Chapter 7

A COMPREHENSIVE ENVIRONMENTAL APPROACH TO THE PROTECTION OF TERRITORIES AND WATER AREAS WHEN HANDLING DRILLING WASTE

Lutsenko S. V., Lutsenko S. M., Rudnev M. Yu.
DOI https://doi.org/10.30525/978-9934-26-596-9-7

INTRODUCTION

Ukraine has significant potential in the field of oil hydrocarbon production. The main deposits of natural resources are concentrated in various regions of the country, covering both land and sea areas, and lie at various depths. However, the process of extracting oil and natural gas is not environmentally safe, waste-free or harmless. On the contrary, during drilling, exploration and operational extraction, an average of 1.05 m³ of drilling waste is generated for every metre drilled[1].

The drilling of oil and gas wells involves the use of various technical solutions that result in the formation of large amounts of multiphase waste, both solid and liquid. These include drilling sludge, spent drilling fluids and drilling wastewater. All these components have a serious anthropogenic impact on the environment: they can lead to soil, surface and groundwater pollution, as well as negatively affect air quality, especially due to evaporation from open sludge ponds[2].

From the point of view of environmental safety, destructive changes in ecosystems and landscapes, disruption of the natural balance and a significant reduction in biodiversity – the consequences of activities in the oil and gas sector – deserve special attention. In this regard, there is a need to introduce effective measures aimed at reducing the anthropogenic impact on nature and its components.

In today's world, it's super important to use environmentally safe and cost-effective ways to deal with drilling waste. Right now in Ukraine, the most common way is to store waste in drilling (slurry) pits, which are built right near drilling sites in specially designated areas. However, this approach does not ensure proper disposal and storage of waste, and its long-term storage

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[1] Екологічна безпека нафтогазового комплексу у західному регіоні : колективна монографія / О. М. Адаменко та ін. Івано-Франківськ: ІФНТУНГ, 2017. 384 с.

[2] Sharif M. D. A., Nagalakshmi N. V. R., Reddy S. S., Vasanth G., Uma Sankar K. Drilling waste management and control the effects. J Adv Chem Eng. 2017. Vol. 7: 166. DOI: https://doi: 10.4172/2090-4568.1000166.

becomes a source of pollution and, as a result, increases the anthropogenic pressure on the environment. A more rational alternative is considered to be reducing the volume of waste generated, processing it and reusing it (recycling). At the same time, existing technological solutions for the disposal of drilling waste are not always comprehensive and universal. Their effectiveness is often reduced due to underestimation of the specific geological, natural and climatic features of the territories and landscapes of a particular region and the technological aspects of drilling operations[3].

Therefore, the scientifically based development and implementation of an effective technological scheme for the disposal of drilling waste, adapted to local conditions and taking into account its individual parameters and properties, is an extremely important task today. This issue is the subject of research aimed at finding the optimal solution to reduce the negative impact of geological drilling and exploration on the environment, landscapes and ecosystems.

1. Drilling waste as a source of technogenic pollution of territories: ecological and geochemical consequences and management (processing)

All activities related to the exploration, extraction, storage and transportation of oil and gas, including the transportation of petroleum products, are accompanied by the generation of waste that poses a potential threat to the environment. A significant portion of the materials and waste generated during drilling operations can have a negative impact on individual components of the natural environment.

Among the pollutants generated by the operation of oil and gas production enterprises are both organic and inorganic compounds. Organic pollutants include oil, its derivatives, gas condensate, lubricants, phenolic compounds, asphaltenes, resins, methanol, acetone, formaldehyde, benzene, toluene and other polycyclic aromatic hydrocarbons with high molecular weight.

Inorganic pollutants are mainly represented by various mineral salts. Many of these substances have a pronounced toxic effect, which adversely affects key components of the environment: atmospheric air, water resources and soil cover.

In the oil and gas industry, it is common for significant volumes of oil-contaminated liquid waste, flushing fluids and solid residues such as sludge to be generated. These formations arise during the drilling of oil and gas wells, intensive industrial exploitation of deposits, oil refining processes, treatment of wastewater containing petroleum products, as well as during the cleaning

[3] Аблєєва І. Ю., Пляцук Л. Д., Будьоний О. П. Дослідження складу та структури бурового шламу з метою обґрунтування вибору методу його подальшої утилізації. Вісник КрНУ імені Михайла Остроградського. 2014. № 2 (85). С. 172–178.

of tanks and other technological equipment of the oil production complex. According to the waste classification system, there are two main types of sludge: oil and drilling[4].

Oil sludge is a stable multi-component system that includes oil residues, petroleum products, sand, water and clay components. Their formation is associated with the physical and chemical interaction of petroleum products with mechanical soil impurities, atmospheric air and moisture, which causes partial oxidation of hydrocarbons and the formation of resinous substances[5,6]. Drilling sludge is semi-solid or solid drilling residue, which includes rock fragments and colloidal phases remaining after the recovery and purification of drilling mud. Since drilling sludge has a complex and variable structure, there is no unified model of the composition or properties of this waste. Most of these sludges are formed during geological exploration and oil well drilling. As a result of the destruction of rock by a drilling tool (bit), a finely dispersed mass is formed at the bottom of the well, which is brought to the surface with the help of circulating drilling fluid. It is this mixture of crushed rock and flushing fluid that constitutes drilling sludge[7].

Depending on their aggregate state, drilling waste is divided into three main groups: liquid, semi-liquid (paste-like) and solid. The main criterion for classification is the ratio of solid and liquid phases in the waste composition. Thus, if the solid phase content does not exceed 35%, such material has high mobility and belongs to liquid drilling waste (spent drilling mud). When the solid phase is between 35% and 85%, the sludge takes on a paste-like appearance and is classified as semi-liquid (spent drilling fluid from drilling sludge). If the waste contains less than 15–16% liquid, it is considered solid and is referred to as drilling sludge[8].

The greatest threat to the natural environment is posed by production and technological waste generated during the drilling process, in particular drilling sludge, spent and contaminated drilling fluid, and drilling wastewater. Such

[4] Державний класифікатор України. Класифікатор відходів ДК 005-96. Затверджено і введено в дію наказом Держстандарту України №89 від 29.02.1996 р. URL: https://zakon.rada.gov.ua/rada/show/vb089217-96#Text (дата звернення: 09.06.2022).

[5] Kazamias G., Zorpas A. A. Drill cuttings waste management from oil & gas exploitation industries through end-of-waste criteria in the framework of circular economy strategy. Journal of Cleaner Production. 2021. Vol. 322. ID 129098. DOI: https://doi.org/10.1016/j.jclepro.2021.129098.

[6] Луценко С. В., Аблєєва І. Ю. Утилізація нафтового шламу у відцентровому полі. Сучасні технології у промисловому виробництві : матеріали VI Всеукраїнської науково-технічної конференції, м. Суми, 16–19 квітня 2019 р. Суми: Сумський державний університет, 2019. С. 172–173.

[7] Адаменко Я. О. Оцінка впливів техногенно небезпечних об'єктів на навколишнє середовище. Екологічна безпека та збалансоване ресурсокористування. 2010. 2. С. 58–63.

