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LOW-DENSITY CEMENT COMPOSITIONS FOR WELL CEMENTING UNDER ABNORMALLY LOW RESERVOIR PRESSURE CONDITIONS

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The paper considers variants of lightweight cement compositions with additives of various substances, such as clay components, ash systems, silica additives, kerogen, gilsonite, microspheres, as well as the process of cement slurry aeration. Recommendations on the use of compositions in different conditions are presented. A decrease in the density of the solution is achieved not only due to the low density of the materials used, but also as a result of an increase in the water-cement ratio. In such conditions, it is not possible to ensure the formation of a durable and impermeable cement stone in the well, which creates high quality inter-reservoir insulation. The characteristics of the physical and mechanical properties of existing lightening additives are given, which allows determining the most rational conditions for the use of cement slurries for improvement of the well cementing quality.

***Key words*:** cement slurry; abnormal low reservoir pressure; cementing; lightweight additives

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Introduction. At drilling of oil and gas wells, one of the main and most difficult tasks is to improve the quality of the inter-reservoir isolation in the casing annulus. This problem is relevant for the fields in Western and Eastern Siberia, a characteristic feature of which is the presence of permafrost and formations with abnormal low reservoir pressure (ALRP). If wells are lined in such conditions, the cement slurry is often absorbed, and the formation is contaminated by its filtrate and solid phase, which leads to a significant deterioration of the borehole bottom zone properties. Furthermore, there is an underlift of cement slurry to the project depth with the subsequent occurrence of complications in the uncemented interval of the wellbore [11, 17, 18].

Statement of the problem. In many cases, at well lining with ALRP, there is low quality cementing of the production casing in the reservoir interval, which creates conditions for inter-reservoir fluid flows. In addition, a high differential pressure arising in a well at high-density cement slurry pumping results in its absorption by the reservoir and under-lifting to the required level in the annulus [10].

In this regard, research in the field of development of new lightweight cement slurries with improved technological properties are relevant for the oil and gas industry. In this paper, the authors present various types of additives recommended for use in low-density cement mixtures at the construction of oil and gas wells. The possibility of using lightweight additives in the composition of the cement slurry for various well conditions is estimated.

Discussion. ***Industry-produced lightweight cements.*** Cement solutions with a density of 1650-1350 kg/m^3 and below are used for cementing the upper sections of deep well casing, for significant height of cement slurry, abnormal low reservoir pressures and for the elimination of drilling mud absorption. According to GOST 1581-96, PCTSh-065-50 and PCTSh-065-100 cements (Table 1) are lightweight, obtained by joint grinding of Portland cement clinker (45-75 %) and lightweight additives of various origin or by thoroughly mixing the same components, but separately crushed. In addition, lightweight cement is produced at the place of consumption by adding clay powder (bentonite is recommended), chalk (up to 33 %), asbestos, kerogen, etc. to the Portland cement. Table 1 presents the characteristics of some low-density cement compositions [1, 3].

In the absence of lightweight prefabricated cements, ordinary Portland cement is used according to GOST 1581-96, the density of the solutions from which is reduced in various ways:

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using lightweight additives, low-density binders, aerated cement slurries, increasing the water-cement ratio [4].

Table 1

Technical requirements for lightweight cements

Indicators	PCTSh -065-100 (GOST 1581-96)	OSC (TC 39-01-08-296-86)	OCG (GOST 22237-85, TC 39-01-08-469-93)
Grinding fineness: residue on sieve No. 008 according to GOST 6613-86,%, no more than	12	15	–
Specific surface, m^2/kg, no less than	–	–	1000±300
Application temperature, °C	25-110	120-250	25-100
The density of the cement slurry, kg/m^3, no more than	1450 ±50	1500 ±50	1450 ±50
The spreadability of cement paste, cm, no less than	20	18	18
Setting time:			
beginning, h, no earlier than	–	2	–
finish, h, no later than	–	8	–
Thickening time of cement paste, min, no less than	90	–	90
Rupture strength after 2 days at t = 75 °C, MPa, no less than	1,7	1,5 (1 day)	1,1
Cement composition, %	Clinker (45-55), gaize (27-30), ash of CPS (15-25)	Blast-furnace slag (60), bentonite clay powder (40)	PCT 11-100 or PC400 by GOST 10178-85 (up to 40), blast-furnace slag by GOST 3476-74 (up to 20), tripoli by FST 21-9-81 (up to 55)

