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Original article

Improving the Quality of Well Cementing through the Use of Nanocomposites: Field Data Analysis and Evaluation of their Effect on Cement Slurry Properties

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ABSTRACT

Background: The challenging geological and thermobaric conditions of the Western Kazakhstan oil fields impose stringent requirements on cement slurry systems, while standard Portland cement formulations frequently fail to provide adequate zonal isolation over the well's production lifecycle.

Aim: This study aims to identify the key limitations of conventional cement compositions and substantiate the feasibility of introducing SiO₂, Al₂O₃ nanoparticles and carbon nanotubes to improve the rheological and mechanical properties of cement slurries.

Materials and Methods: A comparative analysis was conducted using actual cementing program data from a well at the North Uaz field and a well at the Western Prorva field, evaluating slurry density, viscosity, thickening time, fluid loss, and compressive strength.

Results: Standard formulations exhibited fluid loss exceeding acceptable thresholds and compressive strength below the required minimums; nanomodified compositions demonstrated a fluid loss reduction of up to 40% with SiO₂ addition and a 15–25% increase in early compressive strength with Al₂O₃.

Conclusion: The introduction of nanocomposite additives is technically justified for overcoming the limitations of conventional cement systems under Western Kazakhstan field conditions.

Keywords: cement slurry; well cementing; nanomaterials; nanocomposites; cement sheath strength; fluid loss; two-stage cementing; zonal isolation.

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Оригинальное исследование

Повышение качества цементирования скважин с применением нанокompозитов: анализ промысловых данных и оценка их влияния на свойства цементного раствора

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АННОТАЦИЯ

Обоснование. Сложные геологические и термобарические условия месторождений Западного Казахстана предъявляют повышенные требования к системам цементных растворов, тогда как стандартные рецептуры на основе портландцемента нередко не обеспечивают надлежащей зональной изоляции на протяжении всего производственного цикла скважины.

Цель. Настоящее исследование направлено на выявление ключевых ограничений традиционных составов цементных растворов и обоснование целесообразности введения наночастиц SiO_2 , Al_2O_3 и углеродных нанотрубок для улучшения реологических и механических характеристик цементных растворов.

Материалы и методы. Сравнительный анализ проводился на основе фактических данных программ цементирования скважины на месторождении Уз Северный и скважины на месторождении Западная Прорва с оценкой плотности, вязкости, времени загустевания, водоотдачи и прочности на сжатие.

Результаты. Стандартные рецептуры демонстрировали водоотдачу, превышающую допустимые пороговые значения, и прочность на сжатие ниже требуемых минимальных показателей; наномодифицированные составы показали снижение водоотдачи до 40% при введении SiO_2 , увеличение ранней прочности на сжатие на 15–25% при добавлении Al_2O_3 .

Заключение. Введение нанокompозитных добавок признано технически обоснованным для преодоления ограничений традиционных цементных систем в условиях месторождений Западного Казахстана.

Ключевые слова: цементный раствор, цементирование скважин, наноматериалы, нанокompозиты, прочность цементного камня, водоотдача, двухступенчатое цементирование, зональная изоляция.

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Түпнұсқа зерттеу

Нанокөмпозиттерді қолдану арқылы ұңғыманы цементтеу сапасын жақсарту: тампонаждық ерітінді қасиеттеріне әсерін бағалау

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АННОТАЦИЯ

Негіздеу. Батыс Қазақстан кен орындарының күрделі геологиялық және термобарикалық жағдайлары цемент ерітінділері жүйелеріне жоғары талаптар қояды, ал портландцементке негізделген стандартты рецептуралар ұңғыманың өндірістік циклі бойына тиісті аймақтық оқшаулауды жиі қамтамасыз ете алмайды.

Мақсаты. Бұл зерттеу дәстүрлі цемент ерітінділері құрамының негізгі шектеулерін анықтауға және цемент ерітінділерінің геологиялық және механикалық сипаттамаларын жақсарту үшін SiO_2 , Al_2O_3 нанобөлшектері мен көміртекті нанотүтіктерді енгізудің орындылығын негіздеуге бағытталған.

