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Utilisation of industrial waste in heat and power industry

Abstract. The study aims to address the physical properties and chemical composition of ash and slag waste from a thermal power plant to determine the possibility of its reuse in the heat and power industry. This included classification and chemical analysis of ash and slag waste generated by the Bishkek thermal power plant to determine its composition. The received material samples were also subjected to laboratory tests to determine the particle size distribution and moisture content. Once the fractionation boundaries were established, a detailed study of the ash mass was carried out, including carbon distribution analysis and flotation experiments to determine effective methods of carbon recovery from ash and slag waste. The results confirmed the significant potential of ash and slag waste from the Bishkek coal-fired thermal power plant for reuse in the heat and power industry. Analysis of the chemical components revealed the content of unburned coal particles within 10-11%, and the content of water-soluble sulphur and sulphuric acid compounds ranged from 0.18% to 0.71%. Experimental data confirmed the importance of the fractionation of ash and slag by particle size, which makes it possible to further separate coal fractions with different physical properties. The

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fraction of less than 150 microns is characterised by a low carbon content (less than 2.5%), which makes it suitable for use in construction as a fine aggregate. However, the study noted that fractions larger than 150 microns, and especially those larger than 300 microns, are a valuable feedstock for the production of carbon concentrate with a carbon content of more than 75%, which opens up the prospects for its use in the production of water-coal fuel. Thus, the results of the study confirm the potential of ash and slag waste for reuse in the heat and power industry. This can help to reduce waste, reduce the negative impact on the environment, and create efficient and sustainable production processes in the heat and power industry

Keywords: ash and slag waste; flotation; coal particles; carbon concentrate; water-coal slurry; fuel processing

INTRODUCTION

In major cities and towns of Kyrgyzstan, the main suppliers of heat and electricity are combined heat and power plants and boiler houses, which are fuelled by solid fuels. This results in the use of a significant amount of coal, contributing to the release of a significant amount of ash into the atmosphere and its storage in ash dumps. Such ash dumps are becoming a serious problem, occupying large areas of fertile land and having a negative impact on the environment. The environmental impacts of using coal for energy production also impose significant financial costs for environmental remediation and protection. Each tonne of coal used causes significant environmental damage, which leads to huge economic losses. Therefore, issues related to efficient energy management and reduction of negative environmental impact are becoming increasingly important for Kyrgyzstan.

The development of alternative energy sources and the introduction of more efficient technologies for the utilisation of industrial waste, such as ash and slag, can help mitigate this impact and make the energy sector more sustainable and environmentally friendly. Ash and slag waste can become a valuable resource if the right approaches to its disposal are used (Lyubchyk *et al.*, 2015). The integration of innovative methods of using this waste is possible in various industries, including construction, agriculture and others. However, it may be more promising to recycle and reuse them in the thermal power industry, which could make it possible to use ash and slag waste efficiently and reduce dependence on traditional energy sources, while reducing the negative impact on the environment (Orfanova, 2023).

To combat the negative effects of coal use in the energy sector, a detailed study of their composition and properties is essential. M.A. Khoshimkhanova *et al.* (2022) employed a chemical analysis method to determine the composition of ash and slag waste, which confirmed its potential as a valuable product in various industries. Z. Xue *et al.* (2022) also studied ash and slag and revealed that they can be used in the production of environmentally friendly fuels with a high degree of efficiency. O. Svietkina *et al.* (2021), in turn, highlighted that optimising waste management processes, such as ash and slag, can significantly reduce waste volumes and make the production of certain materials more cost-effective. Nevertheless, further research is required to develop technologies and methods for their utilisation, as well as to create an infrastructure for their processing and industrial application, to fully transition to the use of ash and slag waste as raw materials or fuel.

One of the key factors influencing the successful utilisation of ash and slag waste is the development of innovative technologies aimed at turning it into high-quality materials. L. Ren *et al.* (2023) demonstrated that specialised ash and slag treatment methods can produce materials with properties such as increased carbon content, which can be used in the thermal power industry. E. Liu *et al.* (2020) also confirmed the potential of ash and slag to create environmentally friendly and efficient fuels, such as water-coal fuel. However, W. Yu *et al.* (2022) state that the development of more efficient methods of waste treatment and purification is necessary to minimise the content of harmful impurities and ensure high quality of the final product. This, in turn, emphasises the importance of continuous scientific and technological development in the field of industrial waste management and the creation of innovative approaches to its processing.

The development of effective methods for controlling the quality and safety of products made from slag waste. S. Yan *et al.* (2023) addressed the environmental impact of various slag treatment processes and determined that certain processing methods can reduce emissions and improve environmental safety. J. Zhang *et al.* (2023) assessed the environmental safety of slag use in the heat and power industry and confirmed the environmental friendliness of products obtained from ash and slag processing. L. Cuicui *et al.* (2024) identified the need to improve the technologies for treating such waste to increase its popularity and applicability in the heat and power industry. Despite the progress in the study of ash and slag waste, it is necessary to study more deeply the issues related to the long-term perspective of products derived from ash and slag waste. It is also necessary to investigate the possible negative impact of these products on the environment and human health, which will allow for a more complete assessment of the environmental sustainability of such projects.

