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Feasibility of Fine Classification in Processing Watered Coal Sludge from Storage: A Case Study of the Dnipro Coke Chemical Plant

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Abstract
The mining, metallurgical, and energy sectors are among the most significant branches of Ukraine's economy, contributing substantially to national GDP and employment. However, these sectors are also major sources of environmental pollution, particularly through the generation of substantial volumes of liquid industrial waste. A notable portion of this waste includes fine-dispersed coal sludge from coke-chemical production, which poses serious risks to ecosystems and public health if not properly managed. This research addresses the urgent need for effective processing of such waste, demonstrating the feasibility and economic viability of obtaining marketable secondary products through advanced fine classification methods in the 0.05–0.1 mm fraction range, combined with simultaneous dewatering techniques. By implementing these technologies, it is possible to significantly reduce the accumulation of hazardous waste in storage facilities, thereby minimizing environmental damage and the associated long-term remediation costs. This approach contributes to the circular economy by recovering valuable resources from waste streams, thus enhancing the overall profitability and sustainability of industrial operations. The study underscores the importance of integrating low-waste technologies, efficient raw material utilization, and cross-sectoral cooperation to develop a modern system of waste management. Such integration ensures not only the minimization of environmental harm but also supports Ukraine's transition towards more sustainable industrial practices and compliance with European environmental standards. The proposed solutions offer a practical pathway to achieving both ecological and economic resilience in the context of post-war recovery and industrial modernization.

Keywords
coke chemical plants, industrial waste, storage facilities, coal sludge, processing, waste classification

Introduction

The significant scale of natural resource use and energy and raw materials specialization of the Dnipropetrovs'k region (Ukraine), due to large volumes of production and consumption together with an outdated technical base, as well as the rapid development of urbanization and agglomerations determine high rates of annual waste generation and accumulation. Thus, as of 01.01.2021, more than 11.35 billion tons of industrial waste have accumulated in region (State Report, 2022). Statistical information for the upcoming periods is unavailable due to the unstable political situation in Ukraine.

The accumulation and disposal of industrial waste are critical national concerns, as a significant portion of this waste contains substances that pose serious risks to both the environment and human health (State Report, 2022; Woźniak et al., 2024). The improper handling of such waste can lead to soil contamination, water pollution, and air quality deterioration, exacerbating ecological and public health challenges (State Report, 2022; Woźniak et al., 2024; Dychkovskyi et al., 2024). Addressing this issue requires the development and implementation of advanced waste management strategies aimed at minimizing environmental harm while maximizing resource recovery (Woźniak et al., 2024; Lewicka & Lewicka, 2019). Effective solutions include the adoption of recycling technologies, the extraction of valuable by-products, and the integration of sustainable disposal methods. Ultimately, a comprehensive approach to industrial waste management not only mitigates ecological risks but also contributes to economic benefits through resource efficiency and the development of secondary raw material (technogenic) markets. (State Report, 2022).

Recent research has delved into various aspects of coal processing and waste management, exploring innovative methods to enhance efficiency and sustainability (Woźniak et al., 2024; Tabachenko et al., 2016). The computer vision-based approach leveraging deep convolutional neural networks to assess activated sludge-settling characteristics was presented in research (Awan et al., 2020). This method provides a more consistent, automated, and less labor-intensive means of evaluating sludge properties, potentially improving the classification and processing of coal sludge (Awan et al., 2020; Polyanska et al., 2023). Studies are focused on the geotechnical characterization of coal spoil using machine learning algorithms (Thiruchittampalam et al., 2024). Researchers developed an advanced classification approach utilizing remotely acquired images to enhance the accuracy of material characterization, contributing to improved decision-making in coal waste management (Thiruchittampalam et al., 2024; Richert et al., 2024). These advancements highlight the growing role of artificial intelligence in optimizing resource recovery and reducing environmental impacts.

Furthermore, an experimental study examined the dispersion stability of coal fines during hydraulic fracturing flowback in coal seam gas reservoirs (Borzooei et al., 2024). The findings emphasized techniques to mitigate coal fines aggregation, a crucial factor influencing the efficiency of coal processing and wastewater treatment. These studies collectively offer valuable insights into the evolving challenges and technological advancements in coal sludge processing and waste management (Borzooei et al., 2024; Park & Jang, 2011). The integration of AI-driven analysis, geotechnical assessments, and machine learning-based classification techniques signifies a shift toward more precise, data-driven methodologies for optimizing coal waste utilization (Borzooei et al., 2024; Psyuk & Polyanska, 2024). Such developments contribute to enhanced operational efficiency, reduced environmental footprints, and the sustainable management of coal industry by-products.

The research conducted on setting up a complex, combined, and zero-waste gasifier plant for processing watered coal sludge highlights the need for an integrated approach that optimizes energy recovery and minimizes environmental impact (Tabachenko et al., 2016; Falshtynskyi et al., 2020). A key feature of this system is the use of jet-vortex bioheat generators, which enhance combustion efficiency by ensuring thorough mixing of fuel and oxidizer, resulting in higher thermal output and reduced emissions (Tabachenko et al., 2016; Fedoreiko, 2024). Advanced filtration and purification systems are incorporated to capture and neutralize harmful by-products, ensuring compliance with environmental regulations (Fedoreiko, 2024; Polyanska et al., 2022). Additionally, the integration of waste heat recovery improves overall system efficiency by utilizing excess thermal energy for preheating feedstock or generating additional power. The modular design of the plant allows for scalability, making it adaptable to different waste volumes and site-specific conditions (Falshtynskyi et al., 2020; Fedoreiko, 2024; Beshta et al., 2015). This innovative approach not only enhances sustainable energy production but also contributes to a significant reduction in the environmental impact associated with coal waste disposal. By transforming coal sludge into a valuable energy resource, this technology and used technics promotes a more circular economy and aligns global sustainability goals.