Материалдар мен әдістер. Салыстырмалы талдау «Ұаз Солтүстік» кен орнындағы ұңғымасының және «Батыс Прорва» кен орнындағы ұңғымасының цементтеу бағдарламаларының нақты деректері негізінде жүргізілді; тығыздық, тұтқырлық, қатаю уақыты, сұйық бөліну және қысымға беріктік бағаланды.

Нәтижелері. Стандартты рецептуралар рұқсат етілген шектерден асатын сұйық бөліну мәндерін және қажетті ең төменгі көрсеткіштерден төмен қысымға беріктікті көрсетті; наномодификацияланған құрамдар SiO_2 қосқанда сұйық бөлінуді 40%-ға дейін азайтты, Al_2O_3 қосқанда ерте беріктікті 15–25%-ға арттырды.

Қорытынды. Нанокөмпозиттік қоспаларды енгізу Батыс Қазақстан кен орындары жағдайында дәстүрлі цемент жүйелерінің шектеулерін жеңу үшін техникалық тұрғыдан негізделген деп танылды.

Негізгі сөздер: тампонаждық ерітінді, ұңғыманы цементтеу, наноматериалдар, нанокөмпозиттер, цемент тасының беріктігі, сұйықтық сіңіруі, екі сатылы цементтеу, зоналық оқшаулау.

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Introduction

The quality of casing cementing is one of the key factors determining the reliability of well completion and the long-term efficiency of well operation. In mature oil fields of Western Kazakhstan, characterized by high water cut and complex geological and technical conditions, the task of ensuring the integrity of the annulus is of paramount importance [1]. Conventional cement slurry formulations based on Class G cement with traditional additives of fluid loss reducers, retarders, and defoamers often do not provide a sufficient level of strength and durability of the cement sheath under aggressive reservoir conditions, which is especially critical when performing multi-stage cementing of deep wells [2].

In recent years, the potential of nanomaterials as functional additives to cement slurries has been actively investigated in world oil industry practice. Nanoparticles of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), and carbon nanotubes (CNTs), when introduced at concentrations from 0.1 to 3.0% BWOC, can radically change the microstructure of cement hydration products, reduce porosity and permeability, increase compressive strength, and improve resistance to aggressive formation fluids [3, 4]. The mechanism of action of nanomaterials is based on the creation of additional C-S-H gel, filling of nanopores and the formation of a reinforcing network in the cement matrix, providing a synergistic effect in improving physical and mechanical properties of the cement sheath [5]. The present work aims, on the basis of real field data from cementing programs of well US-I (North Uaz field, 2025) and two-stage cementing of well G-I (Western Provrva field, 2025), to carry out a comprehensive comparative analysis of cement slurry formulations used, identify their weaknesses, and substantiate specific directions for nanocomposite application to improve the efficiency and reliability of cementing under various geological and technical conditions of the Western Kazakhstan region.

Three cementing intervals in two wells located in the Atyrau region of the Republic of Kazakhstan were used for the study. The main geological and technical parameters are presented in Tab. 1.

The fundamental difference between the analyzed wells lies in the thermobaric conditions and the depth of productive horizons. Well US-I is representative of mature oil fields with a relatively shallow depth (approximately 1050 m) and moderate bottom-hole temperature of 34°C, which are characteristic of water-flooded reservoirs with a long production history. Under these conditions, the primary challenges are ensuring sufficient strength of the lightweight cement slurry and controlling fluid loss at a high water-to-cement ratio.

Well G-I at the Western Provrva field is characterized by significantly more complex conditions and was cemented using a two-stage cementing scheme with a stage cementing collar (SCC) at a depth of 1450 m. The first cementing stage covers

the interval from 2400 m to 1430 m with a bottom-hole static temperature of 72°C, requiring the use of a setting retarder and comprehensive control of rheological parameters. The second stage is performed after opening the SCC ports and provides isolation of the upper interval from the surface to a depth of 1450 m at a static temperature of 63°C. This two-stage technology optimizes slurry parameters for different thermobaric conditions along the wellbore depth and is widely recognized as the standard practice for completing deep wells [6, 7].

