



H2GEO

**New technology for hydrogen and geopolymer composites
production from post-mining waste**

Deliverable 3.3

**Analysis of possibilities
of using selected fractions from mine wastes
for recovery of rare trace elements and power
production**

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1. Introduction

The legal basis for the work entitled: “New technology for hydrogen and geopolymer composites production from post-mining waste” (acronym H2GEO) is a grant agreement No: 101112386 (RFCS-2022). H2GEO project consortium is composed of seven partners: KOMAG Institute of Mining Technology (KOMAG), Poland; GIG National Research Institute (GIG), Poland; Institute of Construction and Architecture Slovak Academy of Sciences (USTARCH), Slovakia; Institute of Energy and Fuel Processing Technology (ITPE), Poland; VSB - Technical University of Ostrava (VSB), Czechia; Wrocław University of Technology (PWR), Poland, and Haldex S.A. (HDX), Poland.

2. Goal of the work

The goal of this report is to assess the potential for utilizing selected fractions of mining waste for the recovery of rare trace elements and power production. Based on the results of laboratory analyses conducted within Task 3.2. key physicochemical and mechanical parameters of mining waste from three heaps were examined to determine their impact on material quality and usability. By interpreting these findings, the report aims to identify optimal waste management strategies and beneficiation processes that enhance the recovery of valuable elements and support energy production. Report containing of selected separation products results of laboratory analyses (microscopic evaluation of morphology changes, trace elements, metals: Si, Al, Na, K) to give information about possible directions of waste management and development of mine wastes beneficiation system.

3. Methodology

The analysis carried out is based on laboratory analyses carried out on selected post-mining waste separation products as part of Task 3.2. The analysis included:

- Analysis of trace elements and metals (Si, Al, Na, K).
- Microscopic evaluation of the material morphology using polarizing and scanning microscopes (SEM-EDS).
- Proximate and ultimate analyses including ash composition and characteristic melting points.
- Analysis of heavy metals concentration in the coal fraction.



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4. Possible directions of development of the raw material potential of the post-mining heap

Post-mining heaps are often not only an environmental problem, but can also be a source of valuable mineral resources. There are several options for managing a dump to recover these resources:

1. **Trace elements and metals:** Post-mining dumps may contain various metals such as iron, copper, zinc, lead or nickel as well as trace elements. Through appropriate technological processes, these metals and critical elements can be extracted from post-mining waste.
2. **Coal recovery:** In the case of heaps after coal mining, it is possible to recover unused coal, which can be processed or reused in industrial processes.
3. **Use as a building material:** Some heaps may contain materials that are suitable for use as aggregate in construction. After appropriate processing, they can be used, for example, to build roads, embankments or structures.
4. **Energy and chemical products:** Some heaps may contain substances that can be used to produce energy or produce chemical products. For example, the energy fraction from heaps can be burned to produce heat or electricity or subjected to a gasification process to obtain synthesis gas from which products such as hydrogen and methanol.
5. **Use in land reclamation:** Material from heaps can be used to reclaim mining or degraded areas, improving the soil structure and enabling the restoration of the areas' natural functions.

The development of post-mining heaps for the recovery of mineral resources can bring both economic and environmental benefits, contributing to the sustainable use of natural resources and reducing the negative impact of mining activities on the environment. Possible directions for obtaining commercial products from post-mining waste are shown in Fig. 1.

The coal bearing fraction (CBF) containing coal residues can be burned in power plants, where it is used to produce electricity. Another method of its management is the briquetting and granulation process, which allows obtaining solid fuels with better utility properties that is used in the chemical industry. Additionally, there is also possible gasification process, which transforms coal into gaseous fuels, which are used for energy purpose. Although the low quality of the fuels obtained in this way, caused by high moisture content and fine grain size, limits their use in the individual heating sector but they are still used in industrial power engineering.

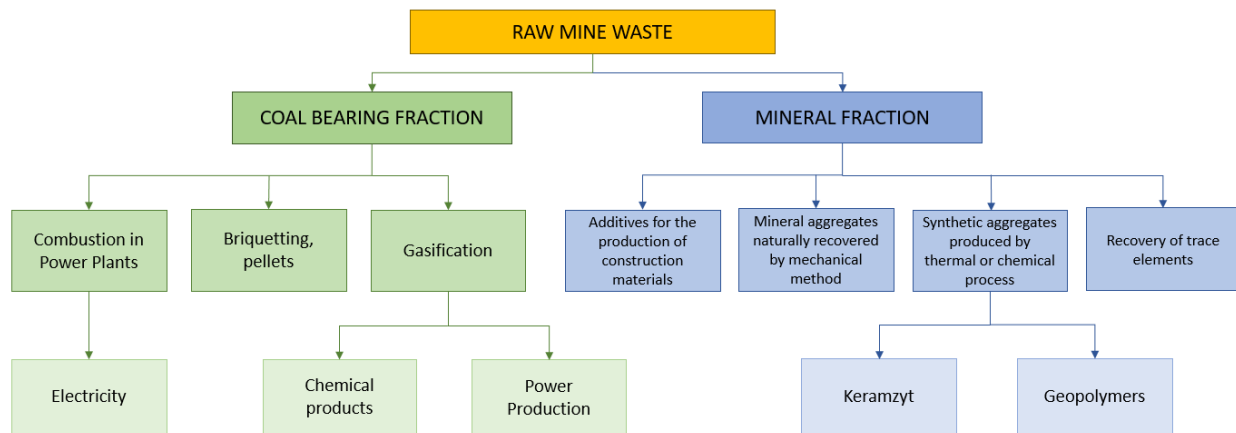


Fig. 1. Post-mining waste in terms of the possibility of producing commercial products.