The study aims to determine the optimal methods of treatment and use of ash and slag waste from a thermal power plant, using the example of the Bishkek Thermal Power Plant (TPP), to identify the potential for its use as an important product in the production of water-coal fuel. The main objectives of the study are to analyse the chemical composition and physical properties of ash materials, determine the optimal methods of waste treatment and purification, and explore the possibilities of reusing the products in production processes.

MATERIALS AND METHODS

The detailed study of ash and slag waste generated by thermal power plants began with a process of classification and chemical analysis to determine its composition. The fuel slag was obtained as a result of coal combustion in a pulverised form, after which its chemical composition and properties were studied. The ash and slag waste and ash from the hydraulic ash removal process were also subjected to chemical analysis and detailed study of properties and characteristics.

To study the possibility of producing coal fuel from ash and slag waste, areas were identified on the territory of the Bishkek CHP plant where a significant amount of slag crushed stone and ash mass with a minimum slag content was concentrated. Material samples were taken to a depth of 1.7 m using a hand-held drill to minimise the impact of external factors and preserve material integrity. Then, the obtained samples of ash and slag crushed stone were subjected to laboratory tests to determine the particle size distribution and moisture content. The particle size distribution was determined by sorting the particles by size, and the moisture content was measured to assess the degree of dryness of the material.

After laboratory tests, the particle size distribution limits were established. Fractions with sizes less than 300 μm were classified as "ash", fractions from 300 μm to 1 mm as "slag sand", and fractions larger than 1 mm as "slag". Hence, the data obtained was systematised and classified for further analysis and use in the study. For a more detailed study of the ash mass, samples with a high ash content were prepared. After that, a series of experiments was conducted to determine the main characteristics of the ash mass, which included detailed fractionation of ash with the definition of the boundaries of separation into fractions.

The process of studying the carbon distribution in different ash fractions included a preliminary dehydration step at 375°C to remove moisture and other volatile components from the samples that could affect the final results. This procedure was followed by an experiment in which the samples were subjected to pyrolysis at temperatures up to 900°C. During the pyrolysis, substances were lost, including carbon components, which made it possible to estimate the carbon content of the ash. Subsequent analysis of the data was used to determine specific values of carbon content in different ash fractions and to analyse its distribution depending on different sample processing conditions.

For a more thorough analysis of the efficiency of flotation methods of carbon extraction from ash and slag waste, a series of experiments were also conducted on a flotation machine using mechanical frothing. This involved the use of various chemicals including paraffin as a collector, rare glass as a mineral particle depressor, and a variety of synthetic surfactants as foaming agents.

The flotation separation process was analysed for two main fractions of ash and slag waste – fine (less than 150 microns) and coarse (more than 300 microns). For the fine fraction, the main priority was to effectively remove carbon residues to reduce the carbon content to less than 2.5%, which is critical to ensure high-quality material for further use in industrial processes. At the same time, for the fraction larger than 300 microns, it was more important to achieve a carbon concentrate with the highest possible carbon content and minimum ash content, which significantly increases its value and applicability in the thermal power industry.

RESULTS

In Central Asian countries, including Kyrgyzstan, the use of ash and slag waste is less than 4% of the total volume, reflecting insufficient attention to waste management and inefficient use of resources. Increasing the use of ash and slag waste can reduce the amount of waste produced by the industry and reduce the negative impact on the environment.

Ash and slag waste (ASW) is an important resource in various fields, including energy, construction and others. The composition of ash and slag waste, including the content of carbon and other substances, makes it a valuable source of energy when burned. Recycling processes for ASW can be optimised to increase the efficiency of their use and reduce harmful emissions into the atmosphere. Using ASW to process and produce important products that can be used as alternative fuels in thermal power plants can reduce the consumption of coal or gas, which helps to reduce greenhouse gas and other pollutant emissions (Guo *et al.*, 2020a; Lv *et al.*, 2023). They are also a valuable component in the production of cement and concrete, due to their positive impact on the structure and properties of materials. Ash and slag waste improves the strength, deformability, frost and chemical resistance of building structures by regulating the concentration of calcium hydroxide in the curing system.

After the process of selecting, incinerating and storing fuel waste, it is classified into three main types: fly ash (FA), ash and slag mixture (ASM) and fuel slag (FS). The hydraulic ash from the Bishkek Thermal Power Plant (TPP) with a moisture content of 40 to 50% is transported to special ash pits in a fine form using a pneumatic system. The combustion of coal produces fuel slag in a dust-like form, which is a compact and durable mass. Its composition is a mixture of particles ranging in size from 0.10 to 30 mm, with some inclusions of larger particles. This material can be considered a natural combination of fine and coarse aggregates. That is why slag produced by thermal power plants is effectively used as the main aggregate in both light and heavy concrete. They can also partially replace crushed stone in the amount of 20 to 50%.