Waste recycling plays a crucial role in environmental protection while promoting the efficient use of raw materials and energy resources. By minimizing the volume of waste requiring disposal, recycling helps reduce pollution, lower greenhouse gas emissions, and conserve natural resources (State Report, 2022; Lewicka & Lewicka, 2019; Hrnčević, 2017). Additionally, the allocation of land for tailings storage facilities poses significant challenges, as it requires the long-term withdrawal of land from productive use, leading to a reduction in the country's available land resources. This not only affects agricultural and industrial land use but also contributes to landscape degradation and potential contamination of surrounding ecosystems (State Report, 2022; Chmura et al., 2022). Therefore, implementing advanced recycling technologies and waste management strategies is essential to mitigating environmental risks, optimizing land use, and fostering sustainable economic development (State Report, 2022; Dychkovskyi et al., 2024).

The main polluters of the environment remain enterprises of the mining, metallurgical industry and electricity producers (State Report, 2022; Golovchenko et al., 2020). One of the high-risk facilities in Ukraine is tailings ponds, which serve as storage sites for vast quantities of liquid industrial waste generated by various industries (Magdziarczyk et al., 2024). These ponds can be either naturally formed depressions or artificially constructed earthen reservoirs designed to contain waste materials safely (Polulyakh, 2014). Industrial waste is typically transported to these storage facilities hydraulically through pipelines, where it accumulates in liquid, sludge, or paste-like states (Polulyakh, 2003). The accumulation of such waste poses serious environmental and safety risks, including contamination of groundwater, soil degradation, and the potential for dam failures (Polulyakh, 2014; Kosenko et al., 2024). The aging infrastructure of many tailings ponds increases the likelihood of leaks and uncontrolled discharges, exacerbating ecological damage (Kosenko et al., 2024; Polulyakh, 2002). The safe management and rehabilitation of these storage sites require comprehensive monitoring, advanced treatment technologies, and adherence to strict environmental regulations (Lewicka & Lewicka, 2019; Patrakeyev et al., 2003). Moreover, the development of innovative waste recycling and utilization methods could help reduce the volume of materials requiring storage, minimizing their long-term impact (Patrakeyev et al., 2003; Kofanov et al., 2003). Addressing these challenges is critical for ensuring environmental sustainability and reducing industrial hazards in Ukraine. (Patrakeyev et al., 2003; Kofanov et al., 2003; Harkushyn et al., 2003; Nikolaeva et al., 2019).

An analysis of existing storage facilities by departmental affiliation has shown (Butenko et al., 2016; Kovalenko et al., 2012; Borysenko et al., 2004; Kasymov et al., 2008) that the largest capacities are associated with thermal power engineering and ferrous metallurgy, reaching more than 500 million m³. These industries generate vast amounts of waste, including ash, slag, and metallurgical by-products, which require specialized storage solutions (Borysenko et al., 2004; Kasymov et al., 2008). The immense volume of accumulated waste poses significant environmental and logistical challenges, particularly in terms of land use, pollution control, and long-term sustainability (Butenko et al., 2016; Kovalenko et al., 2012). The structural integrity of these storage facilities is a growing concern, as an aging infrastructure increases the risk of leaks and failures. Effective waste management strategies, including recycling and repurposing industrial by-products, could help mitigate these risks and reduce the burden on storage facilities (Butenko et al., 2016; Kovalenko et al., 2012; Borysenko et al., 2004; Kasymov et al., 2008). Addressing these issues is crucial for improving environmental safety, optimizing resource use, and ensuring the stability of industrial waste disposal systems. Storage facilities for liquid industrial waste pose a threat to the state of nearby water bodies. Therefore, the need for their processing is relevant.

Metallurgical enterprises are created with a full and incomplete production cycle. One of the branches of ferrous metallurgy is the coke industry, which is represented by large enterprises that process coking coals and are located near full-cycle metallurgical plants. In the process of the coke industry, a significant amount of pasty and solid industrial waste is formed (Golovchenko et al., 2020; Polulyakh, 2003). The largest tonnage of these is fine coke screenings, slags, and sludge. The bulk of this waste is stored at industrial landfills and in storage facilities on the territory of coke plants or in the areas where they are located (Polulyakh, 2003).

Currently, most industrial waste storage facilities in Ukraine suffer from a high degree of wear and tear, with outdated equipment that has not been modernized for decades. Many of these facilities operate without routine or major repairs, leading to increased risks of structural failures, environmental contamination, and safety hazards. The lack of proper maintenance exacerbates the deterioration of storage systems, making them more vulnerable to leaks and breaches. (Butenko et al., 2016; Kovalenko et al., 2012; Borysenko et al., 2004; Kasymov et al., 2008). The almost complete depletion of storage capacity is the main cause of accidents and disasters that negatively affect the environment and human life (Kasymov et al., 2008).

It should be noted that most of the placed waste has a significant amount of resource components that can be extracted to obtain high-quality, cheap raw materials and which, in fact, represent man-made deposits. One of the priority areas for minimizing the accumulation of industrial waste of enterprises is their return to production to extract valuable components and use as secondary resources (material or energy) (State Report, 2022). Therefore, the elimination of raw material losses and the processing of accumulated industrial waste can provide a tangible economic and environmental-social effect. There will be a prerequisite for a constructive solution to the problem of supplying enterprises of the metallurgical complex of Ukraine with commercial products, the secondary use of coke screenings, slags and sludge's, which are currently not used and pollute the environment, the use of coal as a reducing agent and energy fuel (Butenko et al., 2016; Kovalenko et al., 2012; Borysenko et al., 2004; Kasymov et al., 2008).

