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Optimizing Separation of Waste Drilling Muds through Ultraflocculation and Flocculant Selection

Togys KARMANOV*[1], *Nessipbay TUSSUPBAYEV*[2], *Bakytzhan KALIYEV*[1], *Bakhyt ZHAUTIKOV*[3] *and* *Bulbul MAULETBEKOVA*[1]

Authors' affiliations and addresses:
[1] Department of Technological Machines and Transport, Satbayev University, Satpayev Str. 22a, 050013 Almaty, Republic of Kazakhstan
e-mail: karmanov9@hotmail.com
e-mail: kaliyevbakytzhan49@gmail.com
e-mail: bmauletbekova@gmail.com

[2] Laboratory of Flotation Reagents and Benefication, Institute of Metallurgy and Ore Beneficiation, Shevchenko Str. 29/133, 050010 Almaty, Republic of Kazakhstan
e-mail: NTussupbayev@outlook.com

[3] Satbayev University, Satpayev Str. 22a, 050013 Almaty, Republic of Kazakhstan
e-mail: Bakhyt-Zhautikov@protonmail.com

***Correspondence:**
Bulbul Mauletbekova, Satpayev Str. 22a, 050013 Almaty, Republic of Kazakhstan
e-mail: bmauletbekova@gmail.com

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Abstract

The disposal of drilling mud waste from uranium mining operations poses a significant environmental challenge due to their toxicity and potential for contamination. The investigation aims to test different powder flocculants of approximately the same molecular weight and their interaction with waste drilling mud and to identify the flocculant with the best qualities for further use in the industry. The empirical method was applied in the study, during which experiments were carried out on a sample of drilling mud, along with quantitative and statistical analyses. Flocculation was carried out using a Couette cylindrical flocculator. Three flocculants, namely A-150, N-100, N-300, and C-494, from a single manufacturer, Kemira, were also chosen for the study. As a result of the laboratory experiments, it was determined that N-300 was the best flocculant, giving optimum results in the study. It has been found to be capable of separating the drilling mud into water and solids fractions as quickly as possible. In addition, the use of ultra-flocculent treatment to improve the intensity of the sedimentation process of clay suspensions is a prerequisite. Thus, the drilling fluids treated in this way are more environmentally friendly, increase productivity and duration, and reduce production costs. The novelty lies in systematically evaluating various powder flocculants and applying ultraflocculation, a sophisticated hydrodynamic treatment method, to optimize the separation process.

Keywords

DLVO theory, environment, ultrafloccular treatment, suspension, aqueous and solid phases.

Introduction

Uranium mining companies, by means of in-situ leaching (ISL) through the drilling of process wells, namely pumping and injection wells, are working to extract uranium in its deposits. ISL allows the exploration of ore deposits by selectively translating uranium directly into the earth's interior. The drilling of process wells is also accompanied by the removal of the rock that has been drilled during the operation by a flow of flushing fluid, which sends the rock to the surface. This waste has a negative impact on the geological and ecological system when it enters the environment in significant quantities. Drilling mud waste (DMW) is classified as class III-IV toxicity. The composition of these wastes contains heavy and sufficiently reactive elements from the intermediate to the ore horizon of wells. This significantly impacts the ecology of the area where drilling is carried out and drilling fluid waste is stored. Therefore, choosing an environmentally friendly way to dispose of DMW is very important. Therefore, it is very important to choose an environmentally friendly means of disposing of DMW (Antonik et al., 2022; Karmanov et al., 2021; Kuandykov et al., 2020; Akhymbayeva et al., 2021).

Over the past few years, the use of ultrafloccular treatment in suspension separation technology has been gaining popularity (Gu et al., 2022). The effectiveness of the use of flocculants during sedimentation and filtration separation of suspension fractions largely depends on the characteristics of its hydrodynamic treatment mode (medium velocity gradient, G) after introducing the flocculant (Selvakumar et al., 2023; Zhumadullayev et al., 2017). By selecting the appropriate ultra-flocculent treatment mode, the sump performance results are increased, and the number of suspended solids in the drain is reduced. Previously, Paschek et al. (1999) had already studied the hydrophobicity of large molecules but still used more simplified versions of the interaction between molecules and neon atoms, which acted as a hydrophobic particle. Numerous experiments and studies that have been conducted over the past 20 years have shown that the correct selection of the hydrodynamic mode of processing suspensions can reduce the consumption of flocculants and improve filtration processes (Rulyov, 1999a; 1999b). In addition, the operation of the vacuum and belt press filters is accelerated by almost 2 times. The same technology contributes to reducing production costs and enables a closed-loop water system in drilling rigs. This is accomplished by returning the maximum volume of service water (aqueous phase) back into the system.

For this technology to be carried out quickly and efficiently, it is necessary to accelerate and improve the separation of the aqueous and solid fractions of the drilling mud. For this purpose, substances from natural and synthetic high-molecular components or flocculants are used. When introduced into dispersed systems, they are able to adsorb or bind to particles of the dispersed phase, combining particles into floccules and accelerating their deposition. In addition, these reagents are used to thicken the consistency of washing liquids. There is a wide variety of drilling fluids, which has led to the emergence of a wide range of flocculants with unique properties and other technical features (Deryaev, 2023; 2024). The suitable option is selected depending on the cleaning suspension, the cleaning method, and the desired outcomes.

