interpretation of acoustic cement bond logging (CBL) data from more than 100 production wells.

In addition to the conventional testing procedures, the structural-mechanical and colloid-chemical properties of both cement slurries and hardened cement stone were investigated. Experimental studies were conducted at temperatures ranging from 60 to 90 °C and under pressure conditions corresponding to downhole environments encountered in the target wells.

Rheological parameters were measured using a Fann-type rotational viscometer. Fluid-loss characteristics were determined according to API standards, while compressive strength measurements were performed using hydraulic compression testing equipment. Colloid-chemical properties were evaluated indirectly through the analysis of sedimentation stability, aggregation behavior, and zeta potential (ζ -potential).

The obtained results demonstrated that the incorporation of polymer additives and expansive components increased both yield stress and static gel strength, thereby improving particle suspension capacity and reducing sedimentation phenomena. At the same time, a significant reduction in fluid loss and an increase in the aggregative stability of the cement systems were observed.

The expansive cement formulations exhibited enhanced linear expansion of the hardened cement stone and improved adhesion to the casing surface. These effects contributed to the formation of a more continuous cement sheath and correlated well with the improved cement bond logging results obtained during field testing. The relationship between expansion behavior, rheological performance, and cement sheath integrity was further analyzed to assess the effectiveness of the developed systems under conditions of abnormally low and abnormally high formation pressures. The main experimental results obtained for the investigated cement systems are summarized in table 2

Table 2

Results of statistical data processing				
Indicator	Light solution	Heavy solution	Expanding solution	Buffer liquid
1	2	3	4	5
Density, gr/sm ³	1.15–1.20	1.80–1.90	1.75–1.85	1.02–1.05
Plastic viscosity, mPa·s	35–50	60–90	50–75	10–20
Flow limit, Pa	8–12	15–25	18–30	2–5
CHC (10 s / 10 min), Pa	5–10 / 10–20	10–20 / 20–40	12–25 / 25–45	1–3 / 2–5
Water output (API), sm ³ /30 min	70–90	50–70	40–60	—
Sedimentation resistance	Average	High	High	High
ζ-potential, mV	–10...–20	–15...–25	–20...–35	–25...–40
Surface tension, mN/m	—	—	—	30–45
Compressive strength (24 h), MPa	8–12	12–18	10–16	—
Strenhgth (7 days), MPa	15–22	22–35	20–30	—
Adhesion to the column, MPa	1.2–1.8	1.5–2.2	2.0–2.8	—
Linear expansion, %	0–0.2	0–0.3	0.5–2.2	—
Modulus of elasticity, GPa	2.5–3.5	3.5–6.0	3.0–5.0	—

To ensure the reliability and statistical validity of the obtained results, comprehensive statistical and mathematical analyses were conducted. The experimental data were processed using descriptive statistical methods and correlation and regression analysis.

The principal parameters were calculated as mean values from a series of experiments consisting of at least three replicates. Standard deviations and coefficients of variation were determined to evaluate data dispersion and reproducibility [24].

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

where $\bar{x}$ is the mean value of the parameter; x_i – an individual measurement; n – the number of experimental observations.

The standard deviation was calculated using the following equation:

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

The coefficient of variation (CV) was calculated using the following equation:

$$\nu = \frac{\sigma}{\bar{x}} \cdot 100\%$$

The analysis showed that the coefficient of variation for the main parameters (compressive strength, fluid loss, and

rheological characteristics) did not exceed 10–15 %, indicating good reproducibility of the experimental results.

5. Results and discussion

Experimental studies demonstrated that the maximum linear expansion effect was achieved through the use of calcium oxide (CaO) and magnesium oxide (MgO). However, in the absence of stabilizing additives, the rapid hydration of these components reduced the efficiency of the expansion process. The selection of optimal chemical reagents enabled to regulate hydration and ensured controlled expansion of the hardened cement stone.

The developed expanding cement systems provided linear expansion in the range of 0.2–22 % at additive concentrations of 3–8 wt.%, which contributed to improved adhesion of the cement stone to both the casing and the formation rock.

The use of polymer-based spacer fluids improved borehole wall cleaning efficiency and enhanced the displacement capacity of the cementing system. According to the results of acoustic cement bond logging (CBL), the continuity of the cement sheath increased from 55–60 to 80–85 %.

The additional application of two-stage cementing techniques, casing centralizers, and polymer-modified cement systems reduced the risk of inter-casing fluid migration and ensured stable isolation of productive and water-bearing formations.

Conclusions

As a result of the conducted research, a set of technological solutions was developed to improve the quality of production casing cementing under conditions of abnormally low formation pressure (ALFP) and abnormally high formation pressure (AHFP).

Based on laboratory and field investigations, the following key findings were obtained:

1. The effectiveness of expanding cement systems with controlled hydration kinetics was substantiated. These systems compensate for the shrinkage of hardened cement stone during curing. It was demonstrated that the incorporation of calcium oxide and magnesium oxide at optimal concentrations (3–8 wt.%) provides controlled linear expansion in the range of 0.5–2.2 %.

2. A relationship between cement slurry composition and its structural-mechanical properties was established. An increase in the concentration of polymer additives resulted in higher yield stress values (18–30 Pa) and reduced fluid loss (40–60 cm³/30 min), thereby improving the aggregative stability of the system and minimizing sedimentation.
3. Experimental results confirmed that the application of a polyacrylamide-based spacer fluid reduces interfacial tension to 30–45 mN/m and improves borehole wall cleaning efficiency. As a result, the adhesion strength between the cement stone and casing increased to 2.0–2.8 MPa.
4. Statistical analysis demonstrated high reproducibility of the experimental data. The coefficient of variation for the principal parameters did not exceed 10–15 %, while the correlation coefficient between the concentration of the expanding additive and linear expansion ranged from 0.87 to 0.93.
5. Field trials showed that the developed cementing systems increased the continuity of the cement sheath behind the casing from 55–60 to 80–85 %, confirming the effectiveness of the proposed technological solutions.
6. It was established that integrated control of the rheological, filtration, and colloid-chemical properties of cementing systems is a key factor in the formation of a durable and impermeable cement sheath under ALFP and AHFP conditions.

The practical significance of this study lies in the potential application of the developed cement formulations and technological solutions for cementing production casings in oil and gas fields characterized by complex geological and technical conditions. The proposed approach contributes to improved zonal isolation, enhanced long-term well integrity, and reduced risks of interzonal fluid migration during well operation.

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