The mineral fraction (MF), on the other hand, can be used as an additive in the production of building materials, which allows for the reduction of the extraction of natural resources. Purified post-mine waste can be used as aggregates used in road construction, hydrotechnical construction and for the reinforcement and stabilization of soils. Natural mineral aggregates recovered mechanically can be used as components of cement, ceramics and construction materials. In turn, synthetic aggregates, produced as a result of thermal and chemical processes include materials such as expanded clay which is used in construction as a lightweight and durable insulating material.

An additional aspect of the use of mineral waste is the recovery of trace elements which can be recovered through modern hydrometallurgical and pyrometallurgical technologies. These elements are key to modern technologies, including the production of batteries, photovoltaic panels, wind turbines and electronic devices. Their recovery can significantly reduce dependence on imports and contribute to the development of local industry. Currently, the market is dominated by mineral aggregates obtained by mechanical methods, while synthetic aggregates are not yet widely available. Existing plants dealing with the processing of post mining waste focus mainly on the recovery of the coal fraction for sale as low-quality fuel or processing spontaneously burnt coal shale, the share of which in mine waste is relatively small.

It should also be emphasised that the recovery of coal from mine waste dumps is a necessary element in the reclamation of post-mining areas because of the possibility of spontaneous combustion of the dumps and the resulting high environmental impact in terms of CO₂ emissions. An indispensable element of an industrial waste management strategy, which determines the



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choice of technology and the nature and quality of the resulting product, is the determination of the size and quality of the streams of individual raw materials. This approach is important for the economic optimisation of the recovery and management of secondary raw materials.

5. Analysis of trace elements and metals

There are a number of publications available in the literature on the analysis of the composition in terms of trace element content (including rare earth metals) from both coal waste (mining dumps) and coal itself. A number of methods for recovering these elements have also been thoroughly analysed. However, there is a lack of information on research on the direct separation process of mining dumps in terms of the separation of coal and mineral fractions, and then the analysis of trace elements in the products of separation of waste from mining dumps. It should therefore be emphasised that the innovative approach to the management of waste streams from post-mining heaps proposed in the project, based on the classification of waste into combustible and non-combustible, is a novel approach in the context of assessing the economic efficiency of the recovery technologies used.

Due to the current state of knowledge in this field, the content of individual rare earth elements was referred to the literature data available for unprocessed waste raw materials.

Table 1 presents the results of the analysis of trace element contents in coal (CBF) and mineral fractions (developed within Task 3.2). The study focused on elements such as beryllium (Be), cobalt (Co), europium (Eu), gallium (Ga), antimony (Sb), molybdenum (Mo), nickel (Ni), scandium (Sc), samarium (Sm), tungsten (W), yttrium (Y), ytterbium (Yb) and lithium (Li). These elements are considered key for new technologies and have significant economic importance. In CBF, the highest concentrations were observed for lithium (Li) (up to 78.1 mg/kg in Karvina2 CBF), nickel (Ni) (30.4 mg/kg) and gallium (Ga) (13.7 mg/kg). In mineral fractions, lithium (Li) concentrations reached 125 mg/kg in Karvina2 MF, gallium (Ga) 26.0 mg/kg, and scandium (Sc) up to 21.7 mg/kg. The presence of rare earth elements (REE), such as yttrium (Y) and europium (Eu) highlights the potential for their recovery.

In each of the analysed samples, it was noticed that the elements with the highest share (both in the coal and mineral fractions after separation) were: lithium (49.8-125 mg/kg), nickel (27.7-43.6 mg/kg), scandium (3.0-21.2 mg/kg), cobalt (8.5-18.3 mg/kg) and gallium (8.17-26 mg/kg). The content of the remaining trace elements was at the level of <10 mg/kg, and their content was similar to that in the samples analysed by other researchers.

Table 1. Analysis of trace elements and metals in post-mining wastes (Haldex and Karvina).

Element	Symbol	Unit	Haldex 1		Haldex 2		Karvina 2		Literature
			CBF	MF	CBF	MF	CBF	MF	
Beryllium	Be	mg/kg	2.79	2.64	2.77	2.64	2.91	2.95	4-5 ¹
Cobalt	Co	mg/kg	8.49	17.6	9.35	17.4	9.17	18.3	2.3-5.8 ¹ ; 2.5 ² ; 32-442.01 ³
Europium	Eu	mg/kg	0.603	0.425	0.528	0.435	0.748	0.333	6.5 ⁴ ; 1.30 ⁵ ; 0.09 ⁶ ; 0.3-1.6 ⁷
Gallium	Ga	mg/kg	8.17	25.1	8.29	23.2	13.7	26	27.4-32.2 ¹ ; 23.8 ⁶ ; 2.21-2.96 ⁸
Antimony	Sb	mg/kg	2.6	3.87	2.4	3.93	2.15	4.11	2.4-14.4 ¹ ; 2.5 ² ; 0.001-5650 ⁹
Molibdenium	Mo	mg/kg	1.84	0.674	1.8	0.668	0.894	0.46	2.2-3.9 ¹
Nickel	Ni	mg/kg	28.7	44.9	27.7	43.6	30.4	43.1	19.1-27.2 ¹ ; 35 ²
Scandium	Sc	mg/kg	4.35	21.2	3.03	21.7	6.51	19.4	12.4-15.5 ¹ ; 1.9-24.2 ³ ; 20.96 ⁴ ; 14.4 ⁵ ; 41.9; 2.11-3.47 ⁸
Samarium	Sm	mg/kg	2.79	15.1	1.92	14.7	2.85	16.6	1.29-26.24 ³ ; 13.54 ⁴ ; 4.9 ⁵ ; 0.29 ⁶ ; 5.5-8.2 ⁷
Tungsten	W	mg/kg	1.4	3.35	1.37	2.24	0.819	3.04	1.9-2.8 ¹
Yttrium	Y	mg/kg	7.38	4.21	1.87	4.31	20.6	4.42	6.3-12.4 ¹ ; 7.87-34.02 ³ ; <1 ⁴ ; 34 ⁵ ; 1.7 ⁶ ; 18.6-34.2 ⁷ ; 2.14-4.12 ⁸
Ytterbium	Yb	mg/kg	1.16	0.722	0.971	0.776	1.25	6.65	2.29-3.06 ⁸
Lithium	Li	mg/kg	49.8	105	52.6	106	78.1	125	174-324 ¹ ; 177.9 ⁶ ; <1 ³