[8] Ismail A. R., Alias A. H., Sulaiman W. R. W., Jaafar M. Z., Ismail I. Drilling fluid waste management in drilling for oil and gas wells. Chemical Engineering Transactions. 2017.Vol. 56. P. 1351–1356. DOI: https://doi:10.3303/CET1756226.

waste is usually accumulated and stored directly on the territory of drilling sites, mainly in earthen barns, which are equipped in mineral or loose soil[9].

Hazardous substances contained in the extracted products of oil and gas fields include sour gases – hydrogen sulphide and carbon dioxide, whose concentration can reach up to 40%. These gases are present both in a free state and dissolved in oil. Hydrogen sulphide poses a particular threat, as it can have an aggressive effect on drilling equipment, flushing fluids and solutions, as well as various cementing materials[10].

Areas where oil is extracted are also prone to water pollution. This is because oil and its derivatives can simultaneously exist as a surface film, emulsion or dissolved in water[11]. The entry of such substances into surface and groundwater significantly impairs their quality and limits their further use. The main sources of pollution are leaks during oil production, accidents on oil pipelines, depressurisation of technological equipment, as well as rainwater and meltwater runoff from drilling sites and slurry pits. Among all types of pollution, liquid and semi-liquid waste poses the greatest danger. Due to their mobility and ability to quickly penetrate the environment, they accumulate toxic substances, leading to long-term pollution of natural components and disruption of the ecological balance of biocenoses in the places and territories where they end up[12].

Oil, formation water and drilling fluids, which contain a wide range of chemicals, are particularly dangerous. The entry of these compounds into the soil and underground aquifers causes serious damage. The main causes of such pollution are emergencies, in particular uncontrolled well blowouts, breaks in underground and above-ground oil pipelines, breaches in the integrity of technological systems and equipment, accidents, etc.. In addition, soil and vegetation contamination with heavy metals, in particular copper, zinc and lead, is often recorded in oil production areas, which only exacerbates the environmental burden on natural-territorial complexes and ecosystems.

All technical and technological processes related to the exploration, extraction, transportation and storage of oil and gas have a negative impact on

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[9] Заєць В. О., Дмитрик В. В., Дригулич П. Г., Пукіш А. В. Проблеми поводження з небезпечними відходами у нафтогазовій галузі України. Нафтогазова галузь України. 2017. № 1. С. 32–36.

[10] Kausalya Tamalmani, Hazlina Husin. Review on Corrosion Inhibitors for Oil and Gas Corrosion Issues. Applied Sciences. 2020. Vol. 10 (10). P. 3389. DOI: https://doi:10.3390/app10103389.

[11] Дригулич П. Г. Еколого-геологічний моніторинг забруднення довкілля об'єктами нафтогазового комплексу : автореф. дис. …канд. геол. наук : 21.06.01. Івано-Франківськ, 2008. 19 с.

[12] Helmy Q, Kardena E. Petroleum Oil and Gas Industry Waste Treatment; Common Practice in Indonesia. J Pet Environ Biotechnol. 2015. Vol. 6, Issue 5. ID 241. DOI: https://doi:10.4172/2157-7463.1000241.

the environment and create an additional ecological burden on all components of the natural environment[13].

Impact on atmospheric air.

As a result of technical and economic activities in oil and gas fields, the concentration of harmful substances in the air increases due to emissions. Sources of emissions can be stationary or mobile, organised or unorganised. Although the scale and duration of such pollution is not critical, emissions during drilling contain nitrogen dioxide and oxide, carbon monoxide, soot, sulphur dioxide, hydrocarbons and other harmful substances. Their impact on human health and the environment varies in intensity and nature. During the operation of wells, an additional source of emissions may be a horizontal flare unit, which is used to burn gas when purging a well or loop, as well as during exploration, research and repair. Slurry pits, from the surface of which hydrocarbons evaporate, are also stationary sources of emissions. During the preparation of drilling mud, when powdered materials (clay, marble, graphite, lime, chalk) are loaded into the clay mixer, dust is released into the air in the form of aerosols. These particles also pose a danger to the atmospheric environment[14].

Impact on soil.

The main sources of soil contamination are drilling fluid spills, chemical reagents, drilling sludge, wash water, drilled rock and mechanical damage during operations. Drilling, excavation and transport operations lead to disruption of the topsoil, its compaction, loss of humus and reduced water permeability and aeration. This can negatively affect the development of plant root systems, reduce their access to water and affect the quality of the soil cover. Mixing the upper soil horizons can lead to the loss of humus in the root layer if the requirements of SOU 73.1-41-11.00.01:2005[15] are not met. This standard provides for the removal of the fertile soil layer up to 60 cm without distribution or to its entire thickness in layers. Dense soil in a dry state not only hinders the development of the root system of plants, but also poorly transmits water, which requires additional costs for processing.

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[13] Pliatsuk L. D., Ablieieva I. Yu. System approach to oil production wastewater treatment. Water supply and wastewater disposal : collective monograph. Lublin : Lublin University of Technology, 2018. P. 242–250.

[14] Звіт з оцінки впливу на довкілля спорудження пошукової свердловини №3 Деркачівсько-Войтенківської площі глибиною 4900м. Реєстраційний номер 20193153108. ТОВ НТВК "Україна". Харків, 2019. С. 225. URL: https://kovyagi.com/wp-content/uploads/2019/05/ovd-zuravlyna3.pdf.

[15] Про затвердження Методичних рекомендацій щодо структури і змісту розділів ТЕО з екологічного обґрунтування кондицій для підрахунку запасів нафти і газу : наказ Державної комісії України по запасах корисних копалин №191 від 28.05.2009 р. URL: https://ips.ligazakon.net/document/FIN48832.

Impact on water resources.

The protection of groundwater and surface water is a priority at all stages of geological exploration and drilling: from installation to completion of well testing. During well drilling, possible sources of contamination of underground freshwater horizons include drilling mud used to open aquifers and the overflow of mineralised water from underlying aquifers[16].

Chemical reagents used in drilling fluids can be hazardous to the environment. However, the use of environmentally safe chemical reagents in drilling allows drilling fluids and drilling waste to be considered moderately safe and prevents negative impacts on the environment. To prevent drilling fluid leakage during lowering and lifting operations, special drainage devices must be used. Drilling fluids used in well construction must meet modern drilling technology requirements. To prevent the migration of groundwater and fluids, all casing strings are cemented with high-quality cement slurry, which rises to the wellhead.

Sludge pits used in oil and gas production processes are one of the key sources of environmental pollution[17]. Their functional purpose is to accumulate drilling waste, but long-term storage of this waste in open earthen containers significantly increases the level of technogenic impact on landscapes and the environment. In particular, over time, drilling sludge, spent solutions and associated pollutants can penetrate into the soil and groundwater and pollute the atmosphere through evaporation, posing a threat to the ecological balance of the areas surrounding drilling sites. With this in mind, a strategically important step is not only to reduce the amount of waste to be stored, but also to find effective solutions for its disposal and recycling. One way to reduce the negative environmental impact is to introduce drilling waste recycling technologies that reduce the volume of harmful materials and, in some cases, produce useful secondary products. However, there is currently no single unified approach or method that would allow for the effective and safe recycling of all types of drilling waste under any conditions. Each technology has its own application characteristics, advantages and limitations, depending on the composition of the waste, the geographical location of the drilling site, climatic conditions, landscapes, etc.

