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FOREIGN EXPERIENCE OF PROCESSING ASH SLAG WASTE FROM THERMAL POWER PLANTS

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Abstract. Ash slag waste is technogenic mineral formations that are produced in large quantities and represent a serious environmental hazard. On the other hand, it is a valuable mineral raw material for the production of various materials, housing, road, rural and industrial construction, and the mining industry. In accordance with the set goal, the foreign experience of processing ash waste from thermal power plants was studied. The impact of toxic substances contained in waste storage areas on the environment and the human body was studied. An analysis of the composition and characteristics of ash and slag waste was performed. An analysis of the composition and characteristics of ash and slag waste was performed. The experience of their processing in world practice is analyzed. Promising directions for use as an additional raw material in Ukraine are determined. Processing and utilization of ash and slag waste will allow the following: various materials and products for the construction industry can be obtained from cheap and affordable raw materials; when closing and laying mines, to reduce the risk of groundwater and surface water pollution due to the increase in concentrations of total dissolved solids, sulfates, manganese, iron, boron and various trace elements of heavy metals, which significantly exceed the basic concentrations; alkaline coal fly ash is a reliable and safe material for preventing acid drainage or restoring abandoned rock lands; to get additional raw materials for energy. The return of up to 20% of the carbon extracted from the ash, with a daily consumption of about a thousand tons at the thermal power station, will make it possible to reduce the amount of purchased coal and transport costs for its delivery from the station. Processing of ash and slag waste will allow to free and return to economic circulation the fertile land occupied for the storage facilities, to extract a significant profit from the sale of the obtained products and to significantly reduce the impact on the environment. Thanks to the use of ash and slag materials, significant savings will be achieved compared to traditional options for using natural raw materials.

Keywords: coal, ash waste from thermal power plants, CCW, recycling, recycling experience, fly ash, bottom ash, boiler slag, FGD gyps.

1. Introduction

According to the data provided by the Institute of Energy in their statistical survey, world electricity production grew by 2.3% in 2022 which is lower than the growth rate of the previous year, which was 6.2%. Renewable energy sources (excluding hydropower) provided 84% of net demand growth. Wind and solar energy reached a record level of 12% of the share of electricity production, while the share of solar energy was 25%, and wind energy grew by 13.5%. The cumulative production of wind and solar energy once again exceeded the production of nuclear energy. Natural gas electricity production remained stable in 2022 with a share of about 23%. Coal remained the dominant fuel for electricity production in 2022 with a stable share of around 35.4%, which is slightly lower than 35.8% in 2021. In 2022, the total consumption of primary energy increased by 1%, which is approximately 3% higher than the level of 2019 before COVID. The share of renewable energy sources (excluding hydroelectric power) in primary energy consumption reached 7.5%, which is almost 1% more than in the previous year. Fossil fuel consumption as a percentage of primary energy remained stable at the level of 82% [1].

Table 1 shows data on global electricity production in the world depending on primary energy for 2022 [2].

"Green" energy technologies are developing rapidly, but are not yet ready to completely replace energy production from fossil fuels, require a manifold increase in the extraction of minerals and have a number of other, not yet sufficiently studied, impacts on the environment. Coal still leads in electricity production. The world's largest consumer of coal is still China, which accounts for more than half of the world's energy at 53.3%. Second and third places were taken by India (13.6%) and the USA (8.9%). Together, these three countries account for more than three-quarters of the energy generated using coal. Coal combustion - for electricity generation and in metallurgy and cement production - is the world's largest source of CO_2 emissions. However, its use in electricity generation has actually increased by 91.2% since 1997, when the first global climate agreement was signed in Kyoto [2].

Table 1 – Global electricity production in the world depending on primary energy in 2022 [2]

1. Sources of electricity by types of fuel		2. Production of electricity, %	
3. Non-renewable	Coal	4. 35.4	5. 70.7
	Natural gas	6. 22.7	
	Atomic generation	7. 9.2	
	Oil	8. 2.5	
	Others	9. 0.9	
10. Renewable	Hydro generation	11. 14.9	12. 29.3
	The wind	13. 7.2	
	Sunny	14. 4.5	
	Others	15. 2.7	

In Ukraine in 2021, electricity production amounted to 156.576 billion kWh, which is 5.2% more than in 2020. This is stated in data from the Ministry of Energy. The main share in the total output in 2021 was made up of nuclear power plants - 55.1%, thermal power plants and combined heat and power plants – 29.3%, hydroelectric power plants and pumped storage power plants – 6.7% [3–5].