According to world experience, the liquidation of storage facilities is associated with certain difficulties due to the duration of their operation and the joint storage of waste that differs significantly in physical and chemical properties. Under these conditions, a new composite product appears in the storage facilities, the quality of which changes depending on the depth of the layers. Therefore, to select methods for qualified use and extraction methods, it is necessary to conduct studies of the properties of waste from storage facilities at different locations

(Borysenko et al., 2004). Since the sludge in the storage facilities is in a waterlogged state, it is also necessary to take into account the need to dehydrate the finished product during their processing.

One of the cheapest, available on the market, most widely used, environmentally friendly, and effective methods for extracting valuable components through size-based separation is fine classification. This study aims to analyze the potential for processing coal sludge from storage tanks using fine classification, with a focus on the Dnipro Coke Chemical Plant in Kamenske (Ukraine). The research specifically examines coal sludge from the plant's storage tank to assess the feasibility of this method for improving waste management and resource recovery.

Methodology and methods for the research assessment of fine classification for processing watered coal sludge

The research methodology for assessing fine classification as a method for processing watered coal sludge from storage at the Dnipro Coke Chemical Plant consisted of several key stages. First, a comprehensive literature review and data collection were conducted to analyze existing studies on fine classification techniques for coal sludge processing (Tytiuk et al., 2021). This included examining industry reports, regulatory documents, and prior research on coal waste management (Verkhovna Rada of Ukraine, 1991). Data on the physical and chemical properties of coal sludge from the plant's storage facilities were gathered. Representative samples were then selected, and their key parameters, such as particle size distribution, moisture content, ash content, and calorific value, were analyzed using sieving, sedimentation, and laser diffraction techniques.

Next, an experimental setup for fine classification was established by selecting suitable classification equipment, such as hydro cyclones, sieves, or air classifiers. The experiments were conducted under controlled conditions, adjusting feed rate, water-to-solid ratio, and classification efficiency parameters to optimize separation. The efficiency of fine classification was evaluated by measuring separation efficiency based on particle size fractions and assessing the quality of recovered fine coal. Additionally, an environmental and economic assessment was performed, estimating potential waste reduction, environmental impact, and cost-benefit analysis compared to other sludge management techniques. Finally, conclusions and recommendations were formulated, outlining the most effective classification parameters and providing suggestions for industrial implementation and further research.

The research method was based on the structured approach on fine classification techniques, coal sludge processing, and relevant environmental and industrial standards. In this stage authors involved analyzing scientific articles, industry reports, and regulatory documents to identify best practices and technological advancements in coal waste management (Nadutyi & Shevchenko, 2009; Barry et al., 2015; Toraño et al., 2013).

Coal sludge samples were collected from the plant's storage facilities and subjected to laboratory analysis to determine key physical and chemical characteristics. The granulometric composition was studied using sieving (for particles less than 63 µm) and laser diffraction (for finer fractions), allowing determination of the particle size distribution function *f(d)*, where *d* represents particle diameter (Napier-Munn & Wills, 2006). The cumulative undersize fraction was described by the Rosin-Rammler equation:

$$R(d) = 1 - e^{-\left(\frac{d}{d_0}\right)^n} \quad (1)$$

where

$R(d)$	is the cumulative mass fraction of particles smaller than d,
d_0	is the characteristic particle size,
n	is the distribution parameter reflecting the sharpness of separation (*Liu* et al., *2016*).

Other key parameters, including moisture content W, ash content A_d, and calorific value Q were determined through standard analytical techniques such as thermogravimetric analysis (TGA).

For experimental evaluation, fine classification equipment was selected based on the particle size distribution and physicochemical properties of the coal sludge. Hydro cyclones, sieves, and air classifiers were tested under controlled conditions, with variations in feed rate Q_f, water-to-solid ratio C, and operational settings (Barry et al., 2015; Svarovsky, 2000; Guo & Guo, 2024). The efficiency of classification was assessed using the separation function:

$$E(d) = \frac{C_f(d) - C_0(d)}{C_f(d)} \quad (2)$$

where

$E(d)$	is the classification efficiency for particles of diameter d,
$C_f(d)$	is the mass fraction of particles of size d in the feed,
$C_0(d)$	is the mass fraction of particles of size d in the underflow.

The cut size d_1 (the parties with the particle diameter at which 50% of material is classified into the fine fraction) was determined for different classification conditions and compared with theoretical predictions using the Stokes equation for sedimentation:

$$d_1 = \sqrt{\frac{18\eta v\rho}{(\rho_1 - \rho_f)g}} \tag{3}$$

where

η is the fluid viscosity,
v is the terminal velocity of the particle,
ρ_s, ρ_f are the densities of solid and fluid, respectively,
g is the gravitational acceleration (*Brown, 2003*).

Based on experimental and analytical results, recommendations were formulated regarding the most effective classification parameters and the feasibility of industrial implementation. The study provided insights into optimizing fine classification for coal sludge processing, improving resource efficiency, and reducing environmental impact.

Results & Discussions

The environmental impact of storage facilities is aggravated by their long-term use, as well as by the insufficient number of optimal and effective technologies for their elimination. The utilization of fine-dispersed waste from coke plants will not only save material and heat energy resources but also reduce the degree of environmental pollution. A transition to fundamentally new technological systems that provide the maximum resource-energy-saving and environmental protection effect is necessary. In modern conditions, this can only be achieved through the comprehensive use of primary and secondary raw materials, the introduction of low-waste technologies, an increase in the level of inter-industry cooperation and coordination of work in matters of industrial waste utilization and environmental protection.

In 2020, enterprises in the Dnipropetrovs'k region generated 309.4 million tons of waste. Of the total volume of waste generated, 25.93 thousand tons were waste of hazard classes I – III (statistics for 2021 are not available). Some of them are reused or transferred to specialized enterprises for subsequent disposal (State Report, 2022).

One of the priority areas for minimizing the accumulation of industrial waste from enterprises is their return to production to extract valuable components. This approach allows waste materials to be reused as secondary resources, either in material form or for energy generation (Tytiuk et al., 2021). By integrating waste into production cycles, industries can reduce environmental pollution and lower raw material consumption. Such practices contribute to sustainable resource management and enhance the overall efficiency of industrial processes (Tytiuk et al., 2021; Verkhovna Rada of Ukraine, 1991).