Table 1. presents the main existing methods of drilling waste processing used in practice[18].

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[16] Пукіш А.В. Дослідження особливостей формування фізико-хімічного складу поверхневих та підземних вод в межах нафтового родовища. Нафтогазова галузь України. 2017. № 2. С. 36–38.

[17] Системний підхід до підвищення екологічної безпеки нафтовидобувних територій : монографія / Аблєєва І. Ю., Пляцук Л. Д. Суми : Сумський державний університет, 2021. 275 с.

[18] Рикусова Н. І. Сучасні методи переробки та утилізації відходів буріння нафтогазових свердловин. Екологічні науки. 2018. №1 (20), Том 2. С. 130–135.

Table 1

Methods of handling drilling waste

Name of method	Characteristics of method
Thermal	Temperature treatment, burning, followed by the production of bituminous residues
Physical	Separation in a centrifugal field, settling, filtering
Chemical	Extraction using solvents, solidification using organic and inorganic reagents
Physico-chemical	Special treatment with additional reagents that change the physico-chemical properties (coagulants, flocculants)
Biological	Microbiological or biothermal decomposition using microorganisms

When considering the practical implementation of various methods of handling drilling waste, it is advisable to conduct an analysis taking into account the specifics of individual types of waste. Particular attention should be paid to spent drilling fluids (SDF) and drilling sludge (DS), as they constitute the bulk of technogenic waste during drilling and have different physical and chemical characteristics that determine the choice of appropriate disposal or processing technology.

Circulation systems are used to handle drilling mud, which include drilling mud cleaning units, usually consisting of vibrating screens, hydrocyclones and centrifuges. These technological solutions ensure that drilling mud is cleaned of drilled rock, allowing it to be returned for reuse in the preparation of drilling mud.

Physical and physicochemical methods for handling spent drilling fluids (SDF) (and in some cases drilling sludge (DS)) are determined by changes in the physical and physicochemical properties of waste under the influence of various physical factors. For example, under the action of gravitational and centrifugal forces, the components of the suspension layer are separated into individual phase components (Fig. 1)[19].

[19] Луценко С. В., Бережна І. О., Янченко І. О. Практичні аспекти покращення ефективності утилізації нафтошламів та відходів буріння. Сталий розвиток: захист навколишнього середовища. Енергоощадність. Збалансоване природокористування : збірник матеріалів VI Міжнародного конгресу, м. Львів, 23–25 вересня 2020 р. Львів : Західно-Український Консалтинг Центр, ТзОВ, 2020. С. 138.

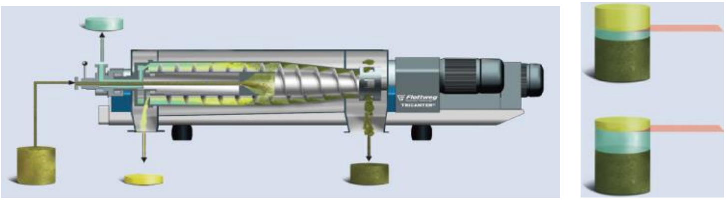

Fig. 1. Separation of the components of the suspension layer into individual phases under the action of centrifugal forces

Dehydration of spent drilling fluid and drilling sludge is the main technological operation for their preliminary preparation, which can potentially be implemented by the following methods: centrifugation, extraction, gravitational compaction, vacuum filtration, filter pressing, freezing.

A systematic analysis of research results indicates that centrifugation is one of the most effective technologies for separating sludge to obtain a solid fraction with a high dry matter content and improve the balance of element content between the two fractions, resulting in a clean liquid fraction for reuse[20]. In addition, a centrifuge with the addition of a coagulant, flocculant or polymer is considered to be highly efficient separation equipment, while a screw press, vibrating screen and rotating drum are low-efficiency separation processes[21].

Decanter centrifuges are used to separate suspensions with relatively low solids content, often in combination with chemical conditioners and additives. Under the influence of high centrifugal force, larger and heavier solid fractions are separated from the solution due to their increased weight and density. Decanter centrifuges are used, for example, to separate sludge and to process various industrial waste streams. Despite their technical complexity and higher cost, centrifuges, unlike belt filter presses, can operate continuously[22]. During the separation of sludge into phases, an oil-containing mixture is obtained, which can then be used as raw material and solid phase. The solid phase is dried in horizontal or vertical dryers, depending on the required productivity. The dry sludge can then be used as a mixture for the production of building materials and road surfaces.

[20] Ablieieva I., Berezhna I., Berezhnyi D., Prast A. E., Geletukha G., Lutsenko S., Yanchenko I., Carraro G. Technologies for Environmental Safety Application of Digestate as Biofertilizer. Ecological Engineering & Environmental Technology. 2022. Vol. 23, Issue 3. P. 106–119.

[21] Akhiar A., Guilayn F., Torrijos M., Battimelli A., Shamsuddin A. H., Carrère H. Correlations between the Composition of Liquid Fraction of Full-Scale Digestates and Process Conditions. Energies. 2021. 14. 971. DOI: https://doi.org/10.3390/en14040971.

[22] Alan Records, Ken Sutherland Decanter Centrifuge : 1st Edition. Handbook. Elsevier Science. 2001. 421 p. DOI: https://doi.org/10.1016/B978-1-856173-69-8.X5000-X.

Among thermal methods of drilling sludge disposal, incineration is the most common. This process is carried out in specialised furnaces of various designs and capacities, including rotary drum furnaces, fluidised bed furnaces, furnaces with bubbling burners or using nozzles. Sometimes incineration can even be carried out in open sludge barns.

Another effective thermal method is the pyrolysis of drilling waste – the process of decomposing organic components at high temperatures without access to air. Pyrolysis is usually carried out at temperatures above 400 °C, resulting in the decomposition of oil, humic and other organic substances into simpler compounds, in particular hydrocarbons, which can be used as fuel or raw materials for the chemical industry. In addition, pyrolysis gas is formed, which also has energy value. Pyrolysis is considered an environmentally sound method of treating drilling waste, as it significantly reduces its volume and minimises emissions of harmful substances into the atmosphere. At the same time, the efficiency of the process depends on the composition of the waste, in particular the presence of toxic components[23]. High-temperature heat treatment of drilling sludge includes two stages: preliminary preparation and main firing at temperatures between 950 – 1200°C. This approach requires the use of special heat-resistant equipment and significant energy resources, which makes it expensive.

The products of thermal decomposition of drilling residues consist of four main components: solid carbon residue (21.45% by weight), water (39.40%), hydrocarbon distillate (30.35%) and hydrocarbon gas (8.80%). In general, thermal methods are versatile in terms of application, as they do not require lengthy preliminary preparation of raw materials, such as the removal of foreign impurities, vegetation, stones or debris. In addition, the volume of the final processed product is significantly smaller than the initial volume of drilling sludge. However, thermal disposal also has significant limitations. During high-temperature combustion, a significant amount of toxic and harmful gaseous substances are released into the atmosphere. To minimise their impact on the environment, territory and public health, it is necessary to install emission purification systems, which requires additional material, energy and financial resources. In addition, the high moisture content of drilling waste significantly increases energy costs, which negatively affects the economic feasibility of using thermal methods[24].