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It is also worth emphasizing that in the mineral fraction (MF) the content of individual trace elements is much higher than in the carbon fraction (CBF) - the exception to this rule is the content of europium and molybdenum but the differences between both fractions are very small.

Interesting is the fact that the lithium content in each of the waste samples tested was the highest. In the context of forecasts of global demand for lithium and other trace elements, the method of its recovery from mining heaps is worth considering. The justification for lithium recovery from samples may become more important due to the intensively changing situation on the raw materials market caused by - among others - geopolitical instability (War in Ukraine, election results in the USA, changes in NATO's defense strategy and others). Lithium has been included in the list of critical raw materials.

The content of some trace elements may affect the properties of the geopolymer, however, some of the metals tested have toxic properties (e.g. cadmium, lead). Yang et al.¹⁰ noticed that the use of metallurgical slag with increased nickel and magnesium content has a beneficial effect on increasing the strength of the geopolymer. Table 2 presents a summary of heavy metal concentrations in CBF, focusing on elements such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), zinc (Zn) and mercury (Hg).

Table 2. Analysis of heavy metals content in Haldex1, Haldex2 and Karvina2 coal fraction samples.

Element	Symbol	Unit	Haldex 1 CBF	Haldex 2 CBF	Karvina 2 CBF
Arsenic	As	mg/kg	2.50	2.51	5.27
Cadmium	Cd	mg/kg	0.739	0.771	0.984
Chromium	Cr	mg/kg	39.3	40.5	56.6
Copper	Cu	mg/kg	53.7	48.6	35.2
Mercury	Hg	mg/kg	0.046	0.06	0.046
Lead	Pb	mg/kg	23.6	18.2	22.4
Zinc	Zn	mg/kg	54.9	51.9	63.6

The highest zinc (Zn) concentration was recorded in Karvina2 CBF (63.6 mg/kg). Chromium (Cr) levels were significant, reaching a maximum of 56.6 mg/kg in CBF Karvina2. Mercury (Hg) concentrations remained relatively low in all samples.

Possibilities of recovery and use of heavy metals:



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- Zinc (Zn) – widely used in the metallurgical industry, in the production of alloys and as a component of protective anti-corrosion coatings.
- Chromium (Cr) – used in the production of stainless steel and corrosion-resistant coatings.
- Nickel (Ni), Copper (Cu) – used in the electronics and metallurgy industries.
- Lead (Pb), Cadmium (Cd), Arsenic (As) – their contents require monitoring to prevent environmental contamination.

5.1. Evaluation of the separation process and potential directions of application of the analysed trace elements

Baron et al.⁸ presented the concept of a system for enriching post-mining waste based on the process of mechanical and magnetic separation of coal fractions and mineral matter collected directly from the heap.

Based on the results obtained in the project, it was shown that the magnetic method of separating raw material into a coal fraction (CBF) and a mineral fraction (MF) contributes to increasing the total content of individual elements compared to the original sample (before separation). On this basis, it can be stated that the proposed separation method helps to increase the potential for obtaining elements and can be an alternative to other methods of enriching coal dumps.

Another important aspect is to consider the directions of use of separation products (CBF and MF), and more precisely, in the direction of recovering trace elements from them. Potential directions of application of individual trace elements are presented in Table 3.

Trace elements (including rare earth elements) are widely used in various industries. They are valued for their ability to improve the mechanical and thermal properties of manufactured objects, specified opto-electric or catalytic properties. In metallurgy and ceramics, they are used as alloy additives to improve the strength of alloys at elevated temperatures, as a component improving the resistance of alloys to oxidation and corrosion or as an additive improving tensile strength (in the case of steel).

Some metals are used as catalysts for reactions in chemical processes or in metallurgical processes and also in nuclear energy - they can act as moderators, catalysts or stabilizers of nuclear fuels. A number of elements are also the basis for the production of electronics, most often in the form of semiconductors, integrated circuits batteries, accumulators for everyday



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products, such as electric vehicles, power tools, computers and elements of advanced electronics.

Table 3. Potential applications of rare trace elements in various industries.

Field	Be	Co	Eu	Ga	Sb	Mo	Ni	Sc	Sm	W	Y	Yb	Li
Iron metallurgy (alloying additives)		✓			✓	✓	✓			✓		✓	
Non-ferrous metallurgy												✓	✓
High-durability utility items							✓			✓			
Magnets		✓							✓			✓	
Optics (including lasers)											✓		
Ceramics		✓			✓				✓		✓	✓	✓
Glass					✓							✓	✓
Electronics – lamps, displays, and others	✓		✓	✓			✓			✓	✓		
Electronics – semiconductors. Integrated Circuits	✓			✓	✓								
Oxygen sensors											✓		
Fuel cells		✓					✓				✓		
Solar cells				✓									
Microwave devices											✓	✓	
Catalysts (chemical and metallurgical industries)		✓					✓		✓		✓	✓	
Medicine (including pharmaceuticals and medical equipment)	✓				✓							✓	
Chemical industry		✓			✓								✓
Nuclear energy (radiation shielding, moderators)			✓		✓				✓		✓		
Aerospace						✓							✓
Defense industry	✓				✓	✓				✓			
Space industry	✓						✓						
Telecommunications	✓												
Accumulators and batteries		✓			✓		✓						✓



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Rare trace elements and their contribution to various industrial sectors are depicted in Fig. 2.