Kamenske is one of the cities in Ukraine with a high concentration of industrial enterprises, which in turn contributes to the formation of a large volume of industrial waste. The following enterprises have the greatest impact on the ecology: Public Joint-Stock Company Dnipro Metallurgical Plant", Private Joint-Stock Company Yuzhkoks, Joint-Stock Company Dniproazot and Private Joint-Stock Company Dnipro Coke Chemical Plant. Modern requirements, legalized by government documents and decisions of local authorities (Verkhovna Rada of Ukraine, 1991; MDSDR, 2018; Kamianske City Council, 2018), for such enterprises regulate measures for waste management and reducing the impact on the environment.

Let us consider the possibilities of waste recycling using the example of the Dnipro Coke Chemical Plant (DCCP) (until 2010 Public Corporation Dneprodzerzhinsk Coke Chemical Plant (PC DCCP); from 2011 to 2017 Public Joint Stock Company EVRAZ Dneprodzerzhinsk Coke Chemical Plant). An integral part of the technological process is the accumulation, storage, dosing and shipment of coal charge for coking (Tytiuk et al., 2021). In the process of its activity, a significant amount of waste is generated (coal sludge – particles with a size from +0 to 5 mm), which is removed from the technological process by hydro transport and stored in a storage facility on the territory of the plant.

Fig. 1 presents Google Maps Plan #2, depicting the storage facility of the Dnipro Coke Chemical Plant, including sludge deposits, access routes, and infrastructure. This layout helps assess logistical challenges and identify optimal locations for implementing fine classification technologies to improve sludge processing efficiency. Utilizing geospatial tools like Google Maps supports sustainable waste management strategies and enhances the environmental performance of the facility.

Fig. 1. Google Maps Plan #2 of the Dnipro Coke Chemical Plant storage facility

The environmental situation combines an assessment of the state of the main components of the environment: air, water bodies and waste management. To improve it in the city of Kamenske and ensure the solution of urgent environmental problems (Verkhovna Rada of Ukraine, 1991; MDSDR, 2018; Kamianske City Council, 2018), Dnipro Coke Chemical Plant carried out the following activities from 2017 to 2020:

– to reduce the impact on the air environment, coking equipment was replaced and improved using modern technologies; during 2018–2019, the number of emissions was reduced by 6.9%;

– to reduce the impact on water bodies, the technological scheme of biochemical wastewater treatment has been improved by deactivating activated sludge in mineralizers (Ivanchenko et al., 2014; Ivanchenko et al., 2015). When air is supplied, the biomass is oxidized to a mineral residue, after which the sediment is pumped into primary settling tanks, and then, together with the sludge, is fed for disposal into the coal charge. This improves the process of extracting pollutants and reduces the volume of excess activated sludge that is sent for disposal;

– priority areas for industrial waste management – implementation of waste recycling and utilization measures, a rational approach to reducing raw material losses and recycling accumulated industrial waste, which will provide a tangible economic and environmental-social effect.

Despite the measures taken, the amount of industrial waste in the storage facility of the Dnipro Coke Chemical Plant remains significant. Therefore, a new fundamental approach to solving this problem is needed. In the implementation of business contract topics and in the order of exchange of experience, the employees of the IGTM of the NAS of Ukraine, together with specialists of the Dnipro Coke Chemical Plant, carried out research aimed at determining the possibilities of processing coal sludge from the storage facility and the area of use of the obtained products.

Since the sludge is a carbon-silicate mass, which cannot be fully separated into components (carbon-silicates) using the existing enrichment technology, an unconventional separation method is required. First, it is necessary to establish the coal and ash content at various points in the storage facility and determine the prospects for its development. The assessment criterion is the permissible ash content in the sludge after processing (no more than 25-27%) with the maximum content of extracted coal (Psyuk & Polyanska, 2024; Falshtynskyi et al., 2020; Fedoreiko, 2024; Nadutyi et al., 2016; Nadutyi et al., 2005).

For this purpose, samples of sludge were collected along the entire perimeter of the storage facility to ensure representativeness. These samples were then subjected to detailed analysis to determine their granulometric composition and the ash content of different particle size classes. The distribution of ash and coal within each class was carefully examined to assess the potential for further processing and recovery.

Tab. 1 shows the results of studies of the properties of coal sludge from the storage facility, carried out according to the methodology developed by specialists of Dnipro Coke Chemical Plant (laboratory data).

Tab. 1. Properties of sludge from storage facility card No. 2 (data from the laboratory of Dnipro Coke Chemical Plant)