The chemical method of drilling waste disposal is based on chemical reactions involving special reagents that promote the transformation of drilling sludge (DS) into less harmful or useful materials for further use. One

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[23] Гречко О.В. Сучасні методи термічної переробки твердих побутових відходів. Промислова енергетика. 2006. № 9. С. 25–29.

[24] Аблєєва І. Ю. Підвищення рівня екологічної безпеки при утилізації відходів нафтогазового видобутку : дис.... канд. техн. наук, 21.06.01. Суми. 2016. 194 с.

of the most effective technologies is considered to be reagent encapsulation, which involves the physical and mechanical transformation of waste into a stable substance that is safe for the environment and surrounding areas. In this method, each waste particle is covered with a hydrophobic protective shell of calcium carbonate, which is formed as a result of the reaction of slaked lime in the presence of water and carbon dioxide. Since the lime slaking reaction is accompanied by heat release (exothermic), this additionally promotes the evaporation of excess moisture and the disinfection of the material by destroying microorganisms. After maturing, the resulting granules are characterised by high strength. The rate of release of harmful substances from such a neutralised product is significantly reduced – hundreds of times compared to the initial input drilling sludge. One of the advantages of the chemical method is the possibility of further use of the treated sludge as a secondary raw material for the production of building materials or road surfaces, which not only reduces the burden on the environment but also increases the economic feasibility of disposal. In particular, a technology for the production of gypsum concrete has been developed, where phosphogypsum in combination with drilling sludge is used as a binding component. This combination allows the creation of an environmentally safe material formed by chemical immobilisation of heavy metals present in the sludge. The process results in a stable crystalline structure of gypsum concrete. According to toxicological, radiation and sanitary-hygienic studies, the resulting product is environmentally safe and has practical applications[25].

The biological method of disposal of drilling waste involves the use of microorganisms capable of breaking down petroleum products and other hydrocarbon compounds through biochemical reactions. As a result of this action, mineralisation, humification and gradual neutralisation of pollutants contained in the soil environment are observed[26]. This method is particularly effective when combined with other methods of processing drilling waste, residues, and areas and landscapes contaminated with petroleum products. For example, after extracting petroleum products from sludge using xylene and then introducing a consortium of specially selected microorganisms, the degree of purification can reach 91%[27]. In addition, biosorption technologies have also shown high efficiency in removing organic substances, toxic compounds and petroleum product residues. The use of various sorbents in aerotanks significantly increases the efficiency of bioremediation. Today, there are about two hundred types of sorbents, both organic and inorganic.

[25] Аблєєва І. Ю. Підвищення рівня екологічної безпеки при утилізації відходів нафтогазового видобутку : дис.... канд. техн. наук, 21.06.01. Суми. 2016. 194 с.

[26] Системний підхід до підвищення екологічної безпеки нафтовидобувних територій : монографія / Аблєєва І. Ю., Пляцук Л. Д. Суми : Сумський державний університет, 2021. 275 с.

[27] Біологічні методи охорони навколишнього середовища від забруднення нафтопродуктами : монографія / В. П. Шапорев та ін. Харків : НТУ «ХПІ», 2015. 216 с.

Organic sorbents include caustobolites, natural substances of plant or animal origin, their processed products, as well as synthetic analogues. Inorganic sorbents include natural, artificial, and organo-mineral materials. Therefore, biological methods should be used as part of a comprehensive system for handling oil-contaminated waste. However, given the relatively low concentration of petroleum products in drilling sludge (unlike oil sludge), the independent use of the biomethode may be less effective and not always justified from an economic or technological point of view.

Thus, a promising and economically viable technology for the disposal of drilling waste is to separate it into fractions in a centrifugal field using physical separation methods. The components obtained in the separation process can be used as raw materials, fuel or as part of new building materials. In addition, such substances are suitable for the preparation of special solutions used during the plugging of depleted and exhausted oil wells in the geological profile[28].

2. Characteristics of the studied deposit and samples of drilling sludge as a component of drilling waste

The research covered samples of drilling sludge obtained during the drilling of wells at the Semyrenkivske gas condensate field and the Machukhsk gas field located in the Poltava region. Thirteen commercial gas condensate deposits have been discovered at the Semyrenkivskyi field, which are confined to the Upper Visean deposits. The geological structure of the sedimentary complex of the Semyrenkivskyi field includes formations from the Palaeozoic, Mesozoic and Cenozoic eras, with a total thickness of up to 8.5 km. Exploration and production wells drilled in the Palaeozoic deposits have revealed Carboniferous and Permian formations, while Mesozoic formations include Triassic, Jurassic and Cretaceous formations, as well as a complex of Cenozoic deposits typical for this part of the basin. The porosity of the reservoirs in the Semirenkovskoye field ranges from 7 to 10%, and the permeability, according to laboratory core studies, ranges from 0.8 to 114 $\cdot 10^{-15}$ m^2. These reservoirs are fine– to medium-grained quartz sandstones, fractured with low capacitance and filtration parameters. The reservoirs are of the porous and fractured-porous type[29]. The waters contained in the Lower

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[28] Луценко С. В., Бережна І. О., Янченко І. О. Практичні аспекти покращення ефективності утилізації нафтошламів та відходів буріння. Сталий розвиток: захист навколишнього середовища. Енергоощадність. Збалансоване природокористування : збірник матеріалів VI Міжнародного конгресу, м. Львів, 23–25 вересня 2020 р. Львів : Західно-Український Консалтинг Центр, ТзОВ, 2020. С. 138.

[29] Ablieieva I., Plyatsuk L., Yanchenko I., Zinchenko V., Berezhna I., Lutsenko S., Prast A. E. Assessment of environmental safety of solid phase of drilling sludge after centrifusion separation. *Scientific and technical journal «Technogenic and Ecological Safety»*. 2020. Vol. 8 (2/2020). P. 3–11.

Carboniferous deposits of the Semirenkovskoye field belong to the calcium chloride type, have significant mineralisation ranging from 123.9 g/l to 212.2 g/l, and are located in a zone of very slow water exchange.

The Machukhskoye gas field is located in eastern Ukraine and belongs to the Glinsk-Solokhovskoye gas and oil bearing area of the Eastern oil and gas bearing region. The area lies at depths of 1.5 km to 5.5 km and includes a significant part of the Paleozoic deposits. This area has developed primary porous sandy-siltstone and cavernous-fractured carbonate reservoirs with high porosity and permeability, in which extensive systems of stratiform, massive stratiform and massive natural reservoirs filled with sedimentary brines are widespread[30].

The geological structure of the deposit includes rocks from the Carboniferous, Permian, Triassic, Jurassic, Cretaceous and Cenozoic systems.

The research covered samples of drilling sludge taken from wells No. 77 of the Semyrenkivske deposit (Nos. 1, 2, 5, 6), Machukha No. 54 (Nos. 3 and 4) and wells using IEP Witer II-based drilling fluid (Nos. 7–10), which are shown in Fig. 2.[31].