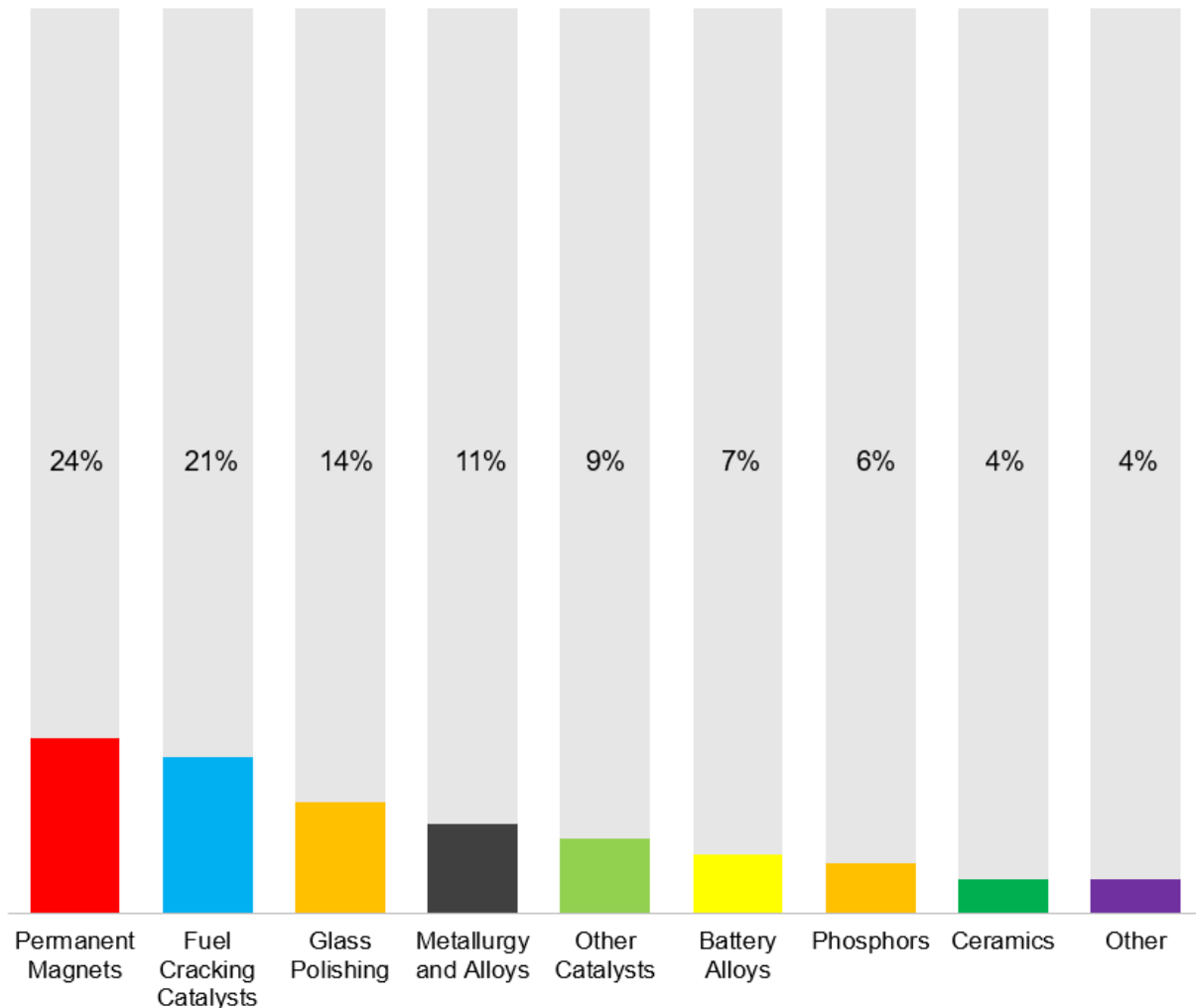


Fig. 2. The percentage rate of REEs used in various industries^{11,12}.

There are two methods of rare trace elements purification: physical and chemical, as seen in Fig. 3^{13,14,15}. Physical purification includes air classification, wet gravity separation, flotation, magnetic separation, and multi-step physical separation. Chemical purification includes leaching, precipitation, solvent extraction, ion exchange, and adsorption. Adsorption has been viewed as one of the most promising methods since it is simple to implement, effective, and widely available^{16,17,18}.



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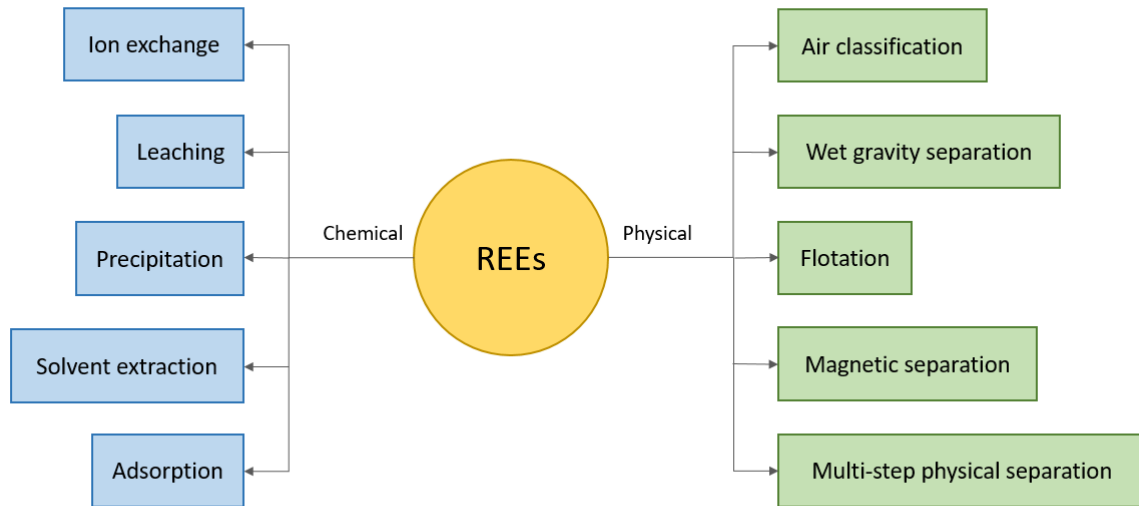