Materials and methods

The study draws on actual cementing program documentation for three intervals across two wells in the Atyrau region of Kazakhstan: single-stage cementing of well US-I at the North Uaz field and two-stage cementing of well G-I at the Western Provrva field. The two wells were selected based on contrasting downhole conditions. Well US-I is a shallow, water-flooded well with a casing shoe at 1049.69 m and a static temperature of 34°C; well G-I is a deep, high-temperature well with a first-stage shoe at 2400 m and a stage cementing collar set at 1450 m. All three cementing intervals used Class G cement as the base, with additive packages tailored to the respective conditions: fluid loss reducer FL-1 (US-I) and HALAD-344/HALAD-413 (G-I), retarder HR-5 (G-I first stage only), expansive agent, defoamer D-Air 5000, and plasticizer. Slurry densities ranged from 1.60 g/cm³ for the lightweight system at US-I to 1.89 g/cm³ for the heavyweight and G-I formulations, with water-to-cement ratios between 0.44 and 0.82. Laboratory testing was conducted in accordance with ISO 10426-2. Measured parameters included compressive strength at 24 and 48 hours, API fluid loss (30 min), free water, slurry spread, thickening time to 40 Bc, and initial set time. Fann viscometer readings at 600 rpm were taken at both ambient (25°C) and elevated temperatures (40–48°C), with test temperatures assigned individually for each slurry based on the calculated circulating temperature of the respective interval.

For well G-I, the cementing process was modeled in Halliburton's iCem® software in both 2D and 3D modes. Inputs included a dynamic temperature profile, fluid density hierarchy, pump schedule, and a +50% washout factor from caliper data. Centralizer placement was optimized using the Soft String method. Model outputs comprised the ECD profile along the wellbore, predicted STOP pressure at plug landing, and mud displacement efficiency.

The evaluation of nanomodified formulations was carried out as a quantitative desk study, applying improvement coefficients from peer-reviewed literature [8–10] to the baseline values recorded in the field programs. Three nanoadditive types were assessed: nano- SiO_2 (10–50 nm, 1.5–2.0% BWOC), nano- Al_2O_3 (0.5–1.0% BWOC), and multi-walled CNTs (0.3% BWOC).

Results

Laboratory Research Results
and Hydrodynamic Modeling

Laboratory tests of cement slurries were conducted in accordance with the requirements of ISO 10426-2

and included determination of compressive strength, fluid loss, free water, spread, thickening time and setting times. Results are presented in Tab. 2. Analysis of the experimental data obtained reveals a number of critical aspects requiring technological improvement.

Table 1. Comparative characteristics of the wells and cementing parameters

Parameter	US-I North Uaz	G-I (1st stage) Western Provro	G-I (2nd stage) Western Provro
Work type	Casing cementing.	1st stage casing cementing	2nd stage casing cementing
OD casing, mm	168.3	177.80	177.80
ID casing, mm	153.7	159.42	159.41
Shoe depth, m	1049.69	2400.0	1450.0
Borehole diameter, mm	215.9	216.0	215.9
Washout factor	1.15	+50%	+50%
Static temperature, °C	34	72	63
Circulating temperature, °C	30	40	40
Mud density, g/cm³	1.23	1.32	1.32
STOP pressure, bar	114.5	110	160
Cement top, m	to surface	1430	to surface
WOC	48 h	per CBL	72 h min
Maximum ECD, SG	—	1.68	1.68

OD – Outer Diameter; ID – Inner Diameter; WOC – Waiting on Cement; ECD – Equivalent Circulating Density; SG – Specific Gravity; CBL – Cement Bond Log

Table 2. Laboratory test results of cement slurries

Parameter	US-I LCS 1.60 g/cm³	US-I HCS 1.85 g/cm³	G-I (1st st.) 1.89 g/cm³	G-I (2nd st.) Lead 1.89 g/cm³	G-I (2nd st.) Tail 1.89 g/cm³
Test temperature, °C	34	34	47.8	40	40
Strength 24h, MPa	10.2	14.9	—	—	—
Strength 48h, MPa	12.4	17.2	—	—	—
Fluid loss, ml/30min	110	76	—	142.4	—
Fluid loss 40°C/68bar	—	—	—	52.0	—
Free water, ml	0.0	0.0	—	0.0	0.0
Spread, mm	245	230	—	—	—
Thickening time to 40 Bc, min	255	250	—	358	310
Initial setting time, h:mm	05:25	05:45	—	—	—
Fann reading 600/25°C	—	—	200	186	149
Fann reading . 600/40-48°C	—	—	190	181	—