The chemical analysis of the selected samples revealed that the content of SiO_2, Al_2O_3 and $FeO+Fe_2O_3$ in the mixture and the ash from the hydraulic removal is identical. However, the chemical composition of the fuel slag is distinguished by a particularly high FeO+Fe_2O_3 content of 5.02%, including 3.96% Fe_2O_3. This is possibly caused by the increased content of molten particles and the formation of fuel slag (Table 1).

Table 1. Chemical composition of ash and slag at Bishkek TPP, %

Waste name	SiO_2	Oxide										Unspecified components
		Al_2O_3	Fe_2O_3	FeO	CaO	MgO	SO_3	MnO	K_2O	Na_2O	TiO_2	
ASM	52.09	20	1.44	0.79	5.74	0.74	0.71	0.02	1	0.5	0.92	15.3
FA	52	21.58	0.97	1.3	6.47	1.14	0.21	0.01	1.7	0.9	1.05	12.13
FS	54.95	20.56	1.06	3.96	7.67	2.22	0.18	0.1	1.2	2.4	0.88	4.07

Source: compiled by the authors

When studying the chemical composition of FA and ASM, it was found that they contain no free lime. The presence of CaO is due to the presence of calcite. The chemical composition of fly ash materials is also characterised by a high content of alumina (Al_2O_3), which has certain properties and prospects for use in various industries requiring materials with high resistance to thermal and chemical influences. The content of unburned coal particles (UCP) in the fuel waste was about 10-11%, while the content of water-soluble sulphur and sulphuric acid compounds, converted to SO_3, ranged from 0.18% to 0.71%. A detailed study of the properties of various components of ash and slag reveals significant differences that prevent their direct use without prior separation.

Regulatory requirements from various industries emphasise the importance of classifying and separating ash components. For instance, the construction industry limits the content of unburned carbon, and the iron and steel industry sets a minimum iron content in ores. These limitations make fly ash unsuitable for many purposes, leaving only limited use as a substitute for aggregates or for landscape amendments. ASW, which is classified as acidic ash, is initially devoid of binding properties. But when they are incorporated into a composite cement binder, an interesting transformation takes place: they begin to interact with calcium hydroxide, acquiring the property of pozzolanic activity already at normal temperatures. This transformation is due to the formation of various firing products in the ash, including clays containing amorphous substances such as metakaolinite and aluminosilicate compounds, as well as amorphous forms of SiO_2, Fe_2O_3 and Al_2O_3. These components exhibit different activities when interacting with calcium hydroxide (Cheah *et al.*, 2021). Metakaolinite is particularly active due to its large specific surface area, which leads to the formation of calcium hydrosilicates and hydrogenated calcium. At higher temperatures, kaolinite decomposes, producing silica and alumina with lower activity due to their sintering and crystallisation, which results in a decrease in their specific surface area. The ash also contains aluminosilicate phases, quartz and feldspars, which are inactive under normal temperature conditions but become more reactive with increasing temperature.

The increase in hydraulic activity of amorphous clay is associated with its high specific surface area, which results from the decomposition of metakaolin ($Al_2O_3x_2SiO_2$). This process converts metakaolin into amorphous silica (SiO_2) and alumina (Al_2O_3). The increase in the specific surface area is due to the enrichment of the material with microscopic cavities and irregularities on the surface of the particles, which in turn contributes to more intensive interaction with water and other components of the concrete mix (Hay & Celik, 2023). The percentage of soluble silicic acid in the ash ranges from 1.5% to 6%. This parameter has a significant impact on the chemical properties of ash and its ability to interact with other components in the creation of building materials. The amount of free alumina, in turn, varies from 0.2% to 2.7%. An important factor is that certain components of ash and slag may represent more valuable raw materials, provided they are extracted and meet quality standards. For example, ash that has been subjected to a carbon purification process can have a value many times higher than the value of the original ash and slag material. Similarly, magnetite powder (Fe_3O_4) derived from ash and slag can have even higher commercial value (Li *et al.*, 2021).

Unburned coal also deserves special attention, as it stands out for its potential for more efficient use against the backdrop of production waste from coal-fired power plants. This coal, which remains after the combustion process and often has a particle size of 50 to 300 microns, is a valuable resource that can be recycled and reused. The reasons for its formation are manifold and are related to the technical complexities of the combustion process, including rapid exit from the high-temperature zone and oxygen depletion. Given the trend towards pelletized coal, which requires more careful processing, unburnt coal continues to be a relevant solution in this area. The idea of recovering and reusing unburned coal from thermal power plant ash and slag is an innovative approach to waste management and the creation of additional resources (Nesterenko & Rosokhata, 2023). This process can be of both economic and environmental importance, given its potential for wide application in various industries. During the process of temperature exposure of coal particles during combustion, a complex chemical and physical transformation takes place. Under the influence of high temperatures, the pyrolysis process takes place, as a result of which volatile components such as sulphur oxides (SO_x), arsenic (As) and mercury (Hg) evaporate from the coal matrix and are removed to a gaseous state. This process is accompanied by chemical reactions of disintegration and decomposition, which result in the formation of simpler chemical compounds (Zeng *et al.*, 2020; Johansson *et al.*, 2021).