Size classes [mm]	Output of classes γ [%]	Ash content of class A^d [%]	Amount of ash c_a [%]	Amount of coal c_c [%]	Output of classes γ [%]	Ash content of class A^d [%]	Amount of ash c_a [%]	Amount of coal c_c [%]
	Pooled sample number							
	Sludge sample № 1				Sludge sample № 2			
+2,5-5,0	0,6	13,9	0,083	0,517	-	-	-	-
+1,0-2,5	1,6	6,9	0,11	1,49	0,9	12,4	0,112	0,788
+0,63-1,0	2,4	7,2	0,173	2,227	1,0	4,4	0,044	0,956
+0,4-0,63	6,6	8,1	0,535	6,065	2,5	7,4	0,185	2,315
+0,3-0,4	23,1	13,2	3,049	20,051	6,8	11,1	0,755	6,045
+0,2-0,3	11,3	35,5	4,012	7,288	9,0	13,3	1,197	7,803
+0,1-0,2	12,7	54,4	6,909	5,791	10,3	29,5	3,039	7,261
+0,063-0,1	10,0	69,8	6,98	3,02	18,7	49,5	9,257	9,443
+0-0,063	31,7	76,5	24,251	7,449	50,8	76,8	39,014	11,786
Σ	100,0	46,7	46,1	53,9	100,0	53,6	53,6	46,4
	Sludge sample № 3				Sludge sample № 4			
+2,5-5,0	1,7	15,5	0,264	1,436	-	-	-	-
+1,0-2,5	2,4	6,3	0,151	2,249	1,9	7,7	0,146	1,754
+0,63-1,0	2,4	7,6	0,182	2,218	2,1	8,0	0,168	1,932
+0,4-0,63	3,4	8,2	0,279	3,121	3,0	9,9	0,297	2,703
+0,3-0,4	6,8	16,9	1,149	5,651	5,9	12,1	0,714	5,186
+0,2-0,3	9,9	35,6	3,524	6,376	5,0	13,9	0,695	4,305
+0,1-0,2	11,0	59,8	6,578	4,422	9,1	40,3	3,667	5,433
+0,063-0,1	19,2	66,3	12,729	6,471	10,7	52,2	5,585	5,115
+0-0,063	43,2	89,8	38,794	4,406	62,3	72,5	45,168	17,132
Σ	100,0	58,8	63,65	36,35	100,0	56,4	56,44	43,56
	Sludge sample № 5				Sludge sample № 6			
+2,5-5,0	0,3	14,5	0,044	0,256	0,6	14,4	0,086	0,514
+1,0-2,5	0,6	7,1	0,043	0,557	0,5	5,0	0,025	0,475
+0,63-1,0	1,1	5,3	0,058	1,042	1,3	4,2	0,055	1,245
+0,4-0,63	3,6	8,2	0,295	3,305	2,2	7,1	0,156	2,044
+0,3-0,4	6,7	12,4	0,831	5,869	19,7	13,2	2,6	17,1
+0,2-0,3	8,8	23,9	2,103	6,697	8,9	37,1	3,302	5,598
+0,1-0,2	5,9	30,9	1,823	4,077	12,1	46,6	5,639	6,461
+0,063-0,1	17,8	45,9	8,17	9,63	14,6	53,7	7,84	6,76
+0-0,063	55,2	70,9	39,137	16,063	40,1	69,8	27,989	12,111
Σ	100,0	52,5	52,5	47,5	100,0	45,3	47,69	52,31
	Sludge sample № 7				Average sludge sample			
+2,5-5,0	-	-	-	-	0,2	14,4	0,029	0,171
+1,0-2,5	0,8	4,1	0,033	0,767	1,1	7,3	0,08	1,02
+0,63-1,0	1,5	5,2	0,078	1,422	1,5	6,3	0,095	1,405
+0,4-0,63	2,3	6,3	0,145	2,155	3,2	8,0	0,256	2,944
+0,3-0,4	7,0	10,1	0,707	6,293	10,6	12,8	1,357	9,243
+0,2-0,3	5,6	20,1	1,126	4,474	8,1	27,1	2,195	5,905
+0,1-0,2	7,3	25,5	1,862	5,438	9,7	43,0	4,171	5,529
+0,063-0,1	18,0	48,9	8,802	9,198	15,4	54,3	8,362	7,038
+0-0,063	57,5	67,9	39,043	18,457	50,2	74,4	37,349	12,851
Σ	100,0	51,8	51,8	48,2	100,0	53,5	53,89	46,11

As can be seen from Tab. 1, the distribution of ash and coal in size classes is uneven; the amount of carbon in the samples varies from 36.35 to 53.9% with an ash content of 46.1 to 63.65%. The maximum ash content is observed in the size class +0-0.05 mm.

To clarify the quantity in the size classes of ash and coal, a detailed breakdown of their distribution is necessary. For this purpose, additional equipment from IGTM of the NAS of Ukraine was used in laboratory conditions to study the properties of coal sludge from the storage facility of the Dnipro Coke Chemical Plant using the method described in (Lapshyn & Shevchenko, 2024). Tab. 2 shows the results of the average (based on the results of 5 samplings) characteristics of the sludge samples.

Tab. 2. Results of studies of the properties of sludge from the storage facility of Dnipro Coke Chemical Plant at the IGTM of the NAS of Ukraine