Fig.3. The purification of REEs is done through physical and chemical methods.

Taking into account the fact that the forecasted systematic increase in demand for trace elements and rare earth metals is several times higher than the current state^{19, 20} with limited supply growth²¹ will increase the profitability of alternative solutions supporting commercial, large-scale methods of metal recovery from ores.

Dugin et al.²² estimated the potential for obtaining rare earth elements from combustion waste (fly ash, sludge, slag) from brown coal combustion. For combusted brown coal with a content of >60 ppm of rare earth elements, the concentration of these elements in fly ash may be >400 ppm (metals tend to accumulate in ash). They also estimated that the content of elements at the level of 400-500 ppm allows the use of this type of ash for cost-effective extraction of rare earth elements.

Analysis of laboratory samples of post-mining heaps (coal and mineral fractions obtained as part of the project) before and after separation into fractions show that the total content of trace elements (including rare earth elements) is approximately 270 ppm.

Taking the above into account, it can be stated that at present such a level of trace and rare earth elements content would require a comprehensive analysis of the possibilities of using available element extraction technologies in terms of profitability. It is probable that the trace element content in the ash sample will exceed the level of 1000 ppm, which is the value achievable for economic justification of the profitability of rare earth elements recovery.



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Due to their increasing importance in the modern world, the recycling of products containing REEs and their extraction from waste is necessary to meet the growing demand for these elements. In the future, more work should be done on technologies to recover REEs from post-mining heaps.

6. Analysis of possibilities of using mineral fraction from post-mining heaps

Based on the physico-chemical analyses of the mineral fraction from the tailings, several directions for its utilisation can be identified. Detailed data on the oxide content, elemental composition and physical properties indicate potential uses in the construction, road building and environmental protection industries. As a result of the analyses carried out as part of Task 3.2, The results is presented in Table 4 and 5 to determine their suitability for future applications.

Table 4. Chemical composition of ash (Mineral Fraction).

Compound	Symbol	Unit	Haldex1 MF	Haldex2 MF	Karvina2 MF
Silicon dioxide	SiO ₂	%	57.09	58.69	56.97
Aluminium oxide	Al ₂ O ₃	%	23.03	22.12	25.20
Diferrous trioxide	Fe ₂ O ₃	%	5.87	5.93	4.59
Calcium oxide	CaO	%	0.47	0.77	0.70
Magnesium oxide	MgO	%	1.72	1.83	1.62
Disodium oxide	Na ₂ O	%	0.33	0.31	0.31
Dipotassium oxide	K ₂ O	%	3.31	3.20	3.74
Titanium dioxide	TiO ₂	%	0.95	0.93	1.00
Trimanganese tetroxide	Mn ₃ O ₄	%	0.06	0.07	0.06
Diphosphorus pentoxide	P ₂ O ₅	%	0.13	0.23	0.13
Sulfur trioxide	SO ₃	%	0.38	0.60	0.25
Barium oxide	BaO	%	0.06	0.06	0.06
Strontium oxide	SrO	%	0.01	0.02	0.02
Silicon	Si	%	22.480	22.706	22.438
Aluminum	Al	%	10.269	9.692	11.238
Sodium	Na	%	0.204	0.188	0.195



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Compound	Symbol	Unit	Haldex1 MF	Haldex2 MF	Karvina2 MF
Potassium	K	%	2.317	2.198	2.618
Magnesium	Mg	%	0.876	0.913	0.823
Titanium	Ti	%	0.481	0.460	0.504
Strontium	Sr	%	0.010	0.012	0.013

Table 5. Characteristic ash fusion temperatures (Mineral Fraction)

Parameter		Unit	MF Haldex 1	MF Haldex 2	MF Karvina 2
Oxidising atmosphere	Deformation temperature, DT	°C	1350	1350	1430
	Sphere temperature, ST	°C	1480	1460	1530
	Hemisphere temperature, HT	°C	1520	1490	1560
	Flowing temperature, FT	°C	1540	1510	1580
Reducing atmosphere	Deformation temperature, DT	°C	1330	1330	1420
	Sphere temperature, ST	°C	1420	1390	1490
	Hemisphere temperature, HT	°C	1450	1420	1520
	Flowing temperature, FT	°C	1490	1460	1550

6.1. Use of the mineral fraction in the production of construction materials (cement, concrete, geopolymers and others)

Chemical analysis of the mineral fraction showed a high silicon oxide (SiO_2) content of 56.97-58.69% and aluminium oxide (Al_2O_3) content of 22.12-25.20% (Table 4). Silicon oxide is a key ingredient in the production of concrete, improving its durability, while aluminium oxide increases chemical and thermal resistance, making the material resistant to weathering. The characteristic ash fusion temperatures of the tested samples of mineral fractions (Table 5), exceed 1200°C , which indicates that there should be no issues related to agglomeration and slagging during the calcination of these fractions in a fluidized bed reactor.