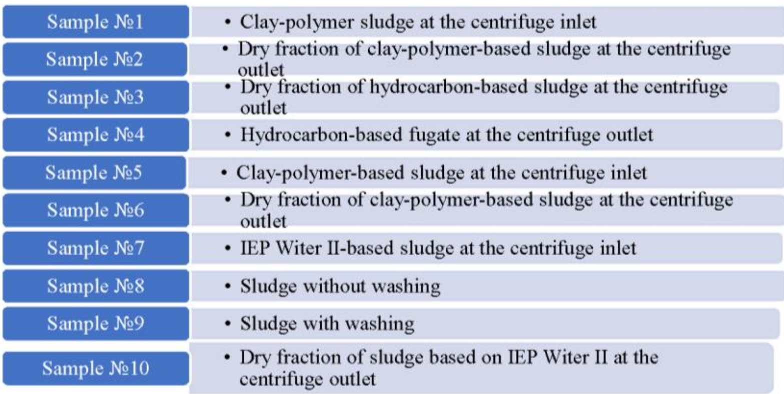

Fig. 2. Test samples of drilling sludge from deposits

Samples of drilling sludge Nos. 7–10 were taken from wells drilled using IEP Witer II-based drilling fluid. Its purpose is for primary and secondary

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[30] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[31] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

opening of productive formations, drilling in emergency zones of any complexity, carrying out major repairs of wells, and use as special fluids for well cementing[32]. For some of the samples studied, a clay-polymer-based drilling fluid was used, which included: weighting agents (barite, hematite, chalk, ground limestone); a suspension of drilled rock or bentonite; carboxymethylcellulose, inhibiting reagents, KCl, thinners, soda ash, graphite. Accordingly, such drilling fluids have different parameters compared to the IEP Witer II-based drilling fluid.

Waste drilling fluids can cause significant damage to the upper layers of the lithosphere, especially for alkaline loamy and clayey soils. However, the negative impact of waste drilling fluids is less significant for acidic soils with a high organic matter content and sandy soils. One way to reduce the volume of waste from used drilling fluids containing drilling sludge and reduce their harmful impact on the environment is to regenerate and reuse waste drilling fluids in the technological process[33].

An environmentally safe technology for handling spent drilling mud is its regeneration and reuse in the technological process[34]. Based on a literature review, it has been established that centrifugation is an effective method for separating spent drilling mud and drilling sludge to obtain technical water suitable for preparing new drilling mud and a solid environmentally safe phase. Experimental studies are aimed at determining the technological, environmental and operational characteristics of the proposed technology, as well as scientific justification of the patterns of the process of intensification and direct separation of drilling sludge in the field of centrifugal forces[35].

In this regard, the experimental methodology included the following stages:

– researching the chemical and phase composition of the waste used for the experiment and its level of environmental safety;

– determining the moisture content of the drilling sludge samples under study;

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[32] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[33] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[34] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[35] Ablieieva I., Plyatsuk L., Yanchenko I., Zinchenko V., Berezhna I., Lutsenko S., Prast A. E. Assessment of environmental safety of solid phase of drilling sludge after centrifusion separation. *Scientific and technical journal «Technogenic and Ecological Safety»*. 2020. Vol. 8 (2/2020). P. 3–11.

– separating the drilling sludge into solid and liquid phases in a centrifuge;

– treatment of the studied samples of drilling sludge with coagulants and flocculants of different concentrations, and separation of drilling sludge in a centrifuge;

– study of the chemical and phase composition of the obtained samples of the solid and liquid phases of drilling sludge;

– determination of the moisture content of the studied samples of the solid phase of drilling sludge after separation and calculation of the degree of dewatering of drilling sludge;

– statistical analysis of the results obtained, establishment of effective concentrations of flocculant and coagulant, determination of the efficiency of the centrifuge dewatering mode[36,37].

All samples were taken in triplicate to ensure the statistical significance of the measurement results. Samples at all stages of drilling sludge separation were subject to research, with the initial sample at the centrifuge inlet being the primary one. To establish the patterns of sludge dewatering in the OVS-950, drilling sludge of different genesis was used for analysis, i.e. formed as a result of drilling different wells and at different depths. Since drilling mud of different composition is used at each stage of the well drilling life cycle, sludges were studied, which included spent drilling mud on a clay-polymer basis, a hydrocarbon basis, in particular on the basis of IEP Witer II[38, 39]. The moisture content of drilling sludge samples was determined according to standard methods in accordance with DSTU B V.2.1–17:2009 and DSTU ISO 11465–2001.

A circulation cleaning system, including a vibrating screen, hydrocyclone and centrifuges or a decanter or tricant, is effectively used to separate drilling waste into phases. The process is intensified by electrocoagulation or reagent coagulation and flocculation. Coagulation results in the formation of aggregates – large (secondary) particles consisting of clusters of small (primary) particles. The primary particles in such aggregates are connected by

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[36] Ablieieva I., Plyatsuk L., Yanchenko I., Zinchenko V., Berezhna I., Lutsenko S., Prast A. E. Assessment of environmental safety of solid phase of drilling sludge after centrifusion separation. *Scientific and technical journal «Technogenic and Ecological Safety»*. 2020. Vol. 8 (2/2020). P. 3–11.

[37] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[38] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[39] Witer II – інвертний емульсійний буровий розчин. ТОВ «Геосинтез інженірінг»: вебсайт. URL: http://gse.ua/produktsiya/sistemi–promivalnikh–ridin/272–witer–ii–invertnij–emulsijnij–burovij–rozchin.html

intermolecular forces of interaction, either directly or through a layer of the surrounding (dispersion) medium[40].

Flocculation is used to intensify the formation of aluminium and iron hydroxide flocs in order to increase their precipitation rate[41]. The use of flocculants allows reducing the required doses of coagulants, shortening the coagulation process and increasing the precipitation rate of the formed flocs. Chitosan, which is a deacetylated derivative of chitin consisting of a linear copolymer of D-glucosamine and N-acetyl-D-glucosamine (Fig. 3)[42], was used for the research.

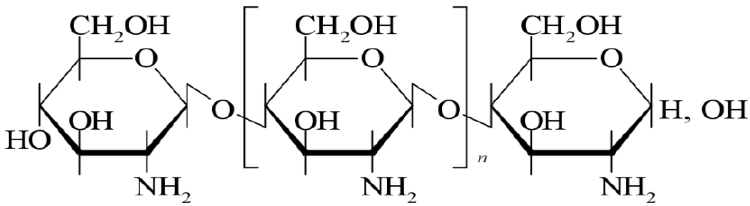

Fig. 3. Chemical formula of chitosan – a copolymer of D-glucosamine and N-acetyl-D-glucosamine

The complete mechanism of flocculation using chitosan has not been sufficiently studied, but it has been established that the bridging mechanism prevails during this process[43]. Flocculation ability, like other properties of chitosan, depends on the degree of deacetylation and the pH of the medium. It is soluble in an acidic medium in which amino groups are protonated, but insoluble in neutral and alkaline media[44].