Considering the data of Table 1, it follows that with other similar values of the main indicators, the thermal stability of lightweight slag cement (LSC) significantly exceeds this value for cements of the PCTS-065-100 and OCG cements, which indicates the possibility of its use in deep and ultra-deep wells. However, the low spreadability of cement slurry requires the introduction of reagents – plasticizers into the cement mixture.

Lightweight additives must meet the following requirements [21]:

• have density less than 1800 kg/m^3; specific surface of more than 1500 m^2/kg; water demand more than 3 m^3/t; moisture – no more than a binder moisture;

• be non-hygroscopic;

• do not pollute the subsoil and the environment;

• do not deteriorate their properties when exposed to temperature and pressure.

General requirements for all lightening additives: they must maintain the maximum concentration of the binder at low temperatures, and at high temperatures, they must be completely chemically bound to the binder. The mechanism of the effect of such additives on the system stability is that they have greater water demand compared to cement and a more developed specific surface (Table 2).

Next, some variants of lightweight cement slurries with various additives (both natural and artificial) and the possibility of using them for cementing reservoirs with ALRP are considered.

As can be seen in Table 2, microspheres, gilsonite and kerogen have the lowest density of these additives, but due to the fact that gilsonite and kerogen are organic high-molecular polymers, their use in water-based cement compositions presents significant technological difficulties. In this regard, to obtain cement slurries of very low density, it is most efficient to use hollow microspheres, despite their increased cost, as compared with the considered additives.

Table 2

Main characteristics of lightweight additives [2, 8]

Additive	Density, kg/m^3	Specific surface, m^2/kg	Water demand, m^3/kg
Clay powder:			
bentonite	2510-2630	470	1.3-3.0
kaolinite	2510-2700	350	0.9-2.7
Diatomite	2510-2630	–	1.2-2.7
Tripoli	2050-2300	1600-3200	1.4-3.8
Gaize	2200-2400	1600-2000	1.3-2.5
Pumice	2200-2600	800-1800	0.8-1.5
Chalk	2300-2600	–	0.9-1.2
Microfiber asbestos	2400-2700	600-1000	0.6-1.0
Gilsonite	1070	260	n/a
Kerogen	1250	–	3.4
Filtroperlite	1250-1350	250-350	n/a
Expanded perlite sand	2100-2300	2500	6.0-7.0
Expanded vermiculite sand	2100-2300	800	5.5-10.0
Ash of CPS	2000-2200	n/a	5.0-10.0
Grinding dust of asbestos rubber technical products	1950-2200	250-450	0.4-0.7
Rubber crumb	1900-2100	420-480	2.3-2.5
Microspheres	160-420	–	8.0-9.5
Lime	1200-1400	240	0.8-1.2
Aluminum powder	2200-2300	900-1500	n/a
Wood flour	900	1800	n/a

Note. n/a – not available

Mixtures «cement – clay». Clays as sedimentary rocks differ in their mineral composition and properties. For example, the SiO_2 content ranges from 45 to 70 %, CaO – from 0.4 to 6 %, MgO – from 0.01 to 6 %, Na_2O and K_2O – from 0.1 to 3.3 %, i.e. 1.5-2 to 10-15 times. The volume of alkaline clays during swelling increases by 15-20 times, while the volume of alkaline-earth clays increases slightly, the dispersion of clays also differs.