In 2022,, total electricity production in Ukraine decreased by 27.5% , consumption – by 31.5%, in particular by industry – by 45%, by population – by 16% compared to 2021,according to Olga Buslavets, former Energy Minister [6].

In January-April 2023 in Ukraine, according to an assessment prepared by the United Nations Development Program (UNDP) and the World Bank, electricity production decreased by 32.5% compared to the same period in 2021.The output of nuclear power plants in the four months of 2023 compared to the corresponding period in 2021 decreased by 32.8% – to 19.5 TWh, thermal power plants – by 45.3%, to 7.6 TWh, combined heat and power plant – by 41, 7%, up to 2.8 TWh, RES – by 34.4%, up to 2.1 TWh, while the production of hydroelectric power plants and pumped storage power plants increased by 36.4% – up to 4.5 TWh. The share of nuclear power plants in the production structure for four months of 2023 amounted to 53.4% (in January-April 2021 – 53.6%), thermal power plants – 20.8% (25.6%), combined heat and power plant – 7.8% (8. 8%), hydroelectric power stations and pumped storage power plants – 12.3% (6.1%), renewable energy sources – 5.7% (5.9%). According to the report, electricity consumption in Ukraine in January-April 2023 amounted to 32.4 TWh, which is 18.9% less than in 2022, and 33.5% less than in 2021 (48.8 TW-year) [6].

Regarding coal, information from international experts is quite contradictory. Some of them talk about a decrease in its role in electricity generation, others that, due to the energy crisis, Europe is temporarily switching to coal-fired electricity generation. In order to ensure energy security, a number of countries are extending the life of coal-fired power plants and returning previously withdrawn capacities [7].

For Ukraine, generating electricity from this resource is an important component of energy security. Coal will be one of the sources of the energy fuel base for many years, given the presence of its powerful deposits on the territory of Ukraine and the lack of alternative to the role of thermal power plants (TPPs) and combined heat and power plants (CHPs) in electricity generation [8, 9]. However, the use of fossil raw materials also has negative consequences, both for Ukraine and other countries.

The annual world production of mineral raw materials is about 100 billion tons, of which only 2% is used as a useful product, the remaining 98% in a modified state is sent to waste. As a result, about 1 billion tons of gaseous waste are emitted annually into the atmosphere, about 15 billion tons of liquid waste - into the hydrosphere, approximately 85 billion tons of solid waste, which are stored in storage facilities, as a result of which up to 10 million hectares of fertile land are withdrawn from economic circulation [10]. Carbon dioxide emissions from energy use in 2022 compared to 2021 increased by 0.9% to 34.4 Gt CO_2-equivalent [1].

One of the main sources of pollution is the facilities of the fuel and energy complex of thermal power plants and thermal power plants that burn solid fuel, resulting in the formation of ash and slag waste (ASW), which can be used as secondary raw materials.

The integrated use of ASW is an urgent need not only for Ukraine, but also for any economically developed state, and, as practice has shown, waste from this industry, firstly, is produced in large quantities, and, secondly, poses a serious environmental hazard. This problem becomes especially acute when equipment is physically and morally worn out. For further improvement and development of ASW processing in Ukraine, it is necessary to study world experience, search for new directions for their use, and sales markets.

2. Methods

The following methods were used in this study: analytical review of literature sources, comparative analysis; monitoring and assessment of the impact of ash and slag waste storage sites on the environment and population; analysis of the composition of the ashes; analysis of the possibilities and prospects for the use of ash and slag materials in the world.

The purpose of the work is to study foreign experience in processing ash waste from thermal power plants.

Object of study: ash and slag waste from thermal power plants.

To achieve this goal, the following tasks were solved:

– the impact of toxic substances contained in ASW storage areas on the environment and the human body was studied;

– the composition and characteristics of ash and slag waste were analyzed;

– the experience of ASW processing in world practice was analyzed;

– the promising areas were identified for the use of ash and slag waste, which need to be developed in Ukraine.

Impact of toxic substances contained in ASW storage areas on the environment and the human body.