[40] Chun-Yang Yin Emerging usage of plant-based coagulants for water and wastewater treatment. Process Biochemistry. Vol. 45, Issue 9. 2010. P. 1437-1444. DOI: https://doi.org/10.1016/j.procbio.2010.05.030.

[41] Lee D. Wilson PhD. An Overview of Coagulation-Flocculation Technology // Water Conditioning & Purification Magazine. URL: https://wcponline.com/2014/04/17/overview-coagulation-flocculation-technology

[42] Yanjun Liu, Junjie Jia, Huifeng Zhang, Shujuan Sun Enhanced Cr(VI) stabilization in soil by chitosan/bentonite composites. Ecotoxicology and Environmental Safety. 2022. Vol. 238. 113573. DOI: https://doi.org/10.1016/j.ecoenv.2022.113573.

[43] Ang T-H, Kiatkittipong K, Kiatkittipong W, Chua S-C, Lim JW, Show P-L, Bashir MJK, Ho Y-C. Insight on Extraction and Characterisation of Biopolymers as the Green Coagulants for Microalgae Harvesting. Water. 2020; 12(5):1388. DOI: https://doi.org/10.3390/w12051388.

[44] Yanjun Liu, Junjie Jia, Huifeng Zhang, Shujuan Sun Enhanced Cr(VI) stabilization in soil by chitosan/bentonite composites. Ecotoxicology and Environmental Safety. 2022. Vol. 238. 113573. DOI: https://doi.org/10.1016/j.ecoenv.2022.113573.

3. Results of experimental tests on the utilisation (separation into separate phases) of drilling sludge and its subsequent uses

Research into the elemental composition of the solid phase of drilling sludge and phase analysis allows its mineral composition to be established and the presence of heavy metals to be detected. This data can be used to make recommendations on waste disposal methods, such as using it in the production of building materials, for road filling and other useful purposes. This has environmental and economic advantages over landfilling or sludge storage.

Based on the results of X-ray fluorescence analysis, it was determined that heavy metals constitute a distinct group of chemical elements present in all analyzed drilling sludge samples. However, their overall concentration is relatively low, not exceeding 0.3%, with some metals detected only at trace levels. Specifically, clay-polymer-based drilling sludge samples (Samples 1 and 2) were found to contain iron, nickel, chromium, cobalt, zinc, and lead. Samples 5 and 6 contained iron, nickel, chromium, zinc, and lead. Hydrocarbon-based samples (Samples 3 and 4) exhibited the presence of iron, nickel, cobalt, copper, and lead, while samples based on the IEP Witer II composition (Samples 7–10) included iron, nickel, copper, and lead.

The study encompassed sludge samples both before centrifugation and after their separation into solid and liquid fractions. To assess the environmental safety of these resulting fractions, it is essential to analyze the distribution of heavy metals between the phases post-separation and to identify the patterns governing the transfer of these elements.

A comparison of the quantitative content of individual metals revealed a general trend toward their accumulation in the solid fraction at the centrifuge outlet, as opposed to the inlet. This suggests that heavy metals tend to concentrate in the solid phase, leading to a corresponding reduction in their levels within the filtrate. Importantly, all measured concentrations were below the maximum permissible concentrations (MPC) established for soils[45, 46].

The experimental results confirmed the hypothesis that, following centrifugation, there is an increase in the concentration of elements typically associated with rock formations, alongside a decrease in the concentration of chemical elements originating from the drilling fluid, which are predominantly transferred to the liquid phase. A comparative analysis of the elemental composition of drilling sludge samples taken at the centrifuge inlet

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[45] Ablieieva I., Plyatsuk L., Yanchenko I., Zinchenko V., Berezhna I., Lutsenko S., Prast A. E. Assessment of environmental safety of solid phase of drilling sludge after centrifusion separation. *Scientific and technical journal «Technogenic and Ecological Safety»*. 2020. Vol. 8 (2/2020). P. 3–11.

[46] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

(Sample No. 1) and outlet (Sample No. 2) revealed a reduction in chlorine content in the drilling fluid, while the concentrations of silicon, iron, and calcium increased in the solid phase.

The results of the chemical composition analysis were corroborated by X-ray phase analysis, which identified the dominant mineral phases present in the studied samples. Furthermore, X-ray fluorescence analysis confirmed the presence of a group of heavy metals–specifically iron, nickel, copper, and lead–in Samples Nos. 7, 8, 9, and 10. Importantly, the concentrations of all detected heavy metals remained below the maximum permissible concentrations (MPC) for soil, indicating that the samples are environmentally safe[47, 48].

Phase analysis was performed for solid phase samples obtained at the centrifuge outlet, on a clay-polymer basis (sample No. 2) and on a hydrocarbon basis (sample No. 3). For the phase composition, the following phase ratios were obtained for samples No. 2 and No. 3 (Fig. 4 and Fig. 5, respectively).

Fig. 4. Relationship between phases for sample No. 2

The solid phase sample obtained at the centrifuge outlet contains a high concentration of quartz (87%), which can be explained by the composition of

[47] Ablieieva I., Plyatsuk L., Yanchenko I., Zinchenko V., Berezhna I., Lutsenko S., Prast A. E. Assessment of environmental safety of solid phase of drilling sludge after centrifusion separation. *Scientific and technical journal «Technogenic and Ecological Safety»*. 2020. Vol. 8 (2/2020). P. 3–11.

[48] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

the rocks in the drilling area. Aluminium oxide (10%) was also found, which originates from the clay-polymer-based drilling fluid used during drilling.

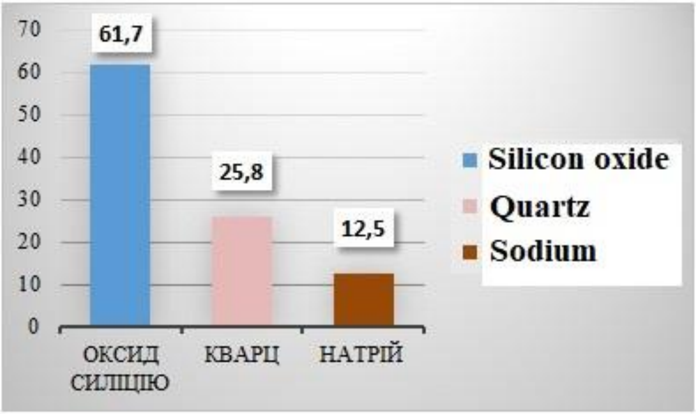

Fig. 5. Relationship between phases for sample No. 3

The X-ray phase analysis results for sample No. 3 reveal a distinct composition compared to sample No. 2, which can be attributed to the use of a hydrocarbon-based drilling fluid with a different chemical formulation. In sample No. 3, silicon oxide was identified as the predominant phase (62%), while the quartz content decreased to 26%. Although both phases share the same chemical formula (SiO_2) and hexagonal crystal system, they differ in their crystal lattice parameters.

The results of the X-ray phase analysis underscore a strong correlation between the mineralogical composition of the drilling sludge samples and both the chemical characteristics of the drilling fluid and the lithological composition of the rock strata disrupted during drilling. These disrupted rocks constitute the primary component of the resulting sludge[49].