Iron oxide (Fe_2O_3) in the range of 4.59-5.93%, which influences the formation of the aluminosilicate phase (C_4AF) responsible for the characteristic greyish colour of the cement, is also an important component of the composition. In addition, C_4AF participates in hydration reactions that influence the setting and hardening rate of the cement²³. Furthermore, the presence of



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calcium oxide (CaO) in the range of 0.47-0.77% and magnesium oxide (MgO) in the range of 1.62-1.83% suggests the possibility of using the fraction in the production of geopolymers and building ceramics. Cement standards (PN-EN 197-1:2012, ASTM C150) limit the MgO content in Portland cement to 5%. Contents below 4-5% are considered generally safe and do not cause significant damage. The SO₃ content (0.15%) is very low and does not compromise the durability of the concrete. In fact, in controlled amounts, SO₃ improves the properties of the cement, aids the setting of the gypsum and regulates the setting time. PN-EN 197-1:2012 specifies a maximum SO₃ content in Portland cements of: ≤ 3.5% for CEM I cements, ≤ 4.0% for metallurgical cements (CEM II, CEM III). BaO and SrO are present in trace amounts and do not significantly affect the mechanical properties of the material.

For the mineral fraction, the most important parameter from the point of view of the formation of geopolymers is the SiO₂/Al₂O₃ ratio. The obtained values (Table 6) are typical of those used by other researchers and are almost in the middle of the scale used (i.e. 2.0–7.0)^{24,25}.

Table 6. SiO₂/Al₂O₃ molar ratio in the part enriched with mineral compounds after separation.

Symbol	Unit	Haldex 1	Haldex 2	Karvina 2
SiO ₂	mol	0.95	0.98	0.95
Al ₂ O ₃	mol	0.23	0.22	0.25
SiO ₂ /Al ₂ O ₃	-	4.21	4.50	3.84

It is worth emphasizing, from the point of view of geopolymer properties, the Na₂O/Al₂O₃ molar ratio. The highest mechanical strength values were obtained with Na₂O/Al₂O₃ at the level of 1.0, although these values were obtained after adding an activator. The obtained sodium content is typical for this type of materials (i.e. ash) used to create geopolymers^{16,17}.

The influence of input parameters (i.e. material, additives and process parameters) on geopolymer properties is presented in review papers^{26,27}.

The high content of SiO₂ and Al₂O₃ in the mineral fractions makes them ideal for geopolymer production. Geopolymers are sustainable alternatives to traditional Portland cement and are characterized by: high thermal stability, excellent mechanical strength and chemical resistance.

In the production of lightweight aggregates such as expanded clay and insulation materials, the content of alkali oxides is important: K₂O (3.20-3.74%) and Na₂O (0.31-0.33%). These components play a key role in the swelling processes of ceramic materials, which is important in the production of lightweight aggregates. In addition, the presence of TiO₂ (0.93-1.00%) suggests the possibility of using the fraction for the production of refractory materials. The calorific value of



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the analysed material is 1,960-2,180 J/g, which allows high temperature sintering and the production of expanded clay - a lightweight, porous building aggregate used for thermal and acoustic insulation.

Physico-chemical analyses of the mineral fraction showed a high ash content on dry basis (83.3-84.3%), indicating a low organic content and suggesting the possibility of using the fraction as a construction aggregate. The volatile matter content (10.09-10.57%) corresponds to values typical of secondary mineral aggregates used in road construction. In addition, the presence of CaO, MgO and Fe₂O₃ improves the mechanical properties, making this material useful in soil stabilisation, embankment construction, dikes and hydraulic infrastructure.

The high SiO₂ and Al₂O₃ content also makes this material a potential raw material for sorbents used in wastewater treatment and gas filtration processes. The use of post-mining wastes in environmental protection, for example as filter materials, is the subject of waste management research.

7. Analysis of possibilities of using Coal Bearing Fraction from post-mining wastes for power production

Coal bearing fractions from post-mining waste present a dual opportunity: they can contribute to sustainable energy production and find applications in industrial processes. Proper utilization of these fractions can minimize environmental impact, reduce waste accumulation, and recover value from mining by-products. This analysis delves into detailed applications, focusing on power generation and other chemical products.

The general characteristics of the CBF analysed in the project are shown in Tables 7 and 8.

Table 7. Characteristics of the Coal Bearing Fraction

Parameter	Symbol	Unit	Haldex1	Haldex2	Karvina2
Moisture content	M_{ad}	%	1.4	1.6	1.3
Ash content	A_{ad}	%	22.5	21.7	39.9
Volatile matter content	V_{ad}	%	26.91	27.24	20.75
Calorific value	$Q_{p, net, ad}$	J/g	24 750	24 830	18 190
Total sulfur content	$S_{T, ad}$	%	0.73	0.77	0.31
Total carbon content	C_{ad}	%	63.5	62.9	47.7
Total hydrogen content	H_{ad}	%	4.17	4.33	3.14
Nitrogen content	N_{ad}	%	1.01	1.04	0.73
Chlorine content	Cl^a	%	0.054	0.054	0.036

Table 8. Characteristic ash fusion temperatures (CBF).