Objects of the fuel and energy complex, in terms of the degree of influence, are among the most intensively affecting the environment. All thermal power plants in the world emit about 700 million tons of pollutants of various hazard classes per year [11, 12]. The air is intensively polluted by emissions containing a variety of substances harmful to the environment (oxides of sulfur, nitrogen, carbon, heavy metals, hydrocarbons, dust particles). It is calculated [12] that a combined heat and power plant with a capacity of 2.4 million kW, operating on coal, consumes (t/h): fuel – 1060, water – $3•10^5$; emits into the environment (t/h): ash – 194, slag – 34.5, warm water – $28•10^5$. Environmental load from aeropollutants (Greek aer means air; English air pollutants means harmful impurities of man-made or natural origin) thermal power plants (TPP) makes significant changes to the atmosphere: the content of particles that are condensation nuclei increases 10 times; gas impurities in the air increase from 5 to 25 times; the number of clouds increases by 5–10%, and the amount of fog in winter increases by 100%, in summer – by 30%; solar radiation is reduced to 20% [12]. Accumulated ash and slag waste exerts a significant environmental load on nature with geomorphological, hydrogeological, geochemical, geothermal, engineering-geological, mineralogical and geophysical consequences [12].

When operating storage areas for ash and slag waste from thermal power industry enterprises, damage to the environment is caused due to the spread of dry ash in the form of dust in adjacent areas and the filtration of contaminated water due to the poorly screened ash disposal bed [8, 9, 11].

The problem of the influence of energy facilities on environmental safety was the subject of scientific research of many scientists; in particular, the work [13] determined the features of the distribution of heavy metals in soils due to the emissions from a thermal power plant. In [14] the impact of the ash dump of the Trypillya TPP on the health of the population living in the adjacent territories is shown. In [15], by analyzing monitoring data, the condition of groundwater in the area of influence of the Sumy combined heat and power plant was assessed. The authors of [16, 17] analyzed harmful emissions from the Burshtyn TPP and the environmental situation around it. Works [18–20] are devoted to the peculiarities of the impact of ash dumps of thermal power enterprises on the environment. An assessment of the risk of pollutant emissions from coal and coal waste combustion plants and the environmental impact of fly ash disposal is given in [21]. Brief review of [12–21] shows that the chemical composition of ash and slag waste is a complex mixture of various, mainly mineral, substances, and their content depends on the composition of the fuel. Facilities of the fuel and energy complex of Ukraine belong to potentially dangerous sources of environmental pollution and create risks for the health of the population living in adjacent territories.

Thus, on the one hand, ASW are technogenic mineral formations (products of pyrotechnological processes occurred in the combustion chambers of thermal power plants). Depending on the type of solid fuel and the physicochemical processes occurred in these boilers, the formation of ash and slag occurs without a melt, or with its formation, or with complete melting of the initial components, accompanied by the release of gas and vapor substances, decarbonization, melting, crystallization and silicate formation of initial raw materials [12]. On the other hand, ash and slag wastes are valuable technogenic mineral raw materials for the production of building materials, housing, road, agricultural construction, agriculture, mining and oil industries. In developed countries, ash and slag are not considered waste, they are a "by-product of thermal power plants," so power plants prepare the product for sale, bringing its characteristics to the requirements of construction regulations. In the countries of the post-Soviet space, ash and slag is still waste, and power plants can offer potential consumers just the waste, and not the technologically modified products with characteristics which meet construction regulatory requirements [12].

The problem of waste disposal, which is the most important element in the overall chain of creating waste-free production systems, is given much attention both in our country and abroad [22–33]. It involves the involvement of various types of waste in new technological cycles or their use for other useful purposes. Greening production is impossible without supplementing production complexes with special facilities designed for waste processing. The degree of waste recycling should be considered as one of the important indicators characterizing the environmental friendliness of the relevant industries, that is, the degree of their impact on the environment and the complete use of natural resources [22–33].

The modern focus on greening the operation of coal-fired thermal power plants in the world leads to significant structural changes. In the countries of the European Union, as well as in the USA and other industrialized countries of the world, recycling of ASW is an integral component of the technological process of coal-fired thermal power plants. Therefore, great attention is paid to these issues [22–33].

3. Theoretical and experimental parts

The main range of ASW products (in foreign publications – CCW coal combustion products) include [28, 33]:

– slag (bottom ash) – porous material obtained in dry furnaces (usually with hydraulic removal);

– cinder (boiler slag) – glassy granular material obtained in wet furnaces;

– phosphogypsum (FGD gypsum) – a product of fuel gas desulfurization;

– fly ash, a fine material that, after burning coal, is captured in filters or electrostatic precipitators, obtained by mechanical or electrostatic deposition of small particles from fuel gases. Fly ash consists of microscopic spheres containing silica, iron, aluminum, calcium, etc.