In turn, drilling cuttings are represented by feldspar-quartz based on the characteristics of the composition. The mineral composition of drill cuttings consists mainly of quartz rock varieties (71%). In addition, they contain feldspar 11.5%, muscovite 4.8%, organics 4%, montmorillonite 3%, kaolinite 1.9%, hydromica 1.3%, sulfides 1.2%, biotite 0.2%, carbonates 0.05%, limonite 0.05%, as well as chlorite and epidote. Based on this, it can be said that the solid phase is practically insoluble in water due to the presence of natural formations (Tusupbayev et al., 2020; Chernets et al., 2008). The study analyzed parameters such as the settling rate of particles, volume of thickened material, quality of clarification of the liquid phase of the slurry, and the presence of foam formation on the surface. The study used the UltraFloc-Tester, which acted as a deposition intensifier. The device shows the optimal type and dosage of the flocculant and sets the appropriate mode of hydrodynamic treatment of the suspension.

Based on the performance of this instrument and other studies (Mpofu et al., 2003; Tussupbayev et al., 2018), a suitable flocculant was selected to improve the separation of DMW into aqueous and solid phases. Firstly, in order to guarantee a fair comparison and rule out molecular size as a complicating factor, the flocculants needed to be roughly the same molecular weight. Secondly, the flocculants that were chosen were representative of the three primary charge categories: cationic (C-494), nonionic (N-100, N-300), and anionic (A-150). This made it possible to evaluate how charge parameters affected the drilling mud's ability to flocculate with clay. To guarantee the findings' industrial applicability and scalability, the flocculants also had to be powder formulations that were readily available in the market.

Although flocculation has been used extensively for solid-liquid separation in various industrial applications, its effectiveness mostly depends on the optimized hydrodynamic treatment conditions and the careful selection of the right flocculant suited to the particular suspension properties. The existing body of research predominantly concentrates on flocculation investigations utilizing simulated suspensions or streamlined systems, inadequately addressing the intricate composition and difficulties linked to waste drilling muds originating from uranium mining activities. By methodically examining the efficacy of various flocculant kinds and utilizing the innovative use of ultraflocculation treatment (a sophisticated hydrodynamic approach that creates very turbulent flow regimes), this study seeks to close this crucial gap.

The purpose of the investigation is to test different powder flocculants of approximately the same molecular weight and their interaction with waste drilling mud, which needs to be separated into aqueous and solid fractions for proper and safe disposal and to identify the flocculant with the best qualities for further use in the industry. The research has important applications for the mining and drilling sectors, especially in areas where in-situ leaching is a common method of uranium extraction. Developing effective methods to separate and treat the waste drilling muds generated during well drilling operations is crucial for minimizing the environmental impacts associated with these activities. The capacity to effectively separate the liquid and solid components of drilling mud waste permits appropriate disposal or possible repurposing of the treated streams in accordance with the concepts of environmental stewardship and sustainable resource management.

Material and Methods

To select a flocculant for drilling mud that would be most effective in economic and technological terms, research and experiments were conducted. For this purpose, flocculants of the following types were tested: anionic A-150, nonionic N-100 and N-300, and cationic C-494. All of them were produced by Kemira and have approximately the same molecular weight. As a result of the experiments conducted on three flocculants, a nonionic type N-300 flocculant was selected for subsequent studies. The experiments were carried out on a slurry with a DMW density of 100 g/litre of solid fraction. A 0.05% flocculant solution was poured into measuring glass cylinders, each with a volume of 0.5 dm3 with DMW suspension, and poured to the 500 ml mark. After the slurry had been thoroughly mixed, the required amount of flocculant was injected into the cylinder, after which the slurry was stirred again. Immediately after that, a stopwatch was turned on, and the sedimentation and separation of the solid phase from the liquid phase were monitored. The time of passage of these processes was recorded (Tussupbayev et al., 2018).

The suspension sample that was prepared for the study and the aqueous flocculant solution were passed continuously through the ultraflocculator by pumping on the UltraFloc-Tester. They were mixed and treated in a hydrodynamic flow for 5 to 15 seconds during this process. The sample was then passed through an optical sensor after a certain time, which analyzed and recorded the performance of the flocculation process. The analyses carried out by the optical sensor are through recognition of the strength of the flux that is present in the sample after the ultraflocculator has processed it. It is also possible to change the flocculant dosage (if the pulp flow rate is always 1 cm^3/s) and control the intensity of the hydrodynamic treatment of the suspension (the average speed of the medium varies from 150 to 4000 s^{-1}). The studied sample of suspension and flocculant were mixed in a specific ratio and, with the help of metering pumps of the device, were passed through a cylindrical Couette flocculator, which has a height and diameter of the rotor of 28 mm, and a gap width of 1.5 mm. During this process, they were subjected to hydrodynamic treatment with a specific intensity for a certain period of time. The estimation of the approximate size of the floccules obtained as a result of the experiment in the device was carried out based on the method proposed by scientists Gregory and Nelson (1984). Based on this technique, the suspension obtained from the flocculator was passed through an optoelectronic sensor. In turn, the sensor recorded fluctuations in the intensity of the light beam, which was passed through a stream of suspension moving in a 3 mm channel.

The optical sensor provided a photoelectric signal, which was processed and recorded as a number on the instrument's digital panel, showing the value of flocculation efficiency in relative units. In the first approximation, it was equal to the calculated average size of the floccules. The other instrument display also showed the rotor speed of the flocculator, which determined the average velocity of the medium G, taking into account the corresponding calibration values. The Deryagin, Landau, Fervey, Overbek (DLFO) theory (Deryagin et al., 1985) was used to analyze the pairwise interaction between the solid fraction of the suspension and the flocculant, and features of the wetting edge angle and its constants were used for a more in-depth consideration.