LCS – Light Cement Slurry; HCS – Heavy Cement Slurry

The strength of the lightweight cement slurry of Well US-I at 10.2 MPa after 24 hours at 34°C is at the lower boundary of acceptable values for ensuring reliable zonal isolation. According to ISO 10426-2 and API recommendations, the minimum acceptable cement sheath compressive strength for intervals subjected to formation fluid effects is 13.8 MPa (2000 psi), which is 35% higher than the value achieved for the LCS [11]. Insufficient strength

creates risks to the integrity of the cement sheath under cyclic thermomechanical loads during well operation, especially during stimulation operations or hydraulic fracturing. The fluid loss value of the lightweight slurry at 110 ml/30 min is critically high and indicates intensive dehydration of the slurry upon contact with permeable formations. Excessive water filtration from the cement slurry into the formation leads to the for-

mation of a dehydrated cake at the cement-formation interface, reducing slurry mobility, risk of premature thickening and formation of water channels in the annulus, disrupting the integrity of isolation [1]. For comparison, the heavyweight slurry of the same well demonstrates significantly better fluid loss values (76 ml/30 min) due to the lower water-to-cement ratio and the use of a plasticizer providing the required mobility with less mixing water.

Test results for scavenger cement of the second stage of well G-I show a fluid loss at 30°C at 142.4 ml/30 min, explained by the absence of specialized fluid loss reducers in the composition (only defoamer D-Air 5000 is present). However, when the temperature increases to 40°C and pressure to 68 bar (conditions approximating downhole conditions), the fluid loss decreases to 52.0 ml/30 min due to the thermal acceleration of hydration processes and C-S-H gel formation [6]. For the main cement slurries of the first and second stages, the application of the complex of fluid loss reducers HALAD-344 and HALAD-413¹ ensures the required level of filtration control in the temperature range 40–72°C.

Hydrodynamic modeling of the cementing process for Well G-I using Halliburton's iCem® software² enabled 2D and 3D visualization of fluid distribution in the annulus, calculation of the ECD profile, determination of calculated surface pressure, and assessment of drilling mud displacement efficiency by cement. The 2D modeling results showed that at the completion of cement plug displacement (time 82.87 min for the first stage and 69.73 min for the second stage), the fluid distribution in the annulus corresponds to the design cement-top heights accounting for a 50% excess volume for borehole washout. The calculated STOP pressure at displacement plug seating is 110 bar for the first stage and 160 bar for the second stage, which correlates with the actual hydrostatic pressure values of the fluid column in the casing and annulus [6, 7].

Comparative Analysis of Technological Approaches and Identification of Problem Areas

A detailed comparison of the cementing programs for wells US-I and G-I allows identifying fundamental differences in technological approaches, conditioned by differences in geological and technical conditions, customer requirements, and the level of technical support of service companies. Data are presented in Tab. 3.

The cementing program for Well G-I, demonstrates a significantly higher level of engineering preparation of the operation, including mandatory three-dimensional computer modeling in the specialized iCem® software package, dynamic cal-

culatation of the temperature profile accounting for heat exchange between injected fluids and rock formations, casing centralizer optimization using the Soft String method, and application of a two-stage buffer system for improved borehole cleaning from drilling mud. Fluid loss control is ensured by application of two specialized fluid loss reducers (HALAD-344 and HALAD-413), working synergistically over a wide temperature range. The rheological hierarchy of fluids is strictly controlled by measuring viscosity at several temperatures and shear rates, allowing prediction of displacement efficiency and minimization of channeling risk.

Table 3. Comparison of technological approaches to cementing

Comparison criterion	US-I	G-I
Volume calculation	Manual (Excel)	iCem® 3D
Hydraulic modeling	Simplified	2D/3D iCem®
Temperature profile	Static	Dynamic
Buffer system	Simple (1 buffer)	Two-stage
Fluid loss control	1 additive (FL-1)	2 additives HALAD
Retarder	Not required	HR-5 (mandatory)
Centralizer design	Standard	iCem® Soft String
Quality criterion	24/48-h compressive strength	CBL ≥80%
Rheology control	Not controlled	Strictly maintained
Nano-additives	None	None

HR – High-temperature Retarder

Despite the indicated differences in technological approaches, both cementing programs demonstrate a common problem – the absence of nanomaterial application for targeted improvement of physical-mechanical characteristics of cement slurries. The identified deficiencies of existing formulations, such as insufficient strength of the lightweight cement slurry (10.2 MPa versus the normative 13.8 MPa), high fluid loss (110 ml/30 min), elevated water-to-cement ratio ($W/C = 0.82$) and risks of retrogressive strength degradation at high temperatures (72°C for the first stage of G-I), can be effectively eliminated by introducing specially selected nanocomposites at concentrations of 0.5–3.0% BWOC [12].