Size classes [mm]	Output of classes γ [%]	Ash content of class A^d [%]	Amount of ash c_a [%]	Amount of coal c_c [%]	Output of classes γ [%]	Ash content of class A^d [%]	Amount of ash c_a [%]	Amount of coal c_c [%]
	Pooled sample number							
	Sludge sample № 1				Sludge sample № 2			
+2,5-5,0	-	-	-	-	-	-	-	-
+1,6-2,5	-	-	-	-	-	-	-	-
+1,0-1,6	0,19	68,91	0,131	0,059	0,30	62,76	0,188	0,112
+0,63-1,0	0,43	54,43	0,234	0,196	0,63	62,51	0,394	0,236
+0,315-0,63	0,64	50,49	0,323	0,317	1,68	59,04	0,992	0,688
+0,2-0,315	0,26	37,21	0,097	0,163	0,73	54,35	0,397	0,333
+0,1-0,2	1,34	17,75	0,238	1,102	1,04	48,83	0,508	0,532
+0,05-0,1	2,64	10,13	0,267	2,373	0,34	23,57	0,08	0,26
+0-0,05	94,50	58,33	55,12	39,38	95,28	58,93	56,15	39,13
Σ	100,0		56,41	43,59	100,0		58,7	41,3
	Sludge sample № 3				Sludge sample № 4			
+2,5-5,0	-	-	-	-	-	-	-	-
+1,6-2,5	-	-	-	-	0,08	65,83	0,053	0,027
+1,0-1,6	0,27	40,0	0,108	0,162	0,46	65,63	0,302	0,158
+0,63-1,0	0,84	18,21	0,153	0,687	0,89	60,60	0,539	0,351
+0,315-0,63	5,95	5,5	0,327	5,623	1,32	53,09	0,701	0,619
+0,2-0,315	7,04	6,47	0,455	6,585	1,15	36,37	0,418	0,732
+0,1-0,2	8,98	9,47	0,85	8,13	1,95	14,77	0,288	1,662
+0,05-0,1	6,42	12,65	0,812	5,608	1,67	8,09	0,135	1,535
+0-0,05	70,50	57,59	40,6	29,9	92,48	62,59	57,883	34,597
Σ	100,0		43,31	56,69	100,0		60,32	39,68
	Sludge sample № 5				Sludge sample № 6			
+2,5-5,0	-	-	-	-	-	-	-	-
+1,6-2,5	0,68	55,79	0,379	0,301	1,34	55,93	0,749	0,591
+1,0-1,6	3,24	46,88	1,519	1,721	1,65	44,16	0,729	0,921
+0,63-1,0	3,49	20,45	0,714	2,776	2,02	32,91	0,665	1,355
+0,315-0,63	3,73	11,1	0,414	3,316	4,59	21,9	1,005	3,585
+0,2-0,315	4,02	6,95	0,279	3,741	3,94	15,94	0,628	3,312
+0,1-0,2	5,39	6,98	0,376	5,014	5,58	18,31	1,021	4,559
+0,05-0,1	2,66	6,61	0,176	2,484	3,56	23,56	0,839	2,721
+0-0,05	76,79	57,34	44,031	32,759	77,32	59,45	45,967	31,353
Σ	100,0		47,89	52,11	100,0		51,6	48,4
	Sludge sample № 7				Sludge sample № 8			
+2,5-5,0	8,74	76,62	6,69	2,05	0,26	20,79	0,054	0,206
+1,6-2,5	4,75	76,83	3,65	1,1	0,83	13,97	0,116	0,714

+1,0-1,6	5,77	67,2	3,88	1,89	3,56	7,06	0,251	3,309
+0,63-1,0	10,15	45,4	4,61	5,54	5,54	6,73	0,373	5,167
+0,315-0,63	14,42	44,3	6,39	8,03	16,22	10,91	1,769	14,451
+0,2-0,315	7,98	38,52	3,07	4,91	7,91	17,36	1,373	6,537
+0,1-0,2	5,49	32,71	1,79	3,7	7,15	22,41	1,602	5,548
+0,05-0,1	4,36	38,96	1,69	2,67	5,7	46,45	2,648	3,052
+0-0,05	38,34	62,86	24,1	14,24	52,83	67,35	35,581	17,249
Σ	100,0		55,87	44,13	100,0		43,77	56,23
		Sludge sample № 9				Sludge sample № 10		
+2,5-5,0	2,66	30,89	0,82	1,84	4,18	15,05	0,63	3,55
+1,6-2,5	3,19	18,73	0,6	2,59	4,88	19,33	0,94	3,94
+1,0-1,6	8,91	39,25	3,5	5,41	13,74	34,13	4,69	9,05
+0,63-1,0	14,13	48,01	6,78	7,35	16,11	46,97	7,57	8,54
+0,315-0,63	35,66	66,79	23,82	11,84	36,62	64,47	23,61	13,01
+0,2-0,315	13,67	72,83	9,96	3,71	7,61	64,43	4,9	2,71
+0,1-0,2	7,67	67,5	5,18	2,49	5,43	62,31	3,38	2,05
+0,05-0,1	2,5	64,84	1,62	0,88	2,34	69,76	1,63	0,71
+0-0,05	11,61	69,25	8,04	3,57	9,09	75,36	6,85	2,24
Σ	100,0		60,32	39,68	100,0		54,2	45,8

For a clear presentation of the data given in Tables 1 and 2, the dependences of the coal content cc and ash ca in classes on the particle size for samples with the maximum, minimum ash content and averaged over the accumulator area are plotted (Fig. 2). In the graphs, the red line with the designation cp marks the permissible ash content in the commercial product. As can be seen from the graphs (Fig. 2), the largest amount of ash is contained in the +0-0.05 mm class. For samples (Fig. 2a and 2c) with the maximum ash content and averaged over the accumulator area, this indicator is higher than the permissible one, and for the sample (Fig. 2b) with the minimum ash content, it does not exceed the permissible standards.

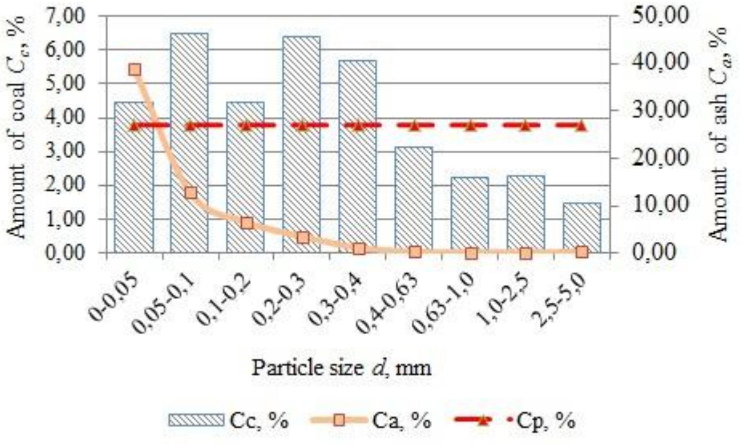
The sample, the characteristics of which are shown in Fig. 2a, has an ash content of 63.65% with a total coal content of 36.35%. In the size class of +0-0.05 mm, the ash content is 38.79% with a coal content of 4.4%. If this class is separated, it is possible to obtain a product with a coal content of 35.9% with an ash content of 24.86%.

The sample, the characteristics of which are shown in Fig. 2b, has an ash content of 46.1% with a total coal content of 53.9%. In the size class of +0-0.05 mm, the ash content is 24.25% with a coal content of 7.45%. If this class is separated, it is possible to obtain a product with a coal content of 46.45% with an ash content of 21.85%.