To assess how well various flocculants and treatment settings performed, the data from the flocculation and ultraflocculation tests were put through a rigorous quantitative analysis. The solid-liquid interface's decline over time was tracked, and the data were fitted to suitable kinetic models to determine the sedimentation rates. Using a nephelometric turbidity metre, turbidity measurements were used to evaluate the supernatant's clarity quality. By using the hypothesis put forward by Gregory and Nelson (1984) in conjunction with the light extinction data from the optoelectronic sensor, floccule size distributions were calculated, allowing for the computation of average floc sizes under various circumstances. The study employed statistical analyses, such as analysis of variance and post-hoc testing, to detect noteworthy variations in performance metrics between the flocculants and treatment settings. Multivariate regression techniques were used to determine the quantitative correlations between response variables like settling rates, turbidity, and floc sizes and operating variables like flocculant dosage and hydrodynamic circumstances. The validity and goodness-of-fit of the regression models were assessed using the coefficients of determination and residual analyses. These thorough data analysis techniques made it easier to compare flocculants in a methodical manner, selected optimal process parameters, and clarified the underlying mechanisms controlling the efficacy of flocculation and ultraflocculation in separating waste drilling mud suspensions.

Results

During the flocculation process, the enlargement of the colloidal particles of the DMW solid phase (which have no charge) occurs through the appearance of bonds between the hydroxide molecules of the multi-charged ion, which appeared as a result of the hydrolysis of the coagulant. The floccules themselves are formed by attaching polymeric macromolecules to microflocules that have been formed during coagulation. Often, a flocculant is added to the slurry after the coagulation step to initiate the flocculation process. The formation and bonding of colloidal particles are made stronger, and the bonding and cohesion of particles into larger units are also improved so that these particles will more easily lend themselves to settling processes and are better separated from the liquid fraction of the slurry. In general, the process of combining particles into larger formations can be divided into stages:

- the first stage, or pyrokinetic stage, involves the Brownian motion of particles without charge. This movement results in the formation of microflocculi;
- the second stage, or the stage of orthokinetic flocculation, consists of a movement that is associated with the laminar mixing mode of the suspension.

Despite the fact that the number of particle collisions increases, which leads to the formation of larger floccules, there are also boundary indicators of the mixing rate of the suspension, which leads to the mechanical destruction of already created formations. Consider the performance of DMW sedimentation processes in different situations (Fig. 1). Three options were used: DMW sedimentation without flocculants (first curve), with some N-100 flocculant (second curve), with N-300 flocculant and hydrodynamic treatment at 1500 c^{-1} on the UltraFloc Tester (third curve). A slurry concentration of 100 g/t was used, and the time for processing the slurry in the ultraflocculator was 15 seconds. Looking at the first curve, it is seen that the DMW suspension without the addition of flocculants settles in 60 minutes. At the same time, a foam of less than 5 mm in thickness is formed on the surface of the cylinder, and the aqueous phase of the suspension has a cloudy appearance. Using a dosed amount of 60 g/t flocculant N-100, separating the suspension into aqueous and solid phases takes 20 minutes, with a surface foam up to 2 mm thick and the aqueous phase clear. Using N-100 at a dosage of 50 g/t, a medium velocity gradient of 1500 c$^{-1,}$ and a 15-second treatment on an ultraflocculator, it is observed that the settling time of the slurry solid phase has decreased to 10 minutes. During the same test, it was noted that no foam layer was detected on the surface, and the sediment on the bottom became denser by about 2-3 times compared with previous indicators.

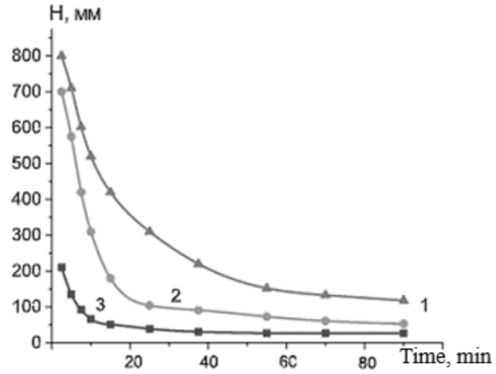

Fig. 1. DMW slurry clarification degree versus time of solids settling. 1 – without flocculants; 2 – with N-100 at 60 g/t; 3 – with N-300 at a medium velocity gradient of 1500 c^{-1} and 50 g/t flow rate.

Based on the experiments, it can be said that the N-300 flocculant with ultraflocculant treatment would be the best choice (Rulyov et al., 2005; Rulyov, 2004). Compared to other treatment methods, this flocculant gives the best results due to the improved flexibility of the polymer chain. Fig. 2 clearly shows the results of a laboratory study of the ultraflocculator treatment of the DMW suspension under investigation, showing the relationship between flocculation efficiency and the consumption of the flocculants themselves. These dependencies were tested with flocculants A-150, C-494, and N-300, treated with an ultraflocculator for 15 seconds and a medium velocity gradient of 1500 c^{-1}.