Application of Nanomaterials for Improving Cement Slurry Characteristics

World experience from laboratory studies and field trials convincingly demonstrates that introducing nanoparticles into cement slurries radically changes the microstructure of cement sheath at the nanometer scale, providing a synergistic effect in improving strength, filtration, and adhesion characteristics.

¹ HALAD-344 and HALAD-413 – are liquid fluid loss control additives for cement slurries manufactured by Halliburton. Official website: www.halliburton.com

² the iCem® software – is a cementing design and simulation platform developed by Halliburton. It enables 2D/3D hydraulic modeling of the cementing process, dynamic temperature profiling, ECD calculation, centralizer optimization, and real-time job monitoring.

The mechanism of action of nanomaterials is realized through a complex of physicochemical processes, including the formation of additional nucleation sites for hydration phases, the filling of nanopores by filler particles, the pozzolanic reaction with calcium hydroxide, and the creation of a reinforcing network in the cement matrix [8–10].

Nanoparticles of Silicon Dioxide (nano-SiO₂)

Silicon dioxide nanoparticles are the most studied and widely used type of nanomodifiers for cement slurries due to the combination of high efficiency, chemical stability, and processability of introduction into cement systems. The mechanism of cement sheath strengthening when introducing nano-SiO₂ is based on the pozzolanic reaction: amorphous SiO₂ nanoparticles 10–50 nm in size enter into chemical interaction with calcium hydroxide Ca(OH)₂, a product of Portland cement hydration, forming additional C-S-H calcium silicate hydrate gel according to the reaction: SiO₂ + Ca(OH)₂ + H₂O → C-S-H. The C-S-H gel has high strength and fills capillary pores in the cement stone structure, reducing overall porosity and permeability of the material [8].

Experimental studies show that with the addition of nano-SiO₂ at concentrations from 1.0 to 3.0% BWOC, an increase in compressive strength of 25–45% compared to the base composition without nanoparticles is observed, a decrease in water permeability coefficient of 60–80%, and a reduction in free water of 70–90%. The optimal concentration of nano-SiO₂ for most cement systems is in the range of 1.5–2.5% BWOC, since further increase in dosage leads to agglomeration of nanoparticles and reduction of their distribution efficiency in the slurry volume [8, 9].

Nanoparticles of Aluminum Oxide (nano-Al₂O₃)

Aluminum oxide nanoparticles provide a mechanism of cement matrix densification by filling nanopores smaller than 100 nm and forming additional bonds in the aluminate phase of cement hydration products. Unlike nano-SiO₂, whose pozzolanic activity manifests mainly at normal and moderately elevated temperatures, nano-Al₂O₃ demonstrates high efficiency at temperatures above 60°C, providing stabilization of cement sheath strength and preventing retrogressive degradation of mechanical properties characteristic of Class G cement systems under prolonged curing at elevated temperatures [9, 10].

Effective concentration of nano-Al₂O₃ for cement slurries is 0.5–2.0% BWOC. At a dosage of 1.0% BWOC, an increase in compressive strength of 15–25% and reduction in permeability of 40–60% are observed at temperatures of 60–90°C. Nano-Al₂O₃ is of particular importance for cementing deep wells with bottomhole temperatures exceeding 60°C, where standard Class G cement formulations without nanomodifiers are subject to strength reduction of 20–30% during the first

6–12 months of operation due to structural rearrangements in the crystal lattice of hydrate phases. For well G-I at the Western Prorva field with a static bottomhole temperature of 72°C (first stage), introduction of nano-Al₂O₃ at a concentration of 1.0% BWOC is critically important for ensuring long-term integrity of the cement sheath. Modeling of the strength kinetics of modified cement sheath shows that application of nano-Al₂O₃ allows stabilizing strength at 95–100% of the initial value for at least 5 years of well operation at 72°C, whereas unmodified cement demonstrates strength reduction to 70–75% of the initial level over the same period [9].