The remaining coal also undergoes physical changes. High temperatures promote the recrystallization and reorganisation of carbon molecules in the coal matrix. This can lead to more stable structures and reduced porosity of the material. Increased density and structural orderliness can affect the physical and chemical properties of the remaining coal, making it more stable and less susceptible to oxidation and decomposition. As a result, the residual coal has a changed chemical composition and structure. Reduced volatile content and improved structural properties make it cleaner and more stable in terms of its applicability in various production processes. When using fine carbon obtained from coal sludge or tailings from coal plants, the high content of volatile components must be considered, requiring specialised purification technologies. The fixation of coal in composites requires the selection of binders with high viscosity. Underburnt coal forming hybrid particles also presents a challenge for separation due to differences in density and structure of the components, which can lead to the separation of concentrate with higher carbon content (up to 60%) requiring additional treatment (Wang *et al.*, 2021).

Effective separation of unburned coal from thermal power plant ash requires a two-stage procedure using specialised processing and separation methods that provide partial separation between these stages. This approach will make it possible to efficiently extract conditioned coal from thermal power plant ash with minimal losses and maximum efficiency. Another serious technical problem that has a significant impact on the combustion processes in TPP boilers is the lack of volatile substances in coal particles present in coal ash. This aspect has a critical impact on the efficiency and stability of energy systems. Since coal particles do not contain volatile components, this slows down the ignition process. This is due to the absence of the formation of hot gas columns necessary to maintain stable combustion. Furthermore, such particles can act as a heat source when interacting with oxygen, tending to initiate and maintain combustion. Thus, the combustion process is less intensive and less stable, which can lead to uneven heat generation and reduced efficiency of the TPP boiler.

One solution to this problem is to add unburned coal to the main fuel of TPPs. This method involves adding a small percentage (about 10-20%) of unburned coal to the main fuel before it is burned in the boilers. This process can increase the calorific value and thermal efficiency of the fuel mixture, which can lead to more efficient use of energy when burned in boilers. This, in turn, can reduce fuel consumption and reduce the operating costs of thermal power plants. However, this method has its limitations and drawbacks. Unburned coal contains high levels of ash and sulphur, which can lead to flue gas pollution and the release of harmful substances into the environment. This creates the need for additional flue gas treatment systems and can increase operating costs for maintenance and waste disposal (Turgunov *et al.*, 2024). In addition, the addition of unburned coal only temporarily increases the efficiency of the combustion process in thermal power plants but does not eliminate the root causes, such as insufficient combustion temperature or improper air distribution in the boiler. This method can only be considered as a temporary solution that requires additional research and development of more effective methods to combat the problem of under-combustion (Wei *et al.*, 2023).

When studying the process of utilisation of unburned coal from thermal power plant ash and slag, products made from ultra-carbon coal are preferable, as they represent an ideal solution due to their characteristics. First, it does not require additional grinding of the feed sulphur for effective demineralisation, which saves time and resources. In addition, it is not critically sensitive to the volatile compounds in the fuel, making it versatile and adaptable to different operating conditions. It should be noted that coal briquettes and pulverised coal fuel (PCI) do not meet all of the above criteria cumulatively. They either require additional processing or have limitations in terms of applicability to different types of thermal power plants. In contrast, water-coal fuel (WCF) has a high compliance with these parameters, which makes it more attractive for use in technical processes of utilising waste coal. Water-based fuels are a complex system involving finely dispersed carbonaceous materials such as coal, coke and graphite that are dispersed in water to form a stable and viscous slurry. This process forms a heterogeneous system similar in viscosity to fuel oil or crude oil. One of the main properties of water-coal fuel is that its quality depends significantly on the size of coal particles. The reduction in size from 300 to 30 microns is accompanied by a noticeable decrease in their ignition temperature. For example, for PCI, such a change in particle size leads to a decrease in this indicator from 560 to 420°C (Xi *et al.*, 2020). Despite this, there is no data on the entrainment temperature for particles smaller than 30 μm due to the complexity of dry grinding coal to this size. However, when using an aqueous medium, the effective grinding limit of coal is much lower and amounts to a few microns. This opens the possibility of relatively simple methods for removing coal with particles smaller than 10 microns.