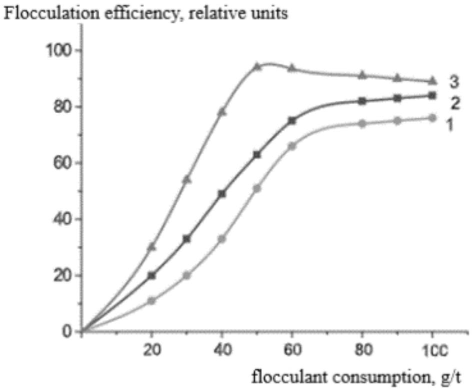

Fig. 2. Investigation of the dependence of the treatment efficiency on the ultraflocculator on the consumption of flocculants. 1 – the use of anionic flocculant A-150; 2 – the use of cationic flocculant C-494; 3 – the use of non-ionic flocculant N-300.

A new study of the flocculant treatment dependencies on flocculant aid consumption showed that N-300 with an optimum flocculant aid consumption of 50 g/t had the best results out of all the flocculants tested. At the same dosage, other studied flocculants showed a lower percentage of the process activity. At the same flow rate, the purity of the drains was observed, and the precipitation density was the highest. With an increase in the dosage and consumption of flocculant, the density of precipitation at the bottom decreased, which is associated with the loose consistency of precipitation. It is worth noting that one of the obvious advantages of processing suspensions in an ultraflocculator is that it is considered to be a cleaner drain after experiments than conventional flocculation in laminar mode. Therefore, it can be said that ultraflocculation treatment of DMW suspensions is more efficient, achieves a cleaner discharge, and also requires less flocculant consumption. In Fig. 3, the results of the experiment related to the dependence of the residual solid phase of the suspension in the drain on the velocity gradient of the ultraflocculator medium are visualized. During the study, the N-300 flocculant with a flow rate of 50 g/t was used, while the concentration of DMW suspension was equal to 100 g/l, and the processing time in the ultraflocculator was 15 seconds. Based on the results obtained, it can be seen that the best results are obtained with an intensity of hydrodynamic treatment equal to 1500 c^{-1}. With conventional treatment at a velocity gradient between 100-300 c^{-1}, the residual DMW concentration in the overflow is large, averaging 200-600 mg/l.

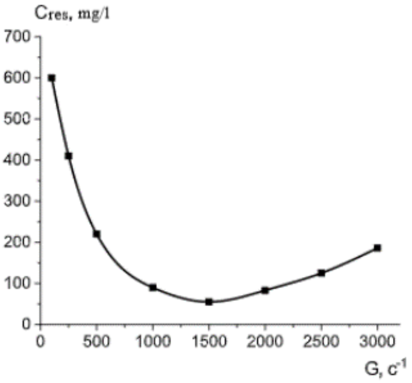

Fig. 3. Study on the dependence of the residual DMW solids concentration in the drain on the velocity gradient of the ultraflocculator medium.

It is also worth noting that in the process of ultraflocculation treatment of the suspension using the optimal amount of flocculant N-300, an acceleration of the precipitation and compaction of the solid phase of precipitation was observed, and changes in precipitation moisture were also identified during the dehydration of the DMW suspension by filtration. Based on the theory of Deryagin, Landau, Fervey, and Overbek (DLFO), it is possible to analyze the pair energy of the interaction between the solid phase of the DMW suspension and the flocculate (Deryagin et al., 1985; Ismayilov et al., 2020). This theory describes the stability of colloidal dispersions. It combines the effects of the two primary forces (the repellent electrostatic forces and the attracting van der Waals forces) acting between colloidal particles. This theory states that a colloidal system's stability is based on how these forces balance out. Particles stay scattered, and a stable colloidal system results when the repulsive electrostatic forces take center stage. The assumptions made in theory were:

1. Particles of the solid phase of the suspension with a size of more than 1 micron are studied.
2. The solid phase particles must be spherical in shape.
3. In the liquid phase of the suspension, the polymer macromolecule should have the shape of a statistical ball, which, in approximation, looks like a sphere.

4. All charged carboxyl groups of the polymer take part in the creation of the surface charge of the tangle.

In the classical DLFO theory, the paired energy of the interaction of particles of the dispersed phase is considered, taking into account the electrostatic component (U_{OTT}) caused by the repulsion of charged ions, as well as the molecular component (U_M) caused by the van der Waals forces of attraction (Yoon & Mao, 1996) (Eq. 1):

$$U_{\text{OTT}} = \frac{\varepsilon_0 \varepsilon r_1 r_2(\varphi_1^2+\varphi_2^2)}{4(r_1+r_2)} * \left[\frac{2\varphi_1\varphi_2}{\varphi_1^2+\varphi_2^2} ln\left(\frac{1+e^{-kh}}{1-e^{-kh}}\right) + ln(1-e^{-2kh})\right], \tag{1}$$

where: ε_0 – absolute permittivity (8.85×10-12 F/m); ε – relative permittivity (for water at T=298, K:80); r_1, r_2 – radii of interacting components, m; φ_1, φ_2 – values of surface potentials, V; h – the distance between surfaces, m; ƙ – Debye radius, m^{-1} (Eq. 2).

$$U_M = \frac{A_{123}^* r_1 r_2}{6h(r_1+r_2)}, \tag{2}$$

where: r_1, r_2 are the radii of the interacting components, m; h – the distance between the surfaces, m; A_{123}^* – the Hamaker constant for the interaction of two components (1 and 2 indices) through the dispersion medium (3 index), J.