In light of these findings, to substantiate the feasibility of repurposing the separated and dried sludge products for specific functional applications, it is recommended to conduct further research involving the chemical analysis of the aqueous extract from the sludge. This should include evaluation of the

[49] Луценко С.В., Пляцук Л.Д., Аблєєва І.Ю. Визначення екологічної безпеки бурового шламу залежно від глибини буріння. Екологія, неоекологія, охорона навколишнього середовища та збалансоване природокористування : матеріали IX Міжнародної наукової конференції молодих вчених, м. Харків, 25–26 листопада 2021 р. Харків: ХНУ ім. В.Н. Каразіна, 2021. С. 172-173.

cationic and anionic composition (K^+, Na^+, Ca^{2+}, Ba^{2+}, Cl^-, SO_4^{2-}, CO_3^{2-}, OH^-) as well as the hydrogen ion concentration (pH)[50].

Such analyses are governed by the Basel Convention, the regulatory standards for technical water, and, where applicable, the Rules for Wastewater Discharge into Municipal Sewer Systems and the Rules for the Protection of Surface Waters from Pollution. According to the Basel Convention, compounds such as sodium, potassium, and calcium chlorides are classified under List B, group B2040. However, since drilling sludge is not classified as dry waste, the majority of the cations and anions–whose presence is determined by the composition of the drilling fluid–are expected to be released into the liquid phase during separation.

During the process of separating sludge into phases, an oil-containing mixture and a solid phase are obtained, which can be used as raw materials. The absolute moisture content indicates the efficiency of separating oil-containing products from drilling sludge[51]. Based on the data obtained on the absolute moisture content of drilling sludge, the arithmetic mean value of relative moisture content was calculated by averaging three parallel measurements. The results obtained indicate the average relative moisture content of drilling sludge. We obtained the following results after dewatering. The efficiency of the degree of drying in a centrifuge for clay-polymer-based drilling sludge for samples No. 1 and No. 5 is 81.45% and 80.55%, respectively. The efficiency of the degree of drying in a centrifuge for drilling sludge for samples No. 7, No. 8 and No. 9 is 51.37%, 50.63% and 55.71%, respectively[52]. Based on the results obtained, it can be concluded that the degree of dewatering of clay-polymer-based drilling sludge is higher than that of hydrocarbon-based sludge. Namely, the degree of dewatering of clay-polymer-based sludge is almost 82%, while for hydrocarbon-based sludge it is 56%[53].

This is due to the chemical and physical properties of the clay-polymer base of the sludge, as well as its water yield indicators. One of these properties is the rheological capacity of the drilling mud used to drill the well. As a result of the analysis of the influence of the initial moisture content of drilling sludge

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[50] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[51] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[52] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[53] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

on the degree of sludge dewatering, no statistical significance of the results was found. In addition, the data show that clay-polymer-based drilling sludge samples No. 1 and No. 5 had higher initial moisture content than hydrocarbon-based sample No. 7. Therefore, the initial moisture content of drilling sludge does not affect the degree of sludge dewatering in a centrifuge[54]. From a rheological point of view, an effective drilling fluid in a downward flow should have a viscosity close to that of water, and in an upward flow, it should have a viscosity that is necessary and sufficient to transport the sludge to the surface without accumulating it in the well. However, real drilling fluid was used for experimental studies, which was the same for both downward and upward flows. The research was conducted on selected samples of two types of drilling fluid bases. Drilling fluid and drilling sludge are examples of Bingham fluids, which behave as solid materials under static conditions and begin to flow when subjected to force[55]. For effective separation of spent drilling fluid with maximum separation of the solid phase containing minimal moisture, the rheological properties of the drilling fluid must correspond to lower values of conditional viscosity and higher filtration indices[56,57]. Another determining factor is the difference in the physical and chemical properties of clay-polymer-based and hydrocarbon-based drilling mud. For samples of spent drilling mud where hydrocarbon-based drilling mud was used, in particular IEP Witer II, hydrophobisation of the sludge surface is observed, which delays the free separation of water from the solid phase, further contributing to lower dewatering rates compared to clay-polymer-based samples.

Comparing the water yield and the degree and quality of drainage of the studied samples, it was found that it is higher in the studied sample on a clay-polymer basis than on a hydrocarbon basis. This is explained by the different

[54] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[55] An Hiroshi Nogami, Jun-ichiro Yagi An Application of Bingham Model to Viscous Fluid Modeling of Solid Flow in Moving Bed. ISIJ International. 2004. Vol. 44, Issue 11. P. 1826-1834. DOI: https://doi.org/10.2355/isijinternational.44.1826.

[56] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[57] An Hiroshi Nogami, Jun-ichiro Yagi An Application of Bingham Model to Viscous Fluid Modeling of Solid Flow in Moving Bed. ISIJ International. 2004. Vol. 44, Issue 11. P. 1826-1834. DOI: https://doi.org/10.2355/isijinternational.44.1826.

rheological properties of these solutions and, as a result, their different physical properties and ability to regenerate[58, 59].

The separation of drilling waste, in particular spent drilling mud and drilling sludge, into solid and liquid phases was carried out using a developed method, which involves preliminary treatment of waste with coagulants and flocculants, followed by separation in an OVS-950 centrifuge. In this case, the liquid phase is reused for the preparation of drilling fluid, and the solid phase is subject to environmentally safe disposal, for example, for the production of building materials, which meets the requirements of water recycling and rational balanced nature management. To accelerate the precipitation of suspended particles, coagulants aluminium polyoxochloride $Al_2(OH)_5Cl$ and aluminium sulphate $Al_2(SO_4)_3$, obtained from coal mining waste – fly ash, were used. Aluminium cations can be leached with both hydrochloric acid and sulphuric acid[60,61]. In the second case, we obtain aluminium sulphate, which is effectively used as a coagulant and meets the requirements of rational nature management for waste disposal. It has been experimentally established that aluminium polyoxochloride has a higher efficiency in terms of coagulation rate at low temperatures and does not form accompanying hydrolysis products, since it has a higher basicity value, on which the coagulation process indicators depend – floc size, sedimentation rate, water purification efficiency. To improve the chemical precipitation process, a chitosan-based flocculant was also used, which increases the size of flocs after coagulation and has a wide range of operating pH values (3.5–10.5) and temperatures (0–100 ºC). Its main advantages are environmental safety compared to polyacrylamide, ease of obtaining and use, complete biodegradability, and the absence of

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[58] Ablieieva I., Plyatsuk L., Yanchenko I., Zinchenko V., Berezhna I., Lutsenko S., Prast A. E. Assessment of environmental safety of solid phase of drilling sludge after centrifusion separation. *Scientific and technical journal «Technogenic and Ecological Safety»*. 2020. Vol. 8 (2/2020). P. 3–11.

[59] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[60] Аблєєва І. Ю., Пляцук Л. Д., Зінченко В. Ю., Луценко С. В., Бережна І. О., Янченко І.О. Оцінка ефективності розділення бурового шламу у полі дії відцентрових сил. Гірничий вісник. 2020. 108. С. 3–9.