Carbon Nanotubes

Carbon nanotubes are cylindrical nanostructures 1–50 nm in diameter and from hundreds of nanometers to several micrometers in length, possessing exceptionally high tensile strength (up to 130 GPa) and elastic modulus (up to 1 TPa). Introduction of CNTs at concentrations of 0.1–0.5% BWOC into cement slurry leads to the formation of a three-dimensional reinforcing network in the hardened cement sheath at the nanoscale level, which effectively prevents the initiation and propagation of microcracks under the action of thermomechanical stresses, cyclic loads, and shrinkage deformations [10]. Experimental studies show that using CNTs at a concentration of 0.3% BWOC increases the tensile strength of the cement sheath by 35–50%, increases the elastic modulus by 20–30%, and increases fracture toughness (critical stress intensity factor) by 40–60% compared to unmodified cement. CNTs are of particular importance for wells subjected to intensive temperature cycling during periodic hot water or steam injection, as well as for wells in seismically active regions where the cement sheath experiences dynamic loads from ground vibrations.

Hybrid Nanocomposites SiO₂/Al₂O₃

The most promising direction for the development of cement slurry nanomodification technology is the application of hybrid binary systems containing two types of nanoparticles in a certain ratio. The combination of nano-SiO₂ and nano-Al₂O₃ in a ratio of 2:1 at a total concentration of 2.0–3.0% BWOC provides a synergistic effect exceeding the simple sum of the effects from separate application of each component. The mechanism of synergy lies in the fact that nano-SiO₂ ensures formation of additional C-S-H gel through the pozzolanic reaction, while nano-Al₂O₃ stabilizes the formed structure through the formation of aluminate bonds and prevention of retrogressive transformations at elevated temperatures [8, 9].

Laboratory tests of hybrid SiO₂/Al₂O₃ nanocomposites show an increase in compressive strength after 24 hours of 40–55% compared to base cement, reduction in fluid loss of 65–75%, decrease in permeability coefficient of 70–85%, and improve-

ment of cement sheath adhesion to the steel surface of the casing by 20–30%. Application of hybrid $\text{SiO}_2/\text{Al}_2\text{O}_3$ nanocomposite (2:1) at a concentration of 2.5% BWOC for the lightweight cement slurry of well US-I will theoretically ensure achievement of strength 14.8–15.8 MPa after 24 hours at 34°C, fluid loss at 35–45 ml/30 min, and a water-to-cement ratio reduced to $W/C = 0.65\text{--}0.70$ while maintaining the required slurry density of 1.60 g/cm³.

Risk Assessment and Recommendations for Nanocomposite Application

Comprehensive analysis of data from three cementing programs (US-I, G-I first stage, G-I second stage) allows formulating targeted recommendations for the application of nanomaterials to eliminate specific identified problems and improve the reliability of zonal isolation. Systematized recommendations are presented in Tab. 4.

Table 4. Targeted recommendations for nanoadditive application

Identified problem	Well	Recommended nanocomposite	Dosage, % BWOC	Expected effect
Low LCS strength (10.2 MPa)	US-I	Nano- SiO_2	2.0	+40% → 14.3 MPa
High fluid loss (110 ml/30min)	US-I	Nano- SiO_2 + FL-1	1.5+0.6	→60 ml/30 min
Degradation at $T > 60^\circ\text{C}$	G-I (1)	Nano- Al_2O_3	1.0	Stabilization 92.5% for 5 years
Channeling	All	Nano- SiO_2 / CNT	0.5–1.0	+20% adhesion
$W/C = 0.82$ in LCS	US-I	Nano- SiO_2	2.0	$W/C \rightarrow 0.65\text{--}0.70$
Rheological instability at 72°C	G-I (1)	Nano- Al_2O_3 + HR-5	0.5+0.25	Viscosity stabilization
Microcracks during workover	US-I	CNT	0.3	+45% fracture toughness

Key risks when using standard formulations without nanomaterials include insufficient strength of the cement sheath in intervals with lightweight slurries, which creates prerequisites for integrity violations under cyclic thermomechanical loads characteristic of well operation at mature fields; high fluid loss leading to formation of fluid channels in the annulus and migration of formation fluids; and retrogressive strength degradation under prolonged curing at temperatures above 60°C, which is especially critical for deep wells such as G-I.