The value (at a temperature T=298 K) is calculated by the Eq. 3:

$$ƙ = 3.29 * 10^{9}\sqrt{\mathrm{C}}, \tag{3}$$

where: C is the concentration of the electrolyte in a dispersed medium, mol/L.

It will be easier to calculate the value of U_{GF} using the methodology in (Borts et al., 1989) (Eq. 4):

$$U_{GF} = -\frac{K_H r_1 r_2}{6h(r_1+r_2)}, \tag{4}$$

where: K_H is the constant of hydrophobic interaction of experimental particles through a layer of dispersion medium; r_1, r_2 – radii of interacting components, m; h – distance between surfaces, m (Koltsov & Kondratyeva, 2018).

For particles in the solid fraction of the suspension, the value is K_H calculated as follows (Eq. 5):

$$K_H = a * e^{b*\theta}, \tag{5}$$

where: a and b are experimental constants depending on θ (Tab. 1).

Tab. 1. Indicators of constants a *and* b

Wetting edge angle	*a*	*b*
θ<86.9°	$2.73*10^{-21}$	0.0414
86.9°<θ<92.3 °	$4.89*10^{-44}$	0.6441
θ>92.3 °	$6.33*10^{-27}$	0.2172

Source: Yoon (2000).

Given this, the particles' total interaction energy potential U in the dispersion phase can be expressed in the following Eq. 6:

$$U = U_{\text{OTT}} + U_M + U_{GF} = \frac{\pi\varepsilon_0\varepsilon r_1 r_2(\varphi_1^2+\varphi_2^2)}{r_1+r_2} * \left(\frac{2\varphi_1\varphi_2}{\varphi_1^2+\varphi_2^2} ln\left(\frac{1+e^{-kh}}{1-e^{-kh}}\right) + ln(1-e^{-2kh})\right) - \frac{A_{123}^* r_1 r_2}{6h(r_1+r_2)} - \frac{K_H r_1 r_2}{6h(r_1+r_2)}, \tag{6}$$

where: U_{OTT} is the electrostatic component; U_M is the molecular component; U_{GF} is the hydrophobic component of the interaction energy, J; ε_0 – absolute permittivity (8.85×10-12 F/m); ε – relative permittivity (for water at T=298, ε=80); r_1, r_2 – radii of interacting components, m; φ_1, φ_2 – values of surface potentials, V; h – the distance between the surfaces, m; A_{123}^* – the Hammaker constant for the interaction of two components (1 and 2 indices) through the dispersion medium (3 index), J; ƙ – the Debye length, m^{-1}; K_H – the constant of the hydrophobic interaction of experimental particles through the layer of the dispersion medium (Read, 1971; Nushtayeva, 2019; Averkina et al., 2020).

It should be emphasized that the U_{OTT} value is used with a positive sign, and also has an increase in the distance between the particles in absolute magnitude has a decrease at a more significant rate than that of the values U_M and U_{GF}. As a result, molecular and hydrophobic attractive forces should be considered long-range, different from the force of electrostatic repulsion (Geiger & Paschek, 2007). In turn, the effect of electrostatic repulsion is of greater importance at smaller distances up to about 15-20 nm. The dependence of U values on h is shown in Fig. 4.

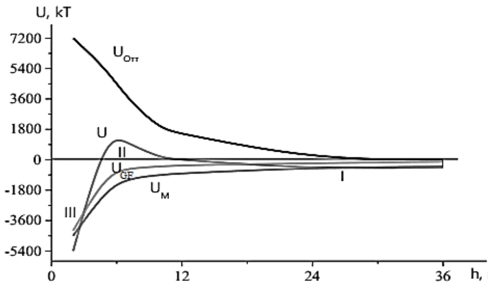

Fig. 4. Study of the distance dependence of interaction potential energy components for DMW particles (θ=60°)

The curve in Fig. 4 has the following areas: I – far potential minimum, which corresponds to distances greater than the sum of the radii of the interacting particles in the suspension; the area of far potential minimum is characterized by long-range forces with molecular and hydrophobic attraction; II – potential barrier, which results from overlapping of the particles' electrical layers, where the present barrier force has an electrostatic repulsive force greater than the molecular and hydrophobic attraction forces; III – near potential minimum, which corresponds to the approach of particles in the DMW solid phase, whose distance equals the radius of the hydrate layers (Fig. 5).

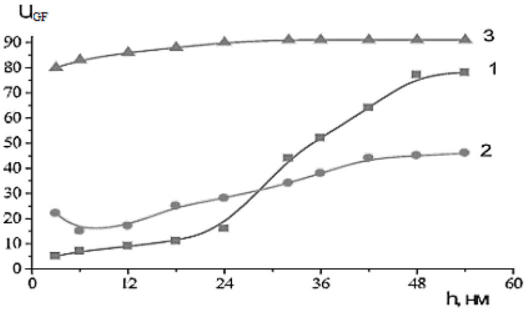

Fig. 5. Study on the distance dependence of the hydrophobic interaction energy of DMW particles

It is important to consider that the distance between particles in a DMW suspension and the wetting edge angle determines how much of the individual components of the potential energy of the particle interaction will be involved. Fig. 5 shows the dependence of the hydrophobic interaction energy of the slurry particles on distance. The following were used in the study: 1 – bentonite clay (θ=25°); 2 – coal sludge (θ=60°); 3 – sulfide minerals ($\theta_{\text{Wed.}}$=92°). The results show that the fractional involvement is within the U_{GF} normal range up to 15 nm (no more than 20%) for hydrophilic clay and charcoal. This is due to the predominance of electrostatic repulsion energy. The greater the distance, the greater the value share becomes and will be equal in the range from 30% to 70%. Also, in other words, it is possible to compare the values U_M and U_{GF}. In the case of a sulfide mineral, it can be seen that here the hydrophobic interaction energy dominates and is at least 80% in a given range of values. Sulfide materials can thus be characterized by a high degree of hydrophobicity (Chandler, 2005). It follows that the hydrophobic fraction must also be included in calculating the potential energy of the DMW slurry particles. This is necessary since for minerals ($\theta < 90^{\circ}$), this value can be compared with the electrostatic and molecular fractions, and in the case of hydrophobic minerals (θ>90°), the same value will be 1-2 orders of magnitude greater than the electrostatic and molecular fractions.