It is known [13] that a decrease in the density of the solution to 1.56-1.43 g/cm^3 is achieved at a water-cement ratio of 0.8-1.1. However, this leads to a sharp decrease in the strength of the cement stone. The gas permeability of the stone, respectively, increases from 8-16 to 28 millidarcies (3:1) and from 3-6 to 2-32 millidarsies (2:1), i.e. the gas permeability of the stone is so great that it becomes practically unusable. As the hardening temperature of the gelcement increases, the gas permeability drops sharply, but it still remains above 1 millidarcy. The strength of the stone also decreases, especially at temperatures above 130 °C. Thus, the optimal conditions for the use of cement-clay mixture (CCM) is a temperature range of 75-130 °C with a water mixture ratio of 0.8-1.1 and a cement-clay ratio of 3:1-2:1, i.e. with the addition to cement of 25-33 % clay, which ensures the production of cement slurry with a density of 1.60-1.45 g/cm^3. At lower hardening temperatures, the amount of clay should not exceed 10 %, which ensures the production of cement slurry with low water loss, but the density of the solution remains high (1.83-1.84 g/cm^3) [6, 19].

It is also possible to use the drilling fluid as a mixing fluid with the condition that it is not treated with chemicals and its mineralization corresponds to the conditions of cementing. The decrease in the bulk cement content and the associated high permeability and contraction are the main cause of the low strength, temperature and corrosion resistance of the CBM cement stone.

Cementing mixtures with industrial waste-based lightening additives. Industrial waste is increasingly used as artificial lightening additives, including fly ash from the burning of coal, shale or peat, waste from various processing plants, ore flotation tailings, dust from cement production, waste from metallurgical plants, etc. [7].

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A distinctive feature of the ashes is the combination of active silica SiO_2 and alumina Al_2O_3, included in their composition with natural high dispersion (S = 2000÷4000 cm^2/g), which eliminates the need for grinding. Moreover, the spherical shape of particles contributes to the increase in the mobility of the cement slurry. The ashes from the burning of coal from different fields differ in the silica content (from 40 to 56 %), as well as the content of non-combustible fuel, which is essential for the hydraulic activity of ashes. In addition, solid fuel combustion technology also affects the reactivity of the ashes. Thus, an increase in the combustion temperature from 1000-1200 °C (grate method) to 1400-1600 °C (dust combustion) adversely affects the hydraulic activity of the ashes. Ashes also differ in dispersion (2000-4000 cm^2/g) and density (2.0-2.4 g/cm^3).

Let us consider the characteristics of the most studied ashes of Aktyubinsk CPS and Dobrotvorskaya GRPS (Table 3). Obviously, a lower bulk density and a large specific surface of Aktyubinsk CPS wastes make them the most attractive lightening additive.

Table 3

Physical properties of ashes

Facility	Bulk density, g/cm^3	Density, g/cm^3	Specific surface, cm^2/g	Sieve residue at particles' size, %	
				0.2 mm	0.7 mm
Dobrotvorskaya GRPS	1.05	2.2	2950	15	22
Aktyubinsk CPS	0.65	2.06	4300	–	–

It is known [6] that the optimum composition for the strength of the cement stone is a composition containing up to 50 % ash. At the same time, the strength of cement stone samples with the addition of 50% ash from the Aktyubinsk CPS and an increase in temperature to 200 °C rises during all periods of hardening (1-7 days). Mixtures on the ash of Dobrotvorskaya GRPS have a thermal resistance limited by a temperature of 150. Thus, lightweight (ρ = 1.50÷1.60 g/cm^3) cement mixtures can be obtained by adding to the cement 50-60 % of dust-like ashes, which can harden in the temperature range of 150-200 °C.

Cement mixtures with silica (pozzolanic) additives. As such lightening additives, which are based on silica (SiO_2), mainly sedimentary rocks (diatomite, tripoli, gaize), volcanic (perlite, pumice, trass, tuff), artificial origin (ashes of CPS, white soot, wastes of superphosphate production, silica gel, etc.). The main difference between these additives and clay powders is that the reactive silicic acid (SiO_2) contained in them interacts with calcium hydroxide released during the hydrolysis of cement minerals to form calcium hydrosilicate of low density and basicity:

$$Ca(OH)_2 + SiO_2 + nH_20 = CaO + SiO_2(n + 1)H_2O.$$

The combination of such additives with various binders allows their use in a wide temperature range, °C:

• with Portland cement – from 60 to 110;
• with Portland cement and quartz sand – from 80 to 200;
• with granulated blast-furnace slag – from 120 to 200;
• with slag-sand cement – from 120 to 200.