Fly ash (FA; taking into account the publications, the names TPP ash or TA, coal ash or CA are used as synonyms,) are the largest type of waste (75–80% of ASW) [34]. Since large-scale combustion of coal to generate electricity began in the 1920s, many millions of tons of ash and associated byproducts have been generated. Coal-fired power plants produce large volumes of ash every year: more than 100 million tons in the United States. India – 112, China – 100, Germany – 40 and Great Britain – 15. Most of the ash is located in landfills and ash lagoons. Ash contains trace elements (As, B, Cr, Mo, Ni, Se, Sr and V), which have negative effects on the environment due to potential leaching by acid rain and groundwater [24, 25].

The characteristics of FA in terms of composition, mineralogy, surface chemistry and reactivity are of fundamental importance in the development of its various applications. Fly ash is generally gray in color, abrasive, generally alkaline and fire resistant in nature. Fly ash contains various elements: P, K, Ca, Mg as well as Zn, Fe, Cu, Mn, B and Mo, which are essential for plant growth. The pozzolanic properties of ash and astringency allow its effective use for the production of cement, building materials and products. The properties of fly ash (bulk density, permeability, internal angular friction and compaction characteristics) make it suitable for use in the construction of roads and structural embankments, mine filling, etc. The chemical composition of FA with a high content of silica (60–65%), alumina (25–30%), magnetite Fe_2O_3 (6–15%) allows it to be used for the synthesis of zeolites, alum and precipitated silica. Other important physicochemical characteristics of fly ash such as particle size, porosity, water holding capacity and surface area make it suitable for use as a low-cost adsorbent for the removal of toxic ions and organic matter from flue gases, wastewater. FA has great potential for environmental applications and represents a resource that has yet to be fully exploited, for example in processing of materials for agriculture and mechanical engineering. To date, no industrial applications have been implemented. It is necessary to overcome the economic barriers associated with the high cost and large volumes of fly ash used in industry [34].

Analysis of the experience of ASW processing that exists in world practice.

Already in the 80s, in developed countries, ash and slag waste was processed into various construction materials and products. Table 2 shows the volumes of ASW recycling and areas of use in the 80s [17, 20, 27, 32, 35, 36].

Table 2 – Volumes of ASW recycling and areas of use in the 80s [17, 20, 27, 32, 35, 36]

Country	Recycling volumes, %	Scope of use
USA	38	Production of mortars and concretes
Great Britain	54	Construction materials and products
Germany	80	
Finland	52	
France	65	
Poland	50	Products made from cellular concrete
Slovakia	75	
Czech	75	

For comparison, the level of ash utilization in post-Soviet countries in the 80–90s was 4–5% [9].

Ashes from thermal power plants and coal preparation wastes were widely used abroad in the production of fired ceramic bricks and artificial porous aggregates. Considering the decisive importance of the maximum permissible content of unburned fuel in the ashes of power plants, foreign regulatory documents allow it in quantities, for example, in Germany (DIN 1 045) – not more than 3.5%, in the Great Britain (BS 3892) – 7%, in the USA (ASTM-C-618) – 10% [17, 20, 27, 32, 35, 36].

Production of artificial porous aggregates based on ashes, slags and coal enrichment waste for their subsequent use in the manufacture of lightweight concrete products has become quite widespread in foreign countries. Large plants for the production of agloporite based on thermal power plant ash with a capacity of 200...600 thousand m^3 per year operate in the state of New York, in Detroit, Philadelphia, Pittsburgh, etc. In the UK, such enterprises operate in Northfleet, Ragley, Tilbury and produce products under the brand name “Lightag”. In Germany, the most famous is the plant for production of agloporite, which was built at the Scholven power plant near the city of Essen. The ash from this plant is also used in road construction and cement production. In the city of Rosalie (Belgium) there is a plant for the production of 160 thousand m^3 of agloporite from coal preparation waste. In Bytom (Poland) there is also a plant for the production of agloporite from coal enrichment waste. The carbon content in waste ranges within 7...12% [17, 20, 27, 32, 35, 36].