Considering the subject of the study, it is crucial to talk about a number of significant environmental factors. The study emphasizes how crucial it is to be able to efficiently separate the leftover drilling mud's liquid and solid components. Recovering and recycling the liquid fraction back into the drilling system allows for greater closed-loop water utilization, which lessens the need to find fresh water sources on a continuous basis. An additional benefit of proper separation is that it makes it possible to dispose of the concentrated solid fraction in a more regulated and sustainable way. The study also discovered that, in comparison to conventional approaches, utilizing the optimal ultraflocculation treatment process in conjunction with the appropriate flocculant (N-300) needed a lower dosage of the flocculant chemical. Using fewer chemical flocculants is better for the environment because these man-made polymers might linger in the ecosystem and could cause harmful consequences if improperly confined (Karches, 2012; Kvasnytskyi et al., 2020).

The ultraflocculation technology in the study can assist uranium mining operations in lowering their overall environmental footprint by increasing process efficiency, decreasing water and chemical consumption, and facilitating better waste segregation. Using this optimized approach has advantages that the authors list, including higher productivity, lower operational costs, and more ecologically friendly disposal of drilling debris. The study emphasizes the significance of minimizing the effects on the surrounding ecosystem and geology of mining sites.

Discussion

Based on the paired energy analysis of the interaction between flocculant and OBR suspension particles carried out in this study, several variations of potential interaction curves were found, as shown in Fig. 6. Considering curve 1, where sulfide minerals were used as mineral particles, it can be noted that the system had aggregate stability at the resulting potential barrier (greater than 10-15 kT) and far potential minimum (less than 1-2 kT). This is because the macromolecules of the flocculant aid penetrate through the particles in the solid fraction of the suspension rather than remaining in the region of the minimum. Curve 2 shows the interaction indicators of flocculant A-150 and bentonite clay. Here, the potential barrier values are relatively low, and the far potential minimum is deep (1-2 kT). It is likely that macromolecules of flocculant will fixate in this area, and bridge bonds will appear between the particles of the solid fraction of the suspension, given the presence of an abscissa of the order of 10-30 nm. It is worth considering that, in this case, large flocs are formed with a lot of water inside the particles. The 3rd curve shows the dependency values of the selected anionic flocculant with the charcoal sludge. The image shows that the system is aggregatively unstable because there is no potential barrier. In this situation, floccules of high density but small size are formed in the suspension.

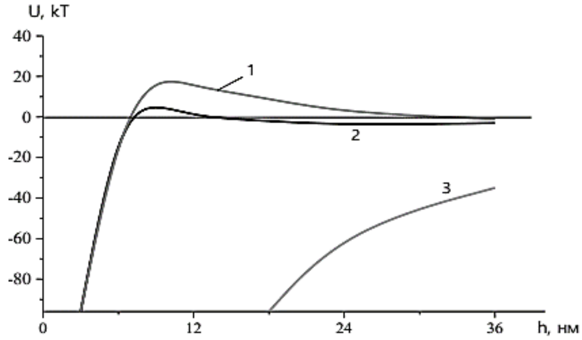

Fig. 6. Variants of potential interaction curves of flocculant A-150 with mineral particles

In the experiments discussed above, only one mineral in the dispersion system was used. Of most importance in the study are the regularities associated with the flocculation of suspensions with more than two elements, which have significant differences between their surfaces in terms of their properties (Gamaker constant, electrokinetic potential, and wetting edge angle (Nushtayeva, 2019)). The most well-known statement is that water-soluble flocculant particles have non-selective actions with respect to mineral suspension (Ben-Naim, 2006; Koltsov & Kondratyeva, 2018). It should be added that in the work of Read (1971), where studies were conducted on the separation of hematite and quartz, it was shown that the process of selective flotation occurs more efficiently if anion-active polyacrylamide derivatives for mineral suspensions, which contain a component with a high negative surface charge, are additionally used. There is almost no interaction with the flocculant aid as shown in curve 1 (Fig. 6), although flocculation of the main particles in the suspension does not stop as in curve 3 of Fig. 6. Experiments with coal OF Raspadskaya have shown that if anion-active polyacrylamide derivatives are used, the coal slurry can be selectively separated into coal concentrate and waste. It is worth noting that the previously used DLFO theory did not consider the processes of solid fraction and polymer impact on the features of their interaction. For this reason, it is important to determine the number of flocculant particles that can interact with particles of the solid fraction of the suspension having a specific diameter parameter. For this purpose, consideration is given to a spherical solid fraction particle with a diameter d_i and its vicinity, which is bounded by another sphere with diameter d_s obtained from the condition (Eq. 7):

$$d_s = d_1 + 2(d_2 + h_k), \tag{7}$$

where: d_1 is the diameter of the sphere of the solid fraction of the suspension; d_2 is the diameter of the statistical tangle of the polymer; h_k is the distance between the suspension particle and the statistical tangle, which correspond to the indicators of near and far potential minima.