The optimal dosage of silica additives of any origin, mixed with fresh and NaCl-mineralized water, is up to 30 % at temperatures up to 60 °C, and those fixed in fresh water – up to 50 % at temperatures up to 110 °C and more. Cements with silica additives are more resistant to suffusion and sulphate aggression, but not sufficiently resistant to polymineral (especially magnesian) and hydrogen sulfide corrosion. Water loss of such mixtures is less, and shrinkage and swelling more than that of Portland cement. The latter factor will contribute to a more dense contact of the cement stone with the borehole wall and the casing body [6, 16].

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The frost resistance of cements with silica additives is lower, the durability after long-term storage also decreases faster than that of Portland cement, due to the high hygroscopicity of active mineral additives [9, 14, 15].

Cement mixtures with additives of organic origin. As lightening additives to Portland cement, kerogen, filtroperlite, gilsonite, etc. are most often used.

With the addition of kerogen, the density of cement slurries decreases due to its low density and to a lesser extent due to the water-mixture ratio, whereas the solutions are sedimentary stable, since water loss is close to zero. To obtain a cement slurry density of 1470 kg/m^3, Portland cement must be mixed with kerogen in a ratio of 67:33 or one bag of cement and kerogen alternately at a water-mixture ratio of 0.67 and a solution output of 1.09 m^3/ton. As can be seen from [20], the ultimate strength of cement stone with the addition of kerogen is significantly higher compared to other lightweight cement mixtures, for example, with LCG or CBM. In addition, the cement stone has an increased corrosion resistance, which is explained by the hydrophobicity of its particles, whose surface prevents the movement of formation water into the pore space due to the large wetting angles, and also by a high content of binder and chemical interaction of the additive with it, due to which pore volume decreases.

Gilsonite is a solid non-porous material of organic origin with ρ = 1070 kg/m^3, bulk density 0.8 g/cm^3, impermeable, chemically inert, resistant to corrosion. The ratio of Portland cement Class A and B – Gilsonite is 80:20 and 65:35 with a water mixture ratio of 0.42 and 0.41. The density of the cement slurry is 1630 and 1500 kg/m^3, and the ultimate strength at compression after 24 hours of hardening (77 °C; 20.68 MPa) is 18.78 and 6.96 MPa. Due to the fact that gilsonite has low density, to increase the stability and homogeneity of the cement slurry, 4% of high-quality bentonite is introduced into the mixture, while the water-mixture ratio is 0.78 and 0.87, the density is 1520 and 1430 kg/m^3, ultimate strength – 7.92 and 7.41 MPa. Gilsonite is available in powder form in bags of 20.7 kg (0.0285 m^3) or 45 kg (0.057 m^3) in the United States [2, 20]. Per 100 kg of gilsonite no more than 33.4 liters of water are consumed. Optimum addition of gilsonite – 138-268 kg/t cement, permissible – 530 kg/t.

Aerated cement slurries. Aerated cement slurries (ACS) are mainly used in countering catastrophic absorption, cementing casing under conditions of abnormally low reservoir pressure and protecting frozen rocks from thawing (ACS has a heat transfer capacity 10 times lower than normal cement slurry). ACS are three-phase foams consisting of solid, liquid and gaseous phases [12].

The composition of the ACS: Portland cement type PCT-1-50 or PCT-II-50 at temperatures from – 10 to 40 °C (if there are aggressive media in the well, the type of cement changes accordingly)

The gas-liquid cement slurry has higher rheological characteristics than conventional cement slurries, and during cementing it contributes to a better removal of drilling fluid in the well.

Cement stone formed from gas-liquid cement mixture, compared with conventional cement slurry, has a plasticity, which exceeds the plasticity of stones obtained from non-aerated cement slurries by an order of ten.

Cement slurries with lightweight microspheres. In recent years, much attention has been paid to the creation of cement compositions with the introduction of microspheres as a lightweight additive. Such solutions may have a density below 1000 kg/m^3 [13].