Parameter		Unit	CBF Haldex 1	CBF Haldex 2	CBF Karvina 2
Oxidising atmosphere	Deformation temperature, DT	°C	1360	1390	1330
	Sphere temperature, ST	°C	1450	1510	1420
	Hemisphere temperature, HT	°C	1481	1520	1440
	Flowing temperature, FT	°C	1500	1540	1460
Reducing atmosphere	Deformation temperature, DT	°C	1220	1290	1210
	Sphere temperature, ST	°C	1380	1450	1350
	Hemisphere temperature, HT	°C	1430	1470	1390
	Flowing temperature, FT	°C	1450	1490	1410



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The characteristic ash fusion temperatures of the tested samples of coal fractions, exceed 1200°C, which indicates that there should be no issues related to agglomeration and slagging during the gasification of these fractions in a fluidized bed reactor. However, the implementation of the concept of using the fraction enriched with combustible compounds after separation in dust furnaces should be approached with caution. The deformation temperature (DT) and sphere temperature (ST) in a reducing atmosphere fall within the ranges of 1220–1290°C and 1380–1450°C, respectively. In the flame core, under air staging conditions—which is a common practice—such high temperatures and reducing conditions may occur.

Laboratory analyses reveal the following key characteristics of the coal bearing fraction, as shown in Table 9.

Table 9. Key characteristics of the coal bearing fraction.

Parameter	Max. value	Significance
Calorific Value	26,920 J/g	High energy content, suitable for energy production applications.
Total Sulfur Content (Analytical State)	0.77%	Moderate sulfur content; requires emissions management.
Total Carbon Content	68.3%	High carbon content, ideal for energy and carbon material applications.
Total Hydrogen Content	4.57%	Contributes to high energy density and syngas production.
Nitrogen Content (Analytical State)	1.04%	Influences NOx emissions; requires mitigation strategies.
Chlorine Content	0.081%	Low chlorine level minimizes risks of equipment corrosion and environmental pollution.

In addition, microscopic morphological analysis of the enriched mining waste samples did not reveal any visible changes indicating that the organic matter contained in the waste had undergone any thermal or chemical transformation.

These properties position the coal bearing fraction as a valuable resource for multiple energy and material applications.

7.1. Direct Combustion in Power Plants

Power boilers, due to their coal combustion technology (pulverized, fluidized bed, and grate-fired), require specific fuel parameters. However, each type of boiler is designed based on the fuel characteristics intended for combustion. The use of fuel with parameters deviating from the designed range may result in improper boiler operation and reduced efficiency.

The parameters determining the suitability for a specific technology include calorific value, ash content, moisture content, combustible matter content, and granulation.



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Different types of boilers (pulverized, fluidized bed, and grate-fired) have varying requirements for hard coal parameters due to differences in their design and combustion processes. These differences include the fuel delivery mechanism, combustion temperature, and ash removal method. Below are the key differences in fuel requirements for these boiler types.

1. Pulverized Coal Boilers (Combustion in the Form of Coal Dust)

- The fuel is ground into a very fine powder (particle diameter < 0.1 mm).
- Combustion occurs in an air suspension, enabling fast and efficient burning.
- High combustion temperatures (1300–1500°C).

Fuel Parameter Requirements:

- Calorific value: >21 MJ/kg
- Total moisture content: <12%
- Ash content: <15%
- Volatile matter content: 30–36% (ensures stable ignition and combustion)
- Granulation: Fuel ground into dust <0.1 mm
- Ash fusion temperature: >1250°C

2. Fluidized Bed Boilers (Combustion in a Fluidized Bed)

- Coal is burned in a bed of particles suspended by air (so-called fluidized bed).
- Lower combustion temperature (800–900°C), which reduces NO_x emissions.
- Capability to burn low-quality fuels, including biomass and coal slurries.

Fuel Parameter Requirements:

- Calorific value: 15–25 MJ/kg
- Total moisture content: up to 30%
- Ash content: <35%
- Volatile matter content: 25–40%
- Granulation: 0.1–20 mm
- Ash fusion temperature: >950°C

3. Grate-Fired Boilers (Combustion on a Grate)

- Fuel is burned on a mechanically moving grate.
- Used in smaller installations (e.g., municipal heating plants).
- Combustion occurs within a temperature range of 850–1200°C.

Fuel Parameter Requirements:

- Calorific value: 18–26 MJ/kg



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- Total moisture content: <20%
- Ash content: <20%
- Volatile matter content: 25–40%
- Granulation: 5–50 mm (pea coal, nut coal, lump coal)
- Ash fusion temperature: >1000°C (prevents grate slagging)

CBF (Coal Bearing Fraction) Haldex samples exhibit a high calorific value of approximately 26 MJ/kg, making the fraction from the Panewnicka waste heap an attractive fuel for combustion in conventional power plants and co-firing processes with biomass. Its chemical composition, characterized by a high carbon content of around 68% and a hydrogen content of approximately 4%, ensures efficient energy release during the combustion process.

A moisture content of approximately 1.5% makes this fuel suitable for blending with other “wet” coals in combustion processes. However, burning this dry fuel alone would not be feasible, as auxiliary equipment and boiler combustion chambers are designed for fuels with higher moisture content. Additionally, despite reducing transportation costs, the low moisture content negatively impacts dust emissions and increases the risk of self-ignition during storage.

The low ash content (around 20.0%) reduces the risk of deposit formation in the boiler and lowers operating costs, while also facilitating the potential use of residues in other industrial processes, such as cement production.

Despite numerous advantages, the use of this material also presents certain challenges, primarily in terms of emission control. The sulfur content of around 0.7% necessitates the use of flue gas desulfurization systems to meet environmental standards for SO_x emissions. Although the nitrogen content is about 1%, which theoretically limits nitrogen oxide emissions, it is recommended to implement appropriate reduction technologies, such as low-emission burners or selective catalytic reduction (SCR) systems, to minimize the impact of exhaust gases on the environment.

Another issue that requires attention is ash management. The ash content of 20.0% indicates the need to develop appropriate methods for its disposal or reuse. Additionally, the melting characteristics of the ash suggest potential operational challenges. In an oxidizing atmosphere, the deformation temperature ranges from 1210°C to 1360°C, which may lead to slag deposition in boilers operating at higher temperatures. On the other hand, the melting temperature in a reducing atmosphere ranges from 1220°C to 1520°C, which may require adjustments to combustion parameters to prevent deposits and potential high-temperature corrosion.