Between the spheres with diameters d_1 and d_s, a volume of space V_x will be formed, which is (Eq. 8):

$$V_x = \frac{\pi}{6}(d_s^3 - d_1^3) = \frac{\pi}{6}[6d_1^2(d_2 + h_k) + 12d_1(d_2 + h_k)^2 + 8(d_2 + h_k)^3], \tag{8}$$

where: d_1 is the diameter of the sphere of the solid fraction of the suspension; d_2 is the diameter of the statistical tangle of the polymer; d_s is the diameter of another sphere, which limits the vicinity of the particle of the solid phase of the suspension; h_k is the distance between the particle of the suspension and the statistical tangle, which correspond to the indicators of near and far potential minima.

It follows from this that the expression of the number of polymer particles in volume V_x at a specific dosage of flocculant d_f and solid particles of suspension C_t can be shown as follows (Eq. 9):

$$N_x = 10^{-3} * \frac{\pi}{6} * d_f * C_T * N_A * \frac{1}{M_f} * [6d_1^2(d_2 + h_k) + 12d_1(d_2 + h_k)^2 + 8(d_2 + h_k)^3], \tag{9}$$

where: N_A is the Avogadro number; M_f – the molecular weight of the flocculant used; d_f is the dosage of the flocculant; C_t is the dosage of the solid particles of the suspension; d_1 – the diameter of the sphere of the solid fraction of the suspension; d_2 is the diameter of the statistical tangle of the polymer; h_k is the distance between the suspension particle and the statistical tangle, which correspond to the indicators of near and far potential minima.

Therefore, it can be said that the number of flocculant particles that interact with a particle of the solid fraction of the suspension will be equal to the square of the diameter of the solid particle (Fig. 7).

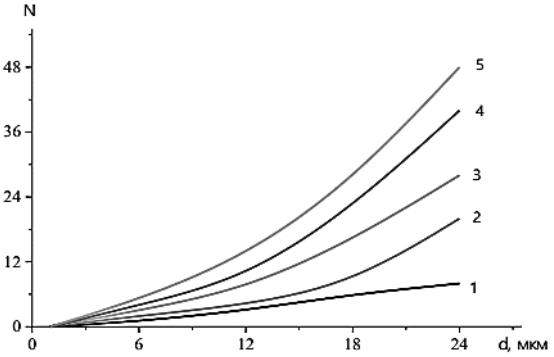

Fig. 7. Study on the dependence of the amount of flocculant with a mineral particle on its size

Fig. 7 shows the values of the magnitude N_x depending on the diameter of the particles (1 curve – 15 g/t; 2 – 30 g/t; 3 – 45 g/ t; 4 – 60 g/t; 5 – 75 g/t). The study used a flocculant with a molecular weight of 2.5×10^7 kg/mol, a dosage of 20 to 100 g/t, and a suspension content of 20 kg/m^3 of solid particles. Considering the fact that the value h_k, given the data used above, does not exceed the value of 25 nm (which is almost 2 orders of magnitude less when compared with the value d_2), it is advisable to ignore its effect on the number of macromolecules of the value N_x .

It follows from Eq. 9 that in the given values of polymer dosages, its macromolecules can approach the h_k particles by an amount, while their diameter should not be less than 5-8 microns. If the particles have a diameter of 1-2 µm, the fact of possible flocculation cannot be ruled out but still occurs less frequently. Studies and laboratory experiments have shown that nonionic superflocculants should be used in industrial plants in Kazakhstan. The use of this substance will help reduce the amount of OBR solids in the drain and improve the quality of the technical and economic performance of the processes. Based on the extended DLFO theory, studies of the paired energy of the interaction of mineral particles with different values of the wetting edge angle and flocculant were carried out. The conditions under which the particles pass through the flocculation process were also highlighted. A modified DLFO equation was used to calculate the number of interacting flocculant particles from various minerals with a solid fraction suspension particle.

The results obtained from this investigation offer fresh perspectives that complement and enhance current theoretical comprehension of flocculation mechanisms in intricate, multi-component suspensions such as waste drilling muds. The observed selective relationships between various mineral fractions and flocculant types are consistent with the extended DLVO theory, which considers hydrophobic interactions when adjusting the total interparticle forces. Instead of depending only on the average properties predicted by DLFO theory, the results show that the highly specific charge characteristics and wetting behavior of drilling mud components require a more thorough consideration of these factors when evaluating flocculant performance. In addition to direct measurements of floc sizes and densities, the systematic assessment of flocculant charge and wetting profiles offers hitherto unheard-of insight into the underlying interactions controlling selective flocculation and the best flocculant design for drilling mud separation.

A similar issue was addressed by Averkina et al. (2020), which also shows the positive effect of various flocculants on clay suspensions. Their study investigated different flocculants, namely BEN-EX, BENTOPLUS, and DRB-9. These flocculants also simplify the work with clay suspensions, but only in certain dosages, as in the case of N-100 and N-300, which were considered in this study. It has been established that certain reagents-flocculants can become a suitable option for obtaining drilling fluids with specified technological parameters (Ben-Naim, 2006; Petrov et al., 2022). Thus, another conclusion can be drawn that the flocculation process is essential in working with drilling fluids, and the right choice of flocculant allows for faster working processes with lower production costs. It can also be said that several types of flocculants can be used to separate the DMW suspension into liquid and solid phases.