The process of introducing water into coal fuel, and transforming it into water-coal fuel, has a significant impact on its chemical and thermal properties, leading to significant changes in combustion conditions. One of the key changes is a reduction in the ignition temperature of coal particles, which can range from 70 to 200°C, depending on the type of coal and particle size. It is noted that the ignition temperature for WCF produced based on anthracite coal with a low content of volatile particles (4-5%) is reduced to 500-560°C. At the same time, the ignition temperature for a WCF made from gas-coal with a high content of volatile particles (40-50%) is 400-440°C. For lignite-based WCF, this figure is even lower and amounts to 300-350°C

(Nussupbekov *et al.*, 2022). Comparing these results with the ignition temperature of PCI, it should be noted that the combustion temperature is significantly lowered when using WCF. For example, the ignition temperature for anthracite-based PCS is 950-1000°C, for gas coal it is 650-700°C, and for lignite it is 380-400°C. Such changes indicate a significant change in the thermal characteristics of coal fuel when it is modified into hydrocarbon fuel, which affects the possibility of its use in energy processes.

Comparative data for PCI and WCF based on different coal grades show that the dependence of the ignition temperature on the volatile content is much weaker for WCF than for PCI. This indicates that the process of combustion of the water-coal slurry is less sensitive to changes in the content of volatile substances compared to traditional methods of coal combustion. Predictions of the ignition temperature for WCF based on micron-sized coal particles suggest that it will be comparable to the ignition temperature of diesel fuel, which is 260-300°C. This indicates the potential for using CCS as an alternative and efficient energy source in various industrial sectors, including power plants and manufacturing plants. Also, one of the advantages of coal-based fuels is the use of wet milling in the production of WCF, which differs from the dry milling process used in the production of PCI. Wet grinding produces finer particles or significantly reduces energy consumption for the same energy input. This is because, in the water environment, coal particles are crushed more efficiently. An important aspect of wet grinding is the ability to efficiently distribute intoxicants in the medium. This makes it possible to control and improve the quality and properties of the produced WCF. Moreover, the process of water formation itself facilitates particle oscillations. This is due to an effect based on the unique properties of water's surface tension. It contributes to a more uniform and stable distribution of particles in the water medium during grinding, which affects the quality and characteristics of the resulting coal fuel (Miao *et al.*, 2020).

WCF is also unique in its ability to significantly reduce nitrogen oxide (NO_x) emissions compared to pulverised coal. This is due to such factors as lowering the flame temperature and maintaining a reducing environment. This leads to a 30-60% reduction in nitrogen oxide generation during WCF combustion compared to the process of combustion of PCI to produce the same amount of heat. The average ignition temperature of the WCF, which is 200-250°C lower than that of the PCI, significantly simplifies the design of the burner and reduces its service life, as less heat energy is required to maintain combustion. The lower ignition temperature also contributes to a more efficient combustion of the fuel, which increases the energy efficiency of the process and reduces the amount of harmful emissions. The uniqueness of water-coal fuel is also manifested in its environmental safety and ability to respond effectively to emergencies, especially in the event of leaks. The WCF consists of a mixture of safe and environmentally friendly materials – water and heat-treated coal. The latter has high thermal conductivity and adsorption capacity, which makes it an effective sorbent. This shows that even in the event of a spill into the environment, its components contribute to the purification of the surrounding water rather than pollution. Thanks to these factors, water-coal fuel does not pose a threat to the environment in the event of an emergency.

To study the possibility of producing WCF from ash and slag waste at Bishkek TPP, areas where slag crushed stone and ash mass with a minimum slag content were concentrated was determined. Samples of these materials were taken at a depth of 1.7 m using a hand-held drill to minimise the impact of external factors. These samples of ash and slag crushed stone were subjected to laboratory tests to determine the particle size distribution and moisture content. After the analysis, the particle size distribution was established. Fractions with sizes less than 300 µm were classified as "ash", fractions from 300 µm to 1 mm as "slag sand", and fractions larger than 1 mm as "slag". The detailed results of this analysis are presented in Table 2.

Table 2. Characteristics of granulometric composition and moisture content of ash and slag waste from Bishkek TPP

Characteristic	Sample number					
	1	2	3	4	5	6
Type of waste	slag. rubble	slag. rubble	ash mass	slag. rubble	slag. rubble	ash mass
Humidity, W, %	7.8	6.6	26.8	7.4	9.7	27.5
More than 1 mm, %	85.2	79.9	22.1	83.2	80.8	15.3
From 300 microns to 1 mm, %	3.9	7.3	5.7	4.4	10.1	2.4
Less than 300 microns, %	10.9	12.8	72.2	12.6	9.1	82.3

Source: compiled by the authors

After careful analysis, it was found that the slag content of the mixture varied in a wide range from 15 to 85%, while the moisture content varied from 6.6 to 27.5%. Samples with high ash content were prioritised due to their potential importance and applicability in the context of further research.

Addressing that the effectiveness of the strategy for further processing of raw materials is determined by the completeness of information on the properties of the feedstock, a series of experiments was conducted to determine the main characteristics of the ash mass. As part of this research, detailed fractionation of ash was carried out, the boundaries of separation into fractions were determined and the properties of each fraction were analysed. An example of such an analysis is the particle size distribution of sample No. 6, details of which are presented in Table 3.