The US professor Oscar Manz, in his review report at the 11th international symposium on the use and regulation of coal combustion by-products in Orlando (1995), provided data on the yield and use of ash from thermal power plants in general, including in construction, from which it can be seen that most countries of the world used ash from 55% to 90% of the output, including in construction from 35% to 70%. The CIS countries mostly occupied one of the last places (7% overall and 4.4% in construction) [37].

Table 3 shows the share of waste used in developed countries until 2000 [17].

Table 3 – Share of waste used in developed countries until 2000 [17]

Country/Region	Recycling volumes, %
North America (USA, Canada)	63
Western Europe (France, Germany, Italy, England)	58
Japan	87
China	37

In January 2003, the 15th International Symposium “Production Management and Use of Coal Combustion Products” was held in the city of St. Petersburg (Florida, USA) organized by the American Coal Ash Association (ACAA) [32]. Ninety five reports on various aspects of this problem were heard at this symposium. A number of technological solutions and equipment samples were presented at the exhibition organized as part of the symposium. Control over the production and disposal of coal combustion products is a major economic and environmental problem. The annual production volume of these products is the second after the volume of production of non-metallic building materials and in 2000–2001 amounted to 107 million tons in the USA, 59 million tons in the European Union (EU), 8.4 million tons in Japan (the share of coal in the fuel balance Japan 17%). Coordination of work in the field of production, marketing, and determination of effective areas for using CCW to obtain market-competitive and environmentally friendly materials in the United States is carried out by the ACAA. In the EU, similar functions are performed by the European Coal Combustion Products Association (ECOWA) [28]. Its associated members are organizations from Canada, Japan and Israel.

Table 4 shows the distribution of CCW by types in the USA and the EU for 2000–2001 [32].

Table 4 – Distribution of CCW by types for 2000–2001 [32]

Countries	Coal combustion products							
	Fly ash		Slag		Boiler slag		Phosphogypsum	
	million tons	%	million tons	%	million tons	%	million tons	%
USA	61.8	57.7	17.1	16	2.3	2	25.9	24.2
EU	38.9	66	5.6	9.5	2.4	4	10.6	18

For the period 1990–2000, the US CCW production increased by 21%, with phosphogypsum production increasing by 58%. An increase in the specific gravity of phosphogypsum was also noted in 2000–2002. A similar trend is observed in the EU. With an increase in the total volume of CCW in 1993–2000, about 4.3%, phosphogypsum production increased 2.7 times. Of the 10.6 million tons of phosphogypsum (2000), 7 million tons were produced in Germany [32].

In the United States, volume of CCW recycling increased by 70% during the period of 1992–2002 and significantly outpaced the growth of their formation. At the same time, the volume of fly ash utilization increased by 67%, and phosphogypsum - by 10 times. The volume of fly ash disposal in the EU increased over the period 1993–2000 from 34% to 40%, and slag – from 25% to 40%. In Japan, coal ash recycling increased from 50% in 1990 to 82% in 2000.

Table 5 shows the volumes of CCW recycling in different countries (data for 2000–2001) [32].

Table 5 – Volume of CCW recycling in different countries (data for 2000–2001) [32]

Countries	Coal combustion products		Fly Ash		Slag		Boiler slag		Phosphogypsum	
	million tons	%*	million tons	%*	million tons	%*	million tons	%*	million tons	%*
USA	19.98	32.3	5.19	30.4	1.65	71.7	6.88	28	33.7	31.3
EU	17.89	46	2.24	40	2.4	100	7.63	72	30.16	52.4
Japan	–	–	–	–	–	–	–	–	6.89	82

* From the total product output; excluding products used for reclamation of open-pit mines;
– no data.

The structure of CCW use (2001) in the USA is presented in Table 6, in the EU – Table 7 [32].

In Germany, 50% of the demand for gypsum raw materials is met by the use of phosphogypsum. In Japan (2001) CCW is used as cement raw material - 64%; additives for cement – 7% and in construction – 5%. Thus, the main areas of use of FA: concrete and cement technology (USA), concrete and cement technology, as well as road construction (EU), cement technology (Japan). The quality of fly ash used in concrete was regulated by ASTM C618 (USA), EN 450 (EU) and national standards. The use of slag, in addition to concrete technology, is as fillers for general construction and road works [32].