In addition, similar studies were conducted by scientists Yevmenova (2006) and Kim (2016). The study by Yevmenova (2006) confirms that high-molecular cationic flocculants positively affect coal sludge thickening. Moreover, properly selected flocculants can remove fine particles of suspension solids in the sludge water. Laboratory tests have shown that the cationic flocculant Magnofloc 1440 excels at separating the suspension into liquid and solid fractions, with even better results when electrostatic repulsion forces are reduced. These studies show that there are many excellent flocculants, and their use will affect productivity and speed. The variability of choice will be useful since, in the work, you can use any of the available flocculants that can be found in the right amount. The study by Kim (2016) discusses the hydrophobicity of molecules, their properties, and their characteristics, describing in detail the hydrophobicity of various molecules as well as the dependence of hydrophobic particles on temperature. It was found that the temperature of the particles can affect the turbidity of clay solutions. This should be considered in further studies of flocculants and clay suspensions to determine the optimal temperature at which the hydrophobic process and the separation of the suspension into liquid and solid fractions will have positive results and improved experimental performance.

Based on the results of the analysis of the paired energy of the interaction of an anion active flocculant with mineral particles, 3 main variants of potential interaction curves can be distinguished:

1. If the potential barrier has values greater than 10-15 kT and the ordinate of the far potential minimum is less than 1-2 kT, the system is considered to be aggregate stable, which is due to the lack of fixation of flocculant macromolecules in the minimum region. Instead, the macromolecules move further to the solid fraction suspension particles. Based on this, it can be argued that a particle flocculation process with a bridging mechanism would be unlikely with this outcome.
2. If the potential barrier is small and the depth of the potential minimum is equal to or greater than 1-2 kT, given an abscissa of the order of 10-30 nm, then polymer macromolecules are expected to form in this region. If the potential barrier is small and the depth of the potential minimum is equal to or greater than 1-2 kT, given an abscissa of the order of 10-30 nm, then polymer macromolecules are expected to form in this region.
3. If there is no potential barrier at all, then the aggregate system will clearly be unstable. With this in mind, the convergence of the solid fraction particles with the flocculant macromolecules will be at minimum distances, resulting in small and dense flocs.

These polymer results should be used to improve the efficiency of flocculation processes during the thickening and filtration of clay drilling muds over the structure of the resulting sediments. Also, to increase flocculation efficiency and speed up this process, the required suspensions should be treated with an ultraflocculator. In contrast to the conventional flocculation process, ultraflocculation uses considerably more heterogeneous hydrodynamic fields (5 to 30 times larger than conventional flocculation), corresponding to medium gradient velocities between 1,000 and 3,000 c^{-1}.

Conclusions

Ultraflocculation treatment, which takes place with the appropriate equipment, has clear advantages in treating drilling fluids. Continuous operation and automated component feeding technology significantly improve productivity and results. The use of ultraflocculation treatment helped to intensify and increase the intensity of the DMW sedimentation processes with the presence of fine particle size classes. In addition, the ultraflocculation equipment used in the process improves the turbidity of the sludge by lowering it to a lower level, reduces the dose of flocculant injected, and also has a positive effect on the filtration properties of the sludge.

Compared to traditional flocculation techniques, using ultraflocculation treatment in conjunction with the ideal flocculant N-300 greatly shortened the separation time, improved clarity, and necessitated a lower flocculant dosage. The following settings were found to be ideal: a medium velocity gradient of 1500 s^{-1}, an ultraflocculation treatment lasting 15 seconds, a suspension concentration of 100 g/L, and a dosage of 50 g/t of N-300 flocculant. The study's conclusions emphasized the significance of using ultraflocculation to speed up the flocculation process and encourage the formation of dense, quickly settling flocs, as well as the importance of carefully choosing the right flocculant type and charge characteristics based on the particular composition of the drilling mud.

The results of this thorough investigation provide insightful analysis and helpful suggestions for industry professionals tackling the difficult work of sorting and processing leftover drilling mud. The charge properties and molecular weight of a flocculant should be carefully studied in connection with the particular composition of the drilling mud when choosing an appropriate flocculant. The best way to determine the type and dose of flocculant for a particular mud mixture is to conduct jar testing or preliminary screening. Furthermore, to optimize flocculation kinetics, maximize clarifying efficiency, and encourage the production of thick, compact sediments amenable to dewatering, the application of ultraflocculation treatment is highly advised. Process intensification depends on optimizing the ultraflocculation parameters, such as velocity gradients and residence periods. Based on the unique characteristics of the drilling mud and the intended separation results, industry operators should invest in specialized ultraflocculation equipment and create customized operating procedures. Process control and optimization depend on the ongoing observation of performance metrics such as floc features, turbidity, and settling rates.

A novel strategy for successfully addressing the complex separation of drilling mud wastes is provided by the synergistic combination of ultraflocculation and customized flocculant selection. By applying strong shear forces, ultraflocculation, in contrast to traditional flocculation techniques, promotes the development of thick, compact flocs and may increase settling rates and clarifying efficiency. The current work is notable for its creative integration of flocculant screening and hydrodynamic process intensification, which offers a technique to optimize drilling mud suspension separation while reducing the environmental impact of disposal.

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