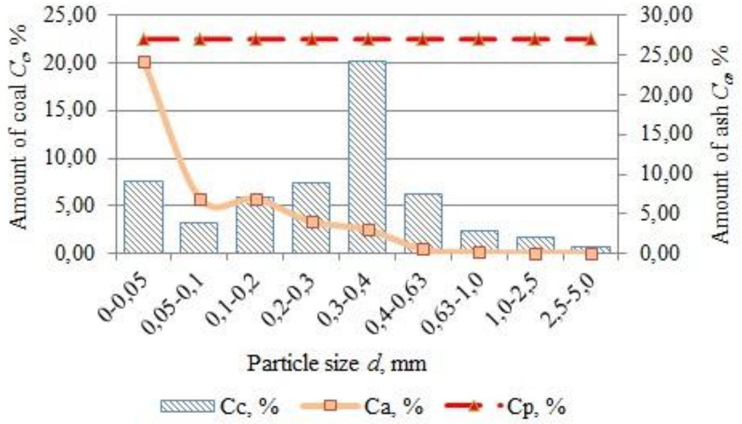
The sample, the characteristics of which are shown in Fig. 2c, has an ash content of 53.89% with a total coal content of 46.11%. In the size class +0-0.05 mm, the ash content is 37.35% with a coal content of 12.85%. If we separate this class, we can obtain a product with a coal content of 33.26% with an ash content of 16.54%. As follows from the analysis of Figures 2, Tables 1 and 2, the ash content of the sludge in different sections of the storage facility varies from 43.31 to 60.32% with a carbon content of 39.68 to 56.69%.

As follows from the analysis of Figures 2, Tables 1 and 2, the ash content of the sludge in different sections of the storage facility varies from 43.31 to 60.32% with a carbon content of 39.68 to 56.69%. The maximum ash content is observed in the +0-0.05 mm size class. If samples 1–6, 8 are divided by the boundary size of 0.05 mm, an oversize product can be obtained with a coal content of 2.17 to 38.98% with an ash content of 1.29 to 8.19%. It can be returned to the coke plant production or used as a raw material for energy. The undersize product with an ash content of 35.58 to 57.88% contains 17.25 to 34.59% coal, and water, and can therefore be used as a coal-water fuel for power engineering.

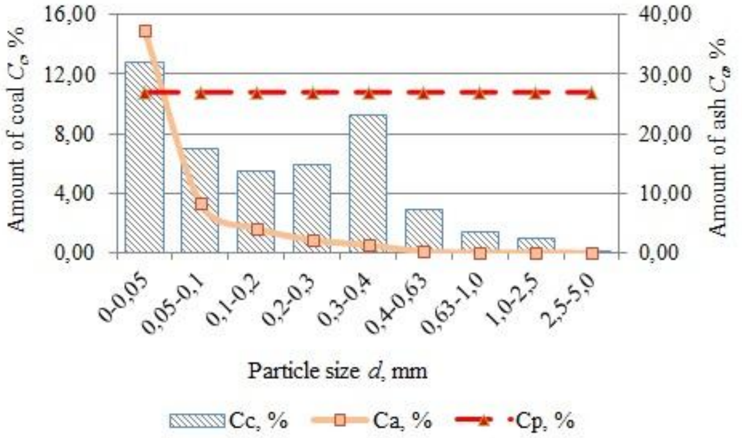
In samples 7, 9, 10, when separated by a boundary size of 0.05 mm, the coal content will be from 29.89 to 43.56% with an ash content of 31.77 to 52.28%, which does not meet regulatory requirements. To obtain a commercial product with an ash content of no more than 25-27%, these samples should be classified in two stages, by the boundary size of 0.63 and 0.315. As a result, three products with standard ash content are obtained. These data indicate that the properties of sludge from different points of the storage tank (by area) have significant differences. Therefore, before its development, it is necessary to study in detail the properties of sludge from the storage tank at different points of occurrence. Based on these data, the storage tank should be developed in sections with adjustment of the boundary size of separation for each section.



a)



b)



c)

Figure 2 – Dependence of coal content cc and ash ca in classes on particle size d: a) maximum ash content in the sample, ca = 63.65%; b) minimum ash content in the sample, ca = 46.1%; c) average sample, ca = 53.89%

The results of the studies indicate the fundamental possibility of obtaining low-ash coal concentrate from high-ash sludge by fine classification without using expensive flotation methods. The main recommendation for working out the details of the new technology consists of two main operations: fine classification of watered coal sludge and maximum possible dehydration of the obtained low-ash coal concentrate (oversize product).

Fine classification by size of 0.05-0.1 mm with high efficiency for narrow strips of separated classes of dry bulk materials is a problem (Nadutyi et al., 2016). The Ukrainian industry does not mass-produce equipment for these purposes. Currently, developments in this direction and individual tests are underway. Classification of pulp with a solid content by these classes is an even more difficult task, since its solution is complicated by the additional viscosity of the liquid and clay inclusions dissolved in it. To overcome these forces on the working surface, accelerations are needed that significantly exceed their level on existing serial vibrating screens (Nadutyi & Shevchenko, 2009).

A new vibratory impact screen for fine classification of dry bulk materials and pulps has been developed at the IGTM of the NAS of Ukraine. To create a pulsed effect on the screening surface and the processed raw material, it is proposed to use modes with "double impacts", when during the excitation period, in addition to the main impact, an additional impact is applied (Lapshyn & Shevchenko, 2024; Lapshin & Shevchenko, 2013).

Due to the main impact, the oversize product is thrown up and during its flight; an additional impact is transmitted to the screening surface, increasing its vibrations. As a result, capillary bridges rupture and meniscus stability in the screening surface cell is lost – the separation and dehydration process are improved.