[61] Hu K., Zhao Q.-L., Chen W., Tang, F. Preparation of an Aluminum and Iron-Based Coagulant From Fly Ash for Industrial Wastewater Treatment. Clean – Soil, Air, Water. 2017. 45. 1600437. DOI: https://doi.org/10.1002/clen.201600437.

harmful substances in purified water[62,63]. Experimental studies to establish the optimal doses of coagulant and flocculant that provide the maximum possible degree of dewatering of drilling sludge were additionally conducted with previously studied samples No. 1, No. 5 and No. 7, corresponding to samples of spent drilling mud obtained from clay-polymer-based drilling fluid (No. 1 and No. 5) and hydrocarbon-based IEP Witer II (No. 7), respectively (see Fig. 2.1). It was proven that an increase in the sedimentation rate of enlarged particles contributes to an increase in the separation coefficient in the field of centrifugal forces, which is realised in a centrifuge, so at the outlet we obtain a solid phase with a lower water content and, as a result, a lower percentage of moisture.

It has been established that the use of a coagulant solution with a mass concentration of 15% and 25% of the proportion of mechanical impurities is insufficient for complete precipitation of impurities, which is due to the formation of a paste-like sediment of viscous consistency. When using a coagulant with a mass concentration of 35%, a loose-structured flake sediment is formed, which contributes to a higher degree of separation of sludge into liquid and solid phases with a lower water content. Increasing the mass concentration of the coagulant to 45% and 55% led to the absorption and binding of the water sediment, which made it harder to separate. So, the most effective solution is a coagulant with a mass concentration of 35%. In addition, it should be noted that the use of aluminium sulphate coagulant is optimal when creating a slightly acidic reaction environment, corresponding to a pH value of 5–7.5. After the coagulant, a flocculant was added – chitosan, which exhibits maximum flocculating properties in a slightly acidic or acidic environment. The studied samples of drilling waste had a slightly alkaline and alkaline reaction of the environment, so they were pre-acidified by adding a solution of hydrochloric acid in an amount calculated to bring the pH of the environment to a level of 5–5.5 units, which is the optimal indicator for both the coagulant and the flocculant. Based on the experiments conducted, the optimal dose of flocculant was established at 0.4% by mass of the mechanical impurities fraction. The sequence of preliminary chemical treatment of drilling waste to accelerate sedimentation was carried out in accordance with the methodology, bringing the initial reaction of the medium to a level of 5–5.5 units by adding hydrochloric acid. In this way, the sediment contains a minimum amount of water and the process of separating drilling sludge in a

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centrifuge into solid and liquid phases is significantly intensified, with their subsequent technological use. The proposed scheme for cleaning drilling sludge and spent drilling fluid allows the purified water to be returned to the well drilling process, which is in line with the principles of rational and efficient use of water resources, recycling and waste management. Thanks to a comprehensive approach to drilling waste management, it is possible to significantly reduce the negative anthropogenic impact on the surrounding landscapes, territories and water areas during the exploration, research and extraction of hydrocarbon minerals.

CONCLUSIONS

Based on the results of theoretical and experimental assessments within the framework of the conducted research, conclusions were made which are science-intensive, practice-oriented and, taken together, significant for improving the environmental safety of the process of handling and managing drilling waste through the justification, development and implementation of environmental protection technology in the oil production industry. In particular:

1. Based on an analysis of the impact of drilling waste on the environment, in particular atmospheric air, groundwater and surface water, and soil, it has been established that the soil surface and deep geological space are primarily subject to significant destructive effects. The feasibility and environmental friendliness of using a physical and chemical method of preliminary waste treatment to intensify separation with the obtaining of separate phases (solid and liquid) has been analysed.

2. The developed experimental methodology focuses on analyzing the properties of drilling waste both before and after phase separation, particularly in terms of environmental safety. It also includes identifying the patterns of waste separation in a centrifuge under conditions of process intensification using chemical coagulation and flocculation. The degree of solid phase dewatering in the centrifuge is proposed as a key indicator for evaluating the efficiency of the intensification process and the operational performance of the dewatering equipment.

3. An environmental safety assessment of drilling waste conducted before and after separation confirmed that the resulting solid phase does not present significant environmental hazards in terms of radioactivity or heavy metal concentrations. These parameters remain within permissible limits, and the environmental hazard coefficient (K) of the solid fraction was determined to be within acceptable levels ($K < 1$).

4. Based on the evaluation of the performance efficiency of the OVS-950 vertical dewatering unit, it was found that the equipment achieves a dewatering efficiency ranging from 51% to 82%, depending on the type of

drilling fluid–IEP Witer II or clay-polymer-based, respectively. The higher dewatering rates observed in clay-polymer-based samples are attributed to their specific rheological characteristics and water yield index, which were substantiated through the analysis.

5. The enhancement of the drilling sludge separation process through chemical coagulation and flocculation is justified. The study demonstrated that the use of aluminum sulfate as a coagulant at 35% of the mass of mechanical impurities, combined with chitosan as a flocculant at 0.4% of the mass, and the maintenance of a slightly acidic medium (pH 5–5.5) via the addition of hydrochloric acid, leads to a significantly high solid phase dewatering rate of up to 95–98%.

SUMMARY

Among the wide range of technological schemes, methods, and approaches for drilling waste disposal, no universally effective and environmentally safe solution currently exists. This is largely due to the insufficient consideration of regional geological, climatic, and operational factors during drilling activities. Consequently, the scientific substantiation, design, and implementation of an optimal technological framework for drilling waste management–tailored to the specific characteristics and parameters of the generated waste–remains an urgent and relevant challenge addressed by this study.

To enhance the environmental safety of oil-producing regions and improve the efficiency of drilling waste treatment, several novel scientific and practical findings have been achieved. The study has scientifically substantiated and experimentally verified the correlation between the degree of drilling sludge dewatering in a centrifuge and the type of drilling fluid base used. This dependency arises from the differing rheological properties of clay-based versus hydrocarbon-based fluids.

To increase the environmental safety of phase-specific waste utilization, the distribution patterns of chemical elements–particularly heavy metals–between the liquid and solid fractions of spent drilling fluids and sludge following centrifugation have been identified. A waste management approach has been proposed that involves the separation of drilling waste into solid and liquid phases using a centrifuge or decanter, followed by the targeted treatment of each phase.

This method is both environmentally sound and economically justified. The liquid fraction meets regulatory standards for reuse in preparing new drilling fluids, while the solid fraction can undergo chemical stabilization to immobilize heavy metals and be repurposed in construction or road maintenance applications.

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Information about the authors:
Lutsenko Serhii Viktorovych,
Doctor of Philosophy,
Senior Lecturer at the Department of General and Regional Geography,
Sumy State Pedagogical University named after A. S. Makarenko
87, Romenska str., Sumy, 40002, Ukraine

Lutsenko Svitlana Mykolaivna,
Doctor of Philosophy in Public administration, Associate Professor,
Dean of the Faculty of Advanced Training and Retraining
Sumy Regional Institute of Postgraduate Pedagogical Education
5, Mykoly Sumtsova str., Sumy, 40007, Ukraine

Rudnev Maksym Yuriyovych,
Master's student at the Department of General and Regional Geography
Sumy State Pedagogical University named after A. S. Makarenko
87, Romenska str., Sumy, 40002, Ukraine