Table 6 – Structure of CCW use in the USA (2001) [32]

Areas of use % of total recycling volume	Fly Ash	Slag	Boiler slag	Phosphogypsum
Additives to cement, concrete, mortar	56.1	13.7	–	6.4
Raw materials for cement clinker	4.7	2.3	–	0.4
Fillers for various purposes	16.3	20.4	0.6	2.4
Road construction: road base mineral powder	4.8 0.2	0.5 0.6	10.5 0.6	–
Replacement of fine sand in the technology of roofing materials and other purposes	0.7	81.8	–	–
Mining	3.7	1.8	–	1.6
Wall elements	–	–	–	82.1
Other	10.6	48	17	6.5

Table 7 – Structure of CCW use in the EU (2001) [32]

Areas of use % of total recycling volume	Fly Ash	Slag	Boiler slag	Phosphogypsum
Additives to concrete	33		6.6	–
Additives to cement	10.7	7.3	–	–
Cement raw materials	23.4		–	–
Concrete blocks	6.1	45.9	–	–
Road construction	21.9	–	51.8	–
Lightweight aggregate	–	2.3	–	–
Replacing fine sand	–	–	30.7	–
Solutions	–	–	7.1	–
Dry plaster	–	–	–	58.9
Gypsum blocks	–	–	–	3.2
Plastering works	–	–	–	10.2
Self-leveling floors	–	–	–	17.3

The work [32] provides a detailed review of 95 reports presented at the 15th international symposium “Production management and use of coal combustion products”. In the countries of the European Union, as well as the United States and other industrialized countries of the world, the recycling of waste, fly ash in particular, is an integral component of technological process of coal-fired thermal power plants. Thermal power plants carry out pre-sale preparation of the product bringing the characteristics of the ash to the requirements of official construction regulations.

The presented reports [32] note that 61.8 million tons of fly ash alone was processed in the USA and 38.9 million tons - in the EU for the period 2000–2001. It is noted that the volumes of recycling of fly ash in these countries significantly outstrip the growth volumes of their formation. 56.1% of fly ash is used as an additive to cement, concrete and mortar. High-ash concrete, along with saving cement, makes it possible to obtain higher water resistance and durability, increase resistance to aggressive environments and the reaction of silicon aggregates with cement alkalis. In the European Union, the problems of ashes and waste disposal and protection of the natural environment are solved simultaneously through the building of roads from ash [32].

Table 8 shows global experience in the use of ash and slag materials [26, 32, 33].

Table 8 – World experience in the use of ash and slag materials [26, 32, 33]

Additives to concrete, %	Road construction, %	Raw materials for the preparation of cement, %	Cements with additives, %	Concrete blocks, %	Aggregates, %	Other, %
32.6	22.7	21.8	13.9	5.0	2.5	1.5

A number of reports discussed the issues of extracting rare metals from ash [32].

Despite debate over whether coal should continue to cover most of the US electricity needs, the US Energy Information Administration projected in the 2009 International Energy Outlook that the United States, along with China and India, is expected to account for 88% net increase in coal consumption between 2006 and 2030. Meanwhile, coal ash waste continues to accumulate at a rate of about 131 million tons per year in the United States alone, and electric utilities are racing to recycle much of the material. The American Coal Ash Association (ACAA) reported in its study on the production and use of coal combustion products that 43% of all CCW produced in the United States in 2007 was put into so-called "beneficial use" (meaning waste is used in production of different materials or as replacement materials). Wastes which are designated by the government as a “beneficial use” are exempt from solid waste regulations governing their disposal [38].

About 71.1 million tons, or 55% of CCW produced annually is fly ash. The largest current use of FA in construction is to replace Portland cement, which binds sand and gravel in concrete. Fly ash has different characteristics depending on the chemical composition of the coal from which it is derived. Brown and sub-bituminous coals produce Class C fly ash, which has self-cementing properties, while anthracite and bituminous coals produce Class F fly ash, which usually must be mixed with water and a binder to solidify.

As a binder in concrete, FA makes up 8–12% [38].

It is estimated [38] that 23% of the total CCW produced in the United States each year (more than 30 million tons) is used in construction products, primarily concrete and wallboard, and also in clinker (the raw material for the production of Portland cement), roofing granules, aggregate for road materials and asphalt fillers. According to the ACAA, in 2007, CCW was used: 14.5 million tons in concrete; 5.0 million tons as clinker and 8.3 million tons in gypsum boards (standard interior wall elements used in the USA), 10.6 million tons for road blocks and embankments, about 6.7 million tons for abandoned mine fillings (often as a measure to neutralize acidic liquid that can flow from these objects into nearby waters). Due to mine development, groundwater and surface waters are degraded due to growing concentrations of total dissolved solids, sulfates, manganese, iron, boron and various trace heavy metals, which significantly exceed baseline concentrations. Alkaline coal ash is inherently a reliable and safe material to prevent acid drainage or the spread of heavy metals in soils [38].