In laboratory conditions, wet coal sludge from the storage facility of Dnipro Coke Chemical Plant was classified by the boundary size of 0.05 mm using a vibratory impact screen model. The ash content of the initial product was 43.77%. As a result of the separation, a product was obtained with a coal content of 35.98% with an ash content of 9.59%. The extraction of particles smaller than 0.05 mm in size into the undersize product was up to 70-80%, while dehydration of the oversize product was ensured to 7-10%. The obtained results confirmed the possibility of obtaining low-ash coal concentrate from high-ash sludge by fine classification and dewatering.

According to the authors (Nadutyi et al., 2016), given the diversity of rocks containing coal seams, their mineralogical composition is of practical interest for the development of technology for deep enrichment of coal sludge to extract not only carbon, but also other useful minerals and metals. For example, it is known that the host rocks contain aluminum, germanium, and iron in quantities of industrial interest. To extract them from the initial raw material, additional research is needed to develop technologies for separating useful components from waste rock, mutual separation of useful components, including, for example, such processes as magnetic, electrical separation, flotation, etc.

The integration of machine learning (ML) and artificial intelligence (AI) in processing watered coal sludge presents a promising direction for optimizing classification accuracy and reducing human error. In the case of the Dnipro Coke Chemical Plant, AI-driven models can analyze particle-size distribution and moisture content in real-time, allowing adaptive control of separation processes (Psyuk & Polyanska, 2024; Polyanska et al., 2022; Beshta et al., 2015). Predictive algorithms trained on historical and sensor data could enhance decision-making for selecting optimal parameters for dehydration and recovery. Moreover, AI enables automated quality assessment of the resulting materials, improving the consistency and commercial viability of recycled products (Polyanska et al., 2022; Falshtynskyi et al., 2020; Fedoreiko, 2024; Hrnčević, 2017). These technologies not only improve process efficiency but also contribute to environmental and economic sustainability by minimizing waste and energy consumption (Polyanska et al., 2022; Ivanchenko et al., 2014; Hrnčević, 2017).

It should also be noted that the authors of publications (Nadutyi & Shevchenko, 2009; Kamianske City Council, 2018; Ivanchenko et al., 2015) indicate the need for preliminary separation of the finest classes of +0-0.05 mm in size when processing coal sludge, since these classes are characterized by high ash content and a significant amount of dust and clay particles, which, in the presence of water, become soaked, stick together in the form of lumps, clog the working areas of the equipment made in the form of narrow gaps (for example, magnetic, electrical separation) and reduce the efficiency of its operation. The presence of clay particles also worsens the flotation indicators. Therefore, to separate the class of +0-0.05 mm in size before these processes, a vibratory impact screen designed by the IGTM NAS of Ukraine can also be used.

The feasibility of coal sludge processing, based on its chemical composition and ash content, suggests that various recycling or utilization methods could significantly improve the quality of the sludge while enhancing resource recovery. Flotation techniques, with expected recovery rates of up to 80%, effectively separate valuable components, while thermochemical processes can offer energy recovery efficiencies ranging from 60-70%. In addition to these approaches, the possibility of deep processing is explored, including the extraction of critical metals, aluminosilicates, and other raw materials of industrial interest. These materials could be repurposed for various applications, including the production of thermal insulation materials. In their future research, the authors aim to investigate the potential for thermochemical treatment of sludge waste, with a focus on producing high-value thermal insulation products tailored for different industrial applications.

Conclusion

The research confirms that the mining, metallurgy, and electricity sectors generate over 150 million tonnes of industrial waste annually in Ukraine, of which an estimated 25–30% consists of liquid or semi-liquid waste stored in outdated accumulators. These accumulators significantly threaten local water bodies, especially due to their prolonged operation – some exceeding 30–40 years of use without modern maintenance or recycling systems. The urgent need for environmentally safe recycling technologies is reinforced by the growing pressure to comply with EU-aligned environmental standards.

It was determined that the utilization of fine-dispersed coke-chemical waste with particle sizes of 0.05–0.1 mm, combined with a dehydration rate of up to 60%, can reduce the volume of stored waste by approximately 45–

55%. Simultaneously, material and heat energy recovery efficiencies of up to 70% were observed under pilot processing conditions. These results highlight the potential of new low-waste and circular-economy-based technological systems to transform waste into valuable raw materials.

To ensure proper extraction and reuse, comprehensive physico-chemical characterization of waste from different storage sites was conducted. In three pilot locations, variations in ash content (ranging from 28% to 41%) and moisture content (32% to 48%) influenced processing decisions. Such site-specific analyses are essential for selecting optimal recovery strategies and tailoring industrial processes to local waste characteristics.

The study demonstrates the technical feasibility of producing a marketable product from waste processing, with recovery yields reaching up to 35% of usable material. This approach not only frees up storage space, by reducing the residual volume by nearly half, but also reduces environmental pressure and generates additional revenue for enterprises, estimated at €60–90 per tonne of recovered product depending on composition and market demand.

In future research, the authors plan to focus on the scientific and technical justification for the implementation of industrial waste recycling technologies, particularly those related to coke-chemical and metallurgical enterprises. Priority will be given to the development of modular and scalable technological solutions that can be adapted to different types of waste accumulators and allow on-site processing with minimal environmental impact. Special attention will be paid to the creation of efficient thermal insulation materials based on fine-dispersed technogenic components such as fly ash, slag mixtures, and aluminosilicates, with studies on their thermal conductivity, strength, moisture resistance, and fire resistance.

In parallel, the authors aim to conduct a comprehensive economic justification of these solutions, including life cycle analysis, profitability, payback period, and environmental benefits. This will enable the formulation of realistic implementation scenarios for recovered materials on the market and assess the potential economic feasibility of the proposed technologies. The results are expected to be integrated into strategies for sustainable development and the green post-war recovery of Ukraine, with the possibility of attracting international funding and support through European research programs.

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