Table 3. Detailed characteristics of sample No.

Parameter	Fraction size (microns)							
Number of particles, %, weight	less than 40	40	90	125	150	300	1 mm	more than 1 mm
Differential	42	14.2	6.2	1.6	2.6	2.1	3.5	12
Integral	42	53.3	77.2	82.9	84.4	85.5	88	100

Source: compiled by the authors

The results of the analysis of various waste fractions show that there are no slag particles in the fine fractions, the size of which does not exceed 90-125 microns. However, when moving to larger fractions, starting from the specified size, the presence of slag particles becomes visually noticeable. This process is accompanied by an increase in slag concentration as the fraction size increases. When studying the fractions larger than 150 microns, particles of unburned coal were observed in the form of coarse particles that stand out from the rest of the material. For a more in-depth analysis of the carbon distribution in different ash fractions, the loss of substances during pyrolysis at high temperatures of up to 900°C was studied. This experiment was carried out after preliminary dehydration of the samples at 375°C, which helped to eliminate moisture and other volatile components that could affect the results (Table 4).

Table 4. Results of substance loss in the pyrolysis process

Fractional size (μm)	less than 50	50-150	150-200	200-300
PCI, %, weight	2.12	2.48	4.15	5.94

Source: compiled by the authors

As a result of classification by particle size (less than 150 microns), a clean ash fraction with a pulverised coal content of less than 2.5% was obtained. This product is becoming a valuable resource that can be used as an active additive or aggregate in concrete mixtures and concretes, opening up prospects for creating materials with improved strength and stability characteristics. However, the fraction larger than 150 microns is noteworthy. This coarse fraction has a higher carbon content, which makes it more promising for the extraction of carbon concentrate with a carbon content of more than 75%. This concentrate can be safely used as a fuel, ensuring efficient combustion and minimising emissions of harmful substances.

The fraction larger than 300 microns consists of slag sand with an increased PCI content of up to 8%. To optimise the use of this fraction, it is advisable to carry out carbon removal procedures to a level of less than 2.5%. This can be achieved through various methods such as leaching or other methods. After cleaning procedures, the material becomes more suitable for use and can be successfully used in various industries. A detailed analysis of the composition of the ash and slag waste revealed the presence of coal particles and composite carbon-mineral compounds. These particles have similar physical properties to ash particles, which opens prospects for their separation. Embedded in thin layers of waste, coal particles represent a valuable source of carbon that can be extracted for further use. To investigate flotation methods of carbon recovery from ash, an experiment was conducted on a flotation machine using mechanical frothing. The experiment tested various chemical reagents, including paraffin as a collector, rare glass as a mineral particle depressor, and various synthetic surfactants as foaming agents. The flotation separation process was analysed for two different fractions of ash and slag waste – fine (less than 150 microns) and coarse (more than 300 microns). For the fine fraction, the main priority was to remove carbon residues to reduce its content to less than 2.5%. This aspiration is driven by the need to refine the material and ensure its high quality for further use in production processes. In contrast, for the fraction larger than 300 microns, the main objective was to produce a carbon concentrate with the highest possible carbon content and minimum ash content. The properties of the products obtained as a result of the experiment are presented in Table 5.

Table 5. The main characteristics of the products obtained

Characteristic	Ash output	Concentrate	Tails
<150 μm			
Mass, g	100	7.1	92.4
PCI, %, weight	2.86	30.2	0.84
>300 μm			
Mass, g	100	6.5	93.1
PCI, %, weight	6.9	73.4	1.9

Source: compiled by the authors

From the analysis of the data presented, a variety of ash fractions show potential for flotation treatment, which opens the way to the production of high-carbon foam products as well as carbon-free residues. The following results can be achieved with the correct flotation process settings: fractions with particles smaller than 150 microns remain as low-carbon mineral residues after processing, which can be used as fine aggregates in the production of construction materials. At the same time, fractions with particles larger than 300 microns allow us to isolate carbon concentrates with a high carbon content (73.4%) suitable for use as fuel. In addition, the foam concentrates from the fine ash treatment, enriched in carbon (30.2%), can be further processed to produce high-carbon concentrates.

Thus, carbon concentrate, obtained from particles larger than 300 microns using various separation methods, is an important intermediate product in the WCF production process. Its high carbon content and low ash content render it desirable for use in the thermal power industry. This confirms the potential of ash and slag waste as an alternative fuel source that can mitigate energy dependence and reduce the negative impact on the environment.