Based on the analysis of the review of world experience in processing ash and slag waste, it can be concluded that the main area of use of ASW is the construction sector. It is necessary to search for new directions and areas of their use. Despite the large number of publications, insufficient attention is paid to the extraction of associated elements, including rare earths, from waste.

At the same time, the global experience of processing ASW is useful and very relevant for Ukraine, given the huge volumes and low degree of their recycling in our country.

4. Results and discussion

In Ukraine, coal energy industry produces about 10 million tons per year of environmentally friendly, mainly separated ash, in which 1.5–2 million tons of unburnt carbon remains (up to 20%) [39, 40]. According to the data given in [41], in Ukraine, about 360 million tons of ash and slag products had accumulated in the dumps of thermal power plants by the end of 2019; approximately 0.5–0.7 million tons or about 10% are recycled annually (mainly road construction), which is 5 –7 times less compared to other countries such as the USA and the EU.

Dumps existing in Ukraine have large areas, are overloaded and require significant operating costs, which affect the cost of electricity production. Considering the continued status of coal as an important energy resource in the next 20 years, the size of ash dumps and the amount of their accumulation in Ukraine will only increase [41]. The constant growth of ash dumps requires the expansion of fencing structures and additional allocation of useful land areas. Measures are needed to prevent the replenishment of ash dumps and to arrange their subsequent disposal. This requires an analysis of the possibilities for processing ash and slag waste from thermal power plants, since ash and slag require different technologies. In addition, the processing of waste ash taken from long-term storage facilities and fresh ash obtained immediately after the combustion of coal and before its storage have differences. Dump ash is a compacted rock that requires preliminary preparation. Fresh ash - is a dry finished product for processing and subsequent disposal, so at the first stage it is necessary to start with fresh ash to eliminate replenishment of the ash dump.

Since ash is a carbon-silicate mass, it is necessary to separate it into its components (carbon-silicates). The results of research [40] indicate the fundamental possibility of obtaining low-ash coal concentrate from fly ash of thermal power plants by fine classification by size of 0.05–0.2 mm with high efficiency for narrow strips of separated classes of dry bulk materials.

For this purpose, the Institute of Geotechnical Mechanics was developed a new vibrating impact screen [42–45], which makes it possible to effectively classify fine-grained materials. Laboratory tests shown that the use of such screens for fine classification makes it possible to extract the maximum amount of coal mass from ash and to use it for energy. The remaining silicate mass can be used for the production of building mixtures. Taking into account the different grades of coal and the composition of the host rocks in ash storage facilities, technology and equipment in each specific case must be adjusted for maximum screening efficiency. The return of up to 20% of carbon extracted from ash, with daily consumption of about a thousand tons at thermal power plants, allows us to reduce the amount of purchased coal and transportation costs for its delivery from the station.

Stopping the expansion of ash dump areas by processing fresh ash without storing it is extremely important since currently a great number of thermal power plants operate on solid fuel in the form of coal of various grades.

For further development and improvement of the processing of ash and slag waste, it is necessary to study their properties and the possibility of their use in other areas.

Processing of ash and slag waste from thermal power plants is an important environmental and scientific problem that requires an integrated approach, the solution of which requires to:

– use the experience of developed countries in increasing the volume of utilization of fly ash, slag and other technogenic mineral impurities in various fields;

– develop new and improve existing standards for ash and slag products;

– apply financial instruments to stimulate the processing of ASW and their use.

As a result of the analysis of the experience of ash waste processing in world practice, promising areas for the use of ash and slag waste are identified which should be developed in Ukraine (Table 9).