Both cementing programs of Well G-I provide as quality assessment criteria the conduct of CBL with a requirement for complete bonding of not less than 80% throughout the entire wellbore and not less than 80% in the productive interval. Risk analysis in the programs directly points to channeling risks with insufficient borehole cleaning from drilling mud and non-optimal casing centralizer placement. Application of nano- SiO_2 at concentrations of 1.5–2.0% BWOC contributes to improving the thixotropic properties of the cement slurry, which reduces the probability of channeling through faster formation of structural gel strength immediately after cessation of shear influence during slurry displacement [6, 7].

The cementing program for Well G-I prescribes mandatory three-dimensional hydraulic process modeling in the iCem® software package prior to work commencement. Entering the rheological characteristics data of the nanomaterial-modified cement slurry into the iCem® simulator will allow more accurate prediction of the ECD profile, optimization of pump rates for different stages (spac-

er, buffer, cement, displacement) and minimization of the risks of lost circulation or hydraulic fracturing during the primary cementing operation.

Mechanism of Nanocomposite Effect on Cement Sheath Structure

From the perspective of physical chemistry of cement hardening processes, introduction of nanoparticles into cement slurry activates four interrelated mechanisms for forming a dense and strong structure of hydrated cement stone.

The first mechanism is the pore filling effect (filler effect) – is realized because nanoparticles 10–100 nm in size are able to penetrate and fill inter-grain voids in the cement gel structure, inaccessible to standard mineral admixtures of micrometer size. The nanoscale of particles ensures their uniform distribution in the volume of the cement matrix and effective filling of capillary pores 50–500 nm in diameter, which form due to evaporation of excess mixing water. The total open porosity of hydrated cement stone when introducing nanoparticles at a concentration of 2.0% BWOC is reduced by 15–30% compared to the unmodified composition, which proportionally improves mechanical strength and reduces fluid permeability [8].

The second mechanism is the acceleration of cement hydration – is due to the fact that nanoparticles act as additional crystallization centers for hydrate phases C-S-H, C-A-H and $\text{Ca}(\text{OH})_2$. The high specific surface area of nanoparticles (for nano- SiO_2 , up to 200–300 m²/g) ensures a manifold increase in the interfacial surface area and intensification of nucleation processes of hydrate crystals

on the surface of nanoparticles. This leads to acceleration of early strength development of cement sheath by 20–40% during the first 12–24 hours of curing, which is especially important when performing operations requiring reduction of WOC time to minimize well downtime [9].

The third mechanism is the pozzolanic activity of nano-SiO₂ – consists in the chemical reaction of amorphous silicon dioxide nanoparticles with calcium hydroxide released during hydration of Portland cement minerals (mainly alite C₃S and belite C₂S), forming additional C-S-H gel according to the reaction: $n\text{-SiO}_2 + m\text{-Ca(OH)}_2 + p\text{-H}_2\text{O} \rightarrow (\text{CaO})_m \cdot (\text{SiO}_2)_n \cdot (\text{H}_2\text{O})_p$. The formed pozzolanic C-S-H gel has a low Ca/Si ratio (approximately 1.2–1.5 versus 1.7–2.0 for primary gel), providing denser packing of the structure and enhanced chemical resistance to aggressive environments. Binding of free calcium hydroxide into additional C-S-H eliminates weak zones in the cement sheath structure formed by local accumulation of portlandite crystals and increases the long-term strength and resistance of cement sheath to leaching under conditions of mineralized formation water circulation [8, 9].

The fourth mechanism is the reinforcing effect of carbon nanotubes. It is based on the formation in the cement matrix volume of a three-dimensional network of nanoscale CNT fibers, which effectively prevents the propagation of microcracks initiated under the action of thermomechanical stresses, shrinkage deformations and external loads. The high tensile strength of carbon nanotubes (up to 130 GPa) and their ability to bridge microcracks with opening widths from nanometers to a few micrometers provides a manifold increase in fracture toughness of cement sheath and its resistance to cyclic loads.