DISCUSSION

Research into the production and recycling of environmentally friendly products based on fuel waste plays a key role in the heat and power industry. They reduce the negative environmental impact associated with the emission and storage of solid waste, including ash and slag, produced by thermal power and industrial enterprises. Environmental issues are becoming increasingly important in the thermal power industry, and the recycling of fuel waste for reuse offers promising ways to reduce the negative impact on the environment. Research in this area also contributes to the development of new technologies and production methods that allow efficient use of fuel waste as a product in the creation of efficient fuel materials. This includes the development of specialised methods for waste treatment and purification, optimisation of material separation processes, and research into their physical and chemical properties to achieve optimum results. Such technologies create industrial products with improved technical characteristics and environmental sustainability. Another important factor is that the utilisation of fuel waste in the heat and power industry can contribute to reducing the costs of heat and power generation, increasing the economic efficiency of the industry (Stoliarov, 2024). This is associated with the possibility of using available and cheap sources of raw materials, such as ash and slag, as the main component to produce fuel products. Thus, research in this area is not only of environmental but also economic importance to the industry.

The chemical analysis of the ash and slag waste samples carried out in this study revealed that the content of coal particles was approximately 10-11%. However, the chemical composition of the fuel slag is distinguished by a particularly high $FeO+Fe_2O_3$ content of 5.02%, including 3.96% Fe_2O_3. This is determined by the increased content of molten particles and the formation of fuel slag, which confirms its specific chemical properties. The study by Hariana *et al.* (2021) also determined that the structural characteristics of waste slag have a significant impact on its physicochemical properties and potential applications in various industries. Y. Wang *et al.* (2022), addressed the processes of slag formation and revealed that an important factor is the temperature regime of the fuel combustion process and the composition of the feedstock. Compared to the results of the above-mentioned works, which focused on fuel slag, this study focused on the properties of ash and slag materials and their application in the heat and power industry, which opens new prospects for the efficient use of slag waste in the production of environmentally friendly fuels.

It should also be noted that an important result obtained during this study is the detection of an increased carbon content in the ash and slag mixture, which makes it more promising for the extraction of carbon concentrate with a carbon content of more than 75%. This indicates the potential for using these materials in various technological processes and applications in the heat and power industry, ensuring efficient combustion and minimising emissions of harmful substances into the environment (Lyubchik *et al.*, 2008). At the same time, C. Wu *et al.* (2024) studied the properties of ash in the context of sustainable heat and power and determined that the use of this component allows it to be used as one of the main products in the production of water-coal fuel. L.J. Nunes (2020) also addressed the possibilities of using ash materials and the quality of such products, as a result of which the data obtained supplemented and confirmed the conclusions. However, this study is of particular importance, as it examines in detail not only the chemical composition of ash materials but also their physical and mechanical properties, especially when used in the thermal power industry. Unlike the above-mentioned studies, this research delves deeper into the analysis of the physical and mechanical properties of ash materials, which presents a more complete picture of their potential reuse in the heat and power industry. Thus, the findings of this study are an important contribution to the understanding of the capabilities of fly ash materials in the industry, as well as their potential for various technological applications.

Innovative methods, including high-temperature pyrolysis and flotation, were used in this study to thoroughly examine the carbon distribution in different fractions of the ash and slag waste. The pyrolysis experiments were carried out after preliminary dehydration of the samples at 375°C to remove moisture and other volatile components that could affect the results. Flotation analysis of fractions of different sizes (150 μm and 300 μm) was used to determine the optimal methods of carbon extraction to ensure maximum efficiency and quality of material processing. W. Wang *et al.* (2020) also used the flotation separation method, which confirmed the results of the study and increased the understanding of the physical properties and structural composition of ash materials. Z. Xue *et al.* (2023), in turn, addressed similar aspects, but focused on other types of ash residues and their potential applications. Nevertheless, this study has contributed to the knowledge of the structure and properties of ash residues, which is important for their further use in various areas of the heat and power industry and technologies. It also provided valuable information on the thermal properties of the ash residues. The analysis of thermal characteristics determines the temperature intervals in which changes in the composition and structure of materials occur. This is important for optimising their processing and subsequent use in various industries. The data obtained on the properties of ash and slag allow for more precise control over the processing and formation of final materials based on ash residues, which contributes to an increase in production efficiency and the quality of the products (Bieliatynskyi *et al.*, 2022).

The data presented in this study also confirms that different ash fractions have the potential to be processed through flotation, which opens prospects to produce high-carbon and carbon-free products. Different results can be achieved by adjusting the flotation process: fractions with particles smaller than 150 microns remain low-carbon and can be used in the production of construction materials as fine fillers. At the same time, fractions with particles larger than 300 microns allow us to produce carbon concentrates suitable for fuel with a high carbon content (73.4%). In addition, the carbon-enriched (30.2%) foam concentrates from the treatment of fine ash provide an opportunity for additional processing to produce high-carbon concentrates. F. Guo *et al.* (2020b) also investigated pyrolysis processes to analyse changes in ash composition at high temperatures, providing a deeper understanding of chemical transformations and the potential for carbon products. O. Kon and S. Caner (2021) covered the analysis of the efficiency of different filtration methods for coal waste treatment, demonstrating their applicability in practical conditions. The results of these studies add to the general understanding of coal waste treatment and utilisation, offering a more complete picture of its potential and applications. The results demonstrate the effectiveness and prospects of using innovative approaches to coal waste treatment and disposal, which opens up new horizons for creating sustainable and environmentally friendly technologies in the coal industry.