Table 9 – Promising areas for the use of ash and slag waste that need to be developed in Ukraine

Areas of use	Directions
Construction	Raw materials for cement clinker (raw materials for the production of Portland cement). Additives to cement, concrete, mortar. Concrete blocks. Production of artificial porous aggregates based on ashes and slags for their subsequent use in the manufacture of lightweight concrete products. Production of fired ceramics. Fillers for various purposes. Road construction: road base, mineral powder, aggregates for road materials and asphalt fillers. Replacement of fine sand in the technology of roofing materials and other purposes. Dry plaster. Gypsum blocks. Plastering works. Self-leveling floors.
Mining	Backfilling of waste mines (as a measure to neutralize acidic liquid that can flow from these objects into underground and surface waters).
Raw materials for energy	Due to the relatively high content of unburned carbon in fly ash (up to 20%), it represents a valuable raw material for processing and its return to the technological process.

The processing and use of ASW in the indicated areas (Table 9) will make it possible to obtain various materials and products for the construction sector, agriculture and mechanical engineering from cheap and accessible raw materials; to reduce the risks of groundwater and surface water contamination during mine development due to increased concentrations of total dissolved solids, sulfates, manganese, iron, boron and various trace elements of heavy metals, which significantly exceed baseline concentrations. Alkaline coal fly ash is a reliable and safe material to prevent acid drainage or the spread of heavy metals in soils; to obtain additional raw materials for energy.

5. Conclusions

Thus, on the one hand, ASW are man-made mineral formations that are produced in large quantities and pose a serious environmental hazard; on the other hand, they are valuable mineral raw materials for the production of various building materials.

In accordance with the stated purpose, foreign experience in processing ash waste from thermal power plants was studied. The impact of toxic substances contained in ASW storage areas on the environment and the human body was studied. An analysis of the composition and characteristics of ash and slag waste was carried out. The experience of ASW processing in world practice was analyzed. The utilization of ash and slag waste in Ukraine is about 10% (mainly road construction), which is 5–7 times less compared to other countries such as the USA and the EU. To increase recycling volumes in Ukraine, promising areas for using ASW as an additional raw material are identified. Their processing will make it possible to free and return to economic circulation fertile lands occupied by storage facilities, to obtain significant profits from the sales of the resulting products and to significantly reduce the impact on the environment. Thanks to the use of ash and slag materials, significant cost savings will be achieved compared to traditional options of using natural raw materials.

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ЗАРУБІЖНИЙ ДОСВІД ПЕРЕРОБКИ ЗОЛОВІДХОДІВ ТЕПЛОВИХ ЕЛЕКТРОСТАНЦІЙ

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Аннотація. Золошлакові відходи є техногенними мінеральними утвореннями, які виробляються у великих кількостях і становлять серйозну екологічну небезпеку. З іншого боку – це цінна мінеральна сировина для різних матеріалів, житлового, дорожнього, сільського та промислового будівництва, гірничодобувної промисловості. Відповідно до поставленої мети вивчено зарубіжний досвід переробки золовідходів теплових електростанцій. Вивчено вплив токсичних речовин, що містяться в місцях зберігання ЗШО на навколишнє середовище та організм людини. Виконано аналіз складу та особливостей золошлакових відходів. Проаналізовано досвід переробки ЗШО у світовій практиці. Визначено перспективні напрямки їх використання як додаткове сировину в Україні. Переробка та використання ЗШО дозволить таке. З дешевої та доступної сировини отримати різні матеріали та вироби для будівельної сфери. Зменшити ризики забруднення підземних та поверхневих вод при закладанні шахт внаслідок зростання концентрацій загальних розчинених твердих речовин, сульфатів, марганцю, заліза, бору та різних мікроелементів важких металів, які значно перевищують базові концентрації. Лужна вугільна летюча зола є надійним та безпечним матеріалом для запобігання дренажу кислоти або відновлення занедбаних гірських земель. Отримати додаткове сировину для енергетики. Повернення витягнутого із золі до 20 % вуглецю, при добовому споживанні на ТЕС близько тисячі тонн, дасть можливість скорочувати кількість купованого вугілля і транспортні витрати на його доставку зі станції. Переробка ЗШО дозволить звільнити та повернути в господарський оборот родючі землі, зайняті під накопичувачами, одержувати суттєвий прибуток із продажу отримуваних продуктів та значно знизити вплив на екологію. Завдяки застосуванню золошлакових матеріалів буде досягнуто значної економії коштів у порівнянні з традиційними варіантами з використанням природного сировини.

Ключові слова: вугілля, золошлакові відходи теплових електростанцій, продукти горіння вугілля, переробка, досвід переробки, летуча зола, шлак, котельний шлак, фосфогіпс.