Discussion

The comparative analysis reveals a clear technological gap between the two cementing programs. Well US-I, designed with manual calculations and a simplified hydraulic model, produced a lightweight slurry with compressive strength of 10.2 MPa at 24 hours – 26% below the ISO 10426-2 minimum of 13.8 MPa. Well G-I, engineered with full 3D modeling in iCem® and a two-component fluid loss system (HALAD-344/HALAD-413), demonstrated substantially better rheological control. This contrast confirms that engineering preparation quality directly determines the baseline properties of the cement system.

The fluid loss value of 110 ml/30 min for the US-I lightweight slurry represents the most critical limitation. At this level, dehydration upon contact with permeable formations is sufficient to cause premature thickening and water channel formation in the annulus. For the second-stage lead slurry of Well G-I, fluid loss dropped from 142.4 ml/30 min at 30°C to 52.0 ml/30 min under downhole conditions (40°C, 68 bar), indicating partial self-mitigation through accelerated C-S-H gel formation.

The first-stage cement of well G-I faces a separate problem: retrogressive strength degradation above 60°C. Class G cement undergoes structural rearrangement of hydrate phases at 72°C, causing a 20–30% strength reduction over five years – a mechanism that retarder HR-5 does not address.

The proposed nanocomposites target each failure mode through distinct mechanisms. Nano-SiO₂ (1.5–2.0% BWOC) raises projected 24-hour strength at US-I to 14.3–15.8 MPa and reduces fluid loss to 35–60 ml/30 min via the pozzolanic reaction. Nano-Al₂O₃ (1.0% BWOC) stabilizes cement sheath strength at 92–100% of its initial value over five years at 72°C for G-I's first stage. CNTs (0.3% BWOC) increase fracture toughness by 35–50%, relevant for wells subject to cyclic mechanical loading during workovers.

A key practical constraint is compatibility: at concentrations above 2.5% BWOC, nanoparticle–polymer interactions can increase slurry viscosity beyond pumpable limits. Pre-screening under laboratory conditions and re-modeling of the ECD profile in iCem® with updated rheological parameters are required before field implementation.

Conclusion

Based on detailed analysis of actual cementing programs for Well US-I at the North Uaz field and two-stage cementing of Well G-I at the Western Prorva, the following key findings have been established.

Standard cement slurry formulations based on Class G cement with traditional additives of fluid loss reducers, retarders, expansive agents, and defoamers provide minimally acceptable physical-mechanical characteristics, which under the conditions of mature fields operation with aggressive formation fluids and the necessity of performing production stimulation operations are insufficient. The strength of the lightweight cement slurry of Well US-I at 10.2 MPa after 24 hours at 34°C does not comply with the minimum standard of ISO 10426-2 (13.8 MPa), fluid loss of 110 ml/30 min is critically high and creates risks of slurry dehydration and channeling, and the water-to-cement ratio W/C = 0.82 leads to formation of excess capillary porosity and reduction of cement stone durability.

Well G-I with a first-stage shoe depth of 2400 m, static bottomhole temperature of 72°C and application of two-stage cementing technology with SCC at a depth of 1450 m demonstrates a significantly higher level of engineering preparation of the operation, including three-dimensional modeling in iCem®, dynamic temperature profile calculation, centralizer optimization, and application of a two-stage buffer system. However, even when using modern Halliburton technologies, the program does not include nanomaterial application, which creates risks of retrogressive cement sheath strength degradation of 20–30% during the first 5 years of operation at 72°C due to structural rearrangements in the hydrate phases of Class G cement.

The application of nanocomposites in combination with modern cementing process design methods (3D modeling in iCem®, centralizer optimization, extended laboratory testing, cement bond log for quality control) represents a promising direction for the development of cementing technology at Western Kazakhstan fields and is recommended for laboratory validation under simulated reservoir conditions of the North Uaz and Western Prorva fields.

The integration of nanomaterial technology into well cementing practice represents not merely a gradual

improvement of existing approaches, but a qualitative transition to a new paradigm of zonal isolation capable of reliably functioning under complex thermomechanical and chemical conditions of mature hydrocarbon fields. As demonstrated through quantitative analysis of actual field programs, systematic application of specially developed nanocomposites can transform marginal cementing operations with limited reliability into highly effective long-term zonal isolation systems, ensuring safe and economically viable operation of oil and gas wells.

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