It should be noted that, in general, all such studies play an important role in the development of the heat and power industry and in increasing the sustainability of infrastructure projects. The data obtained can optimise materials and technologies in the waste management process, as well as economic efficiency and environmental sustainability. Understanding the physical and chemical properties of ash and slag materials at a detailed level allows for the development and use of more optimised technologies, which have a positive impact on process efficiency and environmental safety.

CONCLUSIONS

This study confirmed that ash and slag waste from coal-fired thermal power plants, using the example of Bishkek TPP, has a significant potential for reuse in the heat and power industry. This underscores their importance as a valuable resource that can ensure efficient and sustainable production of water-coal fuel while reducing the negative impact on the environment and reducing the need for primary energy resources.

Chemical analysis of the components showed that the content of unburned coal particles in the fuel waste is about 10-11%, and the content of water-soluble sulphur and sulphuric acid compounds, converted to SO_3, ranges from 0.18% to 0.71%. The results of the experiments demonstrate the importance of separating ash and slag from coal-fired thermal power plants into fractions depending on the particle size. This approach enables the subsequent differentiation of coal fractions into components with different physical properties, which is of fundamental importance for further use. The fraction of less than 150 microns is distinguished by its low carbon content (less than 2.5%), which opens prospects for its use in the construction industry as a fine filler or additive. The additional processing of this fraction through the flotation process results in an even more significant reduction in carbon content (less than 1%), making the resulting product even more in demand in various construction and technical applications. On the other hand, fractions larger than 150 microns, especially those larger than 300 microns, are valuable feedstocks to produce carbon concentrate with a high carbon content (over 75%). The resulting carbon concentrate is a promising product to produce hydrocarbon fuel, which reflects the significant potential of this material in the energy industry. It should be noted that this study has a limited scope of analysis, covering only one thermal power plant. This means that the results may not be fully representative of other stations, requiring additional research. In addition, it is necessary to address the influence of process characteristics on the characteristics of ash and slag waste, which can also affect the accuracy of the study results.

For further research, it is recommended to study in more detail the impact of various technological processes on the chemical composition and physical properties of ash and slag waste from a particular TPP. It is also necessary to investigate the effectiveness of different waste treatment methods to produce products with high value and purity. This will optimise the processes of utilisation and reuse of ash and slag waste, as well as increase production efficiency in the thermal power industry.

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CONFLICT OF INTEREST

None.

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Використання техногенних відходів у теплоенергетичній промисловості

Анотація. Дане дослідження було спрямоване на вивчення фізичних властивостей і хімічного складу золошлакових відходів теплової електростанції, для визначення можливості їх повторного застосування в теплоенергетичній промисловості. Це передбачало класифікацію і проведення хімічного аналізу золошлакових відходів, отриманих в результаті роботи Бішкекської теплової електростанції, для визначення їхнього складу. Отримані зразки матеріалів також були піддані лабораторним випробуванням для визначення гранулометричного складу і вологості. Після встановлення меж поділу на фракції проводилося детальне вивчення зольної маси, включно з аналізом розподілу вуглецю та експериментами з флотації для визначення ефективних методів вилучення вуглецю із золошлакових відходів. Отримані результати підтвердили значний потенціал золошлакових відходів Бішкекської теплової електростанції, що працює на вугіллі, для повторного використання в теплоенергетичній промисловості. Аналіз хімічних компонентів виявив вміст незгорілих вугільних частинок у межах 10-11 %, а вміст водорозчинних сірчистих і сірчанокислих сполук варіювався від 0,18 % до 0,71 %. Експериментальні дані підтвердили важливість фракціонування золи та золошлаків за розмірами частинок, що надає можливість для подальшого розділення вугільних фракцій з різними фізичними властивостями. Фракція розміром менше 150 мкм характеризується низьким вмістом вуглецю (менше 2,5 %), що робить її придатною для використання в будівництві як тонкодисперсний наповнювач. Однак, було відзначено, що фракції розміром понад 150 мкм, і особливо ті, що перевищують 300 мкм, є цінним вихідним матеріалом для виробництва вуглецевого концентрату із вмістом вуглецю понад 75 %, що відкриває перспективи його використання у виробництві водовугільного палива. Таким чином, результати дослідження підтверджують потенціал золошлакових відходів для повторного використання в теплоенергетичній промисловості. Це може сприяти зменшенню обсягів відходів, зниженню негативного впливу на навколишнє середовище, а також створенню ефективних і стійких виробничих процесів у теплоенергетичній промисловості

Ключові слова: золошлакові відходи; флотація; вугільні частинки; вуглецевий концентрат; водовугільна суспензія; переробка палива