Hollow polymer microspheres (HPM) are gas-filled (with nitrogen) microspheres with a size of 50-500 μm, a bulk density of 100-250 kg/m^3. They are obtained from phenol-formaldehyde resin with a density of 420 kg/m^3 or a urea-formaldehyde resin with a density of 160 kg/m^3. The optimal addition of HPM is 5-10 % (up to 20 % is allowed) [13].

The ultimate bending strength is significantly higher than, for example, CBM, whereas in order to obtain 1 m^3 of cement slurry, the mass of the dry mixture is only 0.91-0.77 tons. Another important advantage of such mixtures is a high content of binder and increased resistance to aggressive environments.

Implementing hollow ceramic microspheres (HCM), an increase in the density of the solution at 30 MPa is only 0.08-0.12 g/cm^3, and to reduce water loss with an increased water-cement ratio (0.9), additives of CMC, PAA, etc. are used.

Hollow glass microspheres (HGM), including fine-grained (FGHGM), are produced in the form of a white powder with a particle size of 10-180 μm, bulk density and true density, respectively, 0.16-0.4 and 0.7 g/cm^3. Unlike other lightening additives, they are characterized by relatively high durability (up to 18.0 MPa), low dielectric constant values, good heat insulating ability, high adsorption activity to water, and high surface tension. Cement stone has high durability, which is 1.5-2.0 times higher than that of OCG cements and CTO.

In the composition of cement mixtures polymer, aluminosilicate (ceramic or ash), glass (fine-grained glass) microspheres are used.

Industry produces hollow glass microspheres of the grades A1, A2, A3, B1, B2 and MCO-A9, but physical and mechanical properties of these microspheres are different. Density ranges from 120 to 400 kg/cm^3, and hydrostatic compression strength ranges from 10 to 20 MPa.

In addition, high-durability glass microspheres (HDGM) are produced in Russia, shell durability of which for hydrostatic compression exceeds 50 MPa.

An alternative to the well-known glass microspheres are finely dispersed aluminosilicate hollow microspheres (AHM), which are the product of the fuel combustion in thermal power plants or other industries (the product of the fly ash flotation). Aluminosilicate microspheres are lightweight spherical powder, consisting of individual hollow particles having a density of 400-500 kg/cm^3, hydrostatic compression strength up to 35 MPa.

Experimental studies of the physical and mechanical properties of lightweight cement slurries using these additives have established the possibility of effectively reducing the cement slurry density, which is primarily due to the low density of the additive itself. Despite a slightly increased water-mixture ratio (0.6-0.7), the cement compositions are stable and have acceptable indicators of water sedimentation. Durability properties of the forming cement stone exceed the requirements of industry standards for lightweight cement slurries. It is possible to introduce into the composition of the cement slurry nitrilotrimethylphosphonic acid and $CaCl_2$, depending on the temperature and pressure conditions of the lining intervals.

Conclusion. The most common way to obtain lightweight cement slurries is to replace part of the binder with additives, which have a higher specific surface and lower density. The decrease in the density of the solution utilizing such materials is achieved not only due to their low density, but also, as a rule, because of an increase in the water-cement ratio.

Considered lightweight cement solutions, along with a positive effect on the density of cement slurry, have a number of disadvantages. Despite the fact that clay is a natural material, is widely distributed, has a large range of chemical composition and conditions of use, its excess addition in cement slurry leads to a decrease in durability and increase in gas permeability of the cement stone.

When silica additives are used as lightening substances, a higher resistance to suffusion and sulfate aggression is noted, but at low and negative temperatures, the durability of the cement stone decreases. With the addition of kerogen to the cement slurry, the resulting cement stone has a high corrosion resistance.

Aerated cement slurries show their effectiveness in countering catastrophic absorption, cementing casing under conditions of abnormally low reservoir pressure and protecting frozen rocks from thawing, but the depth of the well and the need to use special equipment limits their use.

The inclusion of microspheres in the cement slurry enables to get a density below 1000 kg/m^3, which is an indispensable advantage of this technology, but this leads to a more expensive composition due to the use of special technological processes of its production.

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