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In summary, the CBF from the Panewnicka dump (Haldex1 and Haldex2) is an attractive fuel for combustion in power plants due to its properties. However, its use requires consideration of various aspects related to the specific design parameters of combustion installations to ensure efficient operation, including compliance with environmental standards.

7.2. Gasification for Syngas Production

One of the directions for processing the carbon fraction, which enables versatile utilization of coal—from high-efficiency electricity generation to the production of chemical substances, including gaseous and liquid fuels—is the technology of coal gasification (Fig. 4). This process involves converting the carbon fraction into synthesis gas (syngas), which mainly consists of carbon monoxide (CO), hydrogen (H₂), and methane (CH₄). The syngas can then be used both for energy production and as a chemical feedstock for the production of hydrogen, synthetic fuels, and other chemical products.

The primary stage of gasification is fuel preparation, which involves drying and grinding the coal to an optimal particle size, facilitating subsequent chemical reactions. The actual conversion process takes place in a controlled oxidizing atmosphere, where the coal undergoes partial oxidation in the presence of oxygen and steam. As a result, a gas mixture is produced, the composition of which can be modified according to technological needs—such as through additional hydrogen separation to obtain pure fuel or further hydrocarbon synthesis.

Among the key advantages of this technology is its versatility, as syngas can be used both in the power industry and in chemical manufacturing, opening the path to more sustainable coal utilization. Additionally, compared to direct combustion, gasification allows for more effective control of pollutant emissions—particularly the ability to capture and store CO₂ during the process stage, significantly reducing the carbon footprint.



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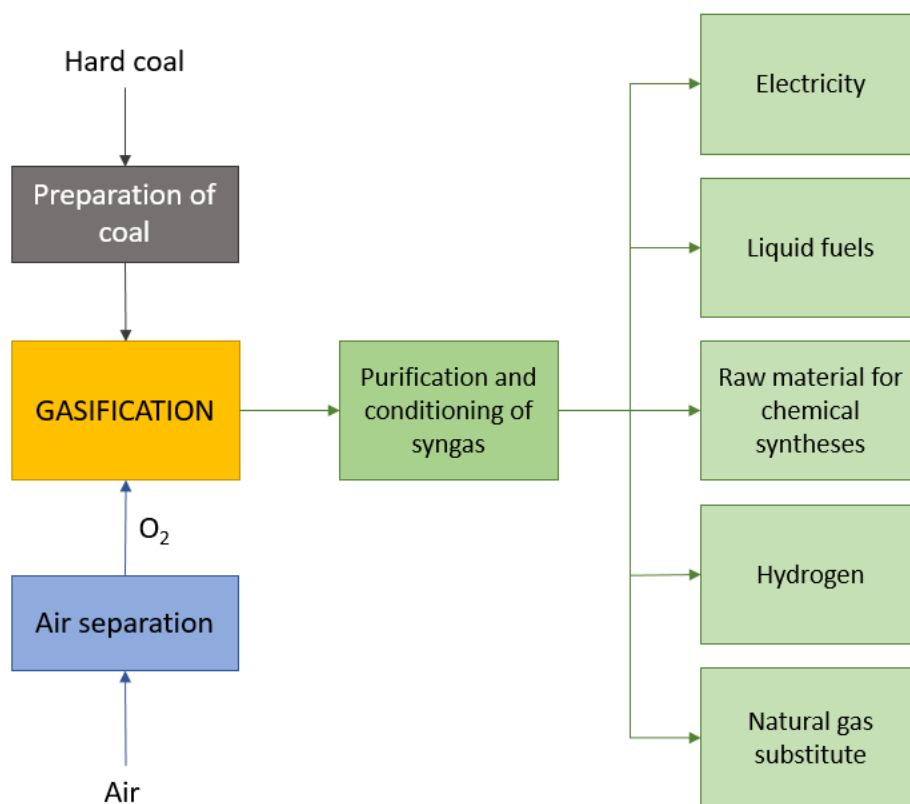


Fig. 4. General coal gasification diagram.

There are several different coal gasification technologies used worldwide. The process solutions of these technologies and reactor designs can be divided into three main types (Table 10): moving bed reactors, fluidized bed reactors, and entrained flow reactors. In the case of coal gasification, the most promising technological solutions, which allow for high conversion efficiency and high system performance, are entrained flow and fluidized bed reactors. The former are commercially available and have found widespread application in industry. The latter, due to many advantages, represent a promising direction for the development of the technology.



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Table 10. Characteristics of gasification reactor types.

REACTOR TYPE	MOVING BED	FLUIDISED BED	ENTRAINED FLOW
Fuel characteristics			
Grain size	5 ÷ 80 mm	<6 mm	<0,1 mm
Maximum ash content	<ul style="list-style-type: none"> No limitations <25% – ash removal in the form of slag 	No limitations	<25%
Required ash softening temperature, °C	<ul style="list-style-type: none"> >1200 <1300 slag 	>1100	<1300
Operational characteristics			
Fuel residence time	<ul style="list-style-type: none"> 15 – 60 min Several hours 	10 – 100 s	Several seconds
Gas outlet temperature, °C	Low (400 ÷ 650)	Average (900 ÷ 1050)	High (>1260)
Gasification pressure, bar	1 – 30 (100)	1 ÷ 30	<50 (80)
Oxidizer	Air/oxygen/steam	Air/oxygen/steam	Oxygen/steam
Unit power, MWth	10 – 350	20 – 150 (700)	up to 700
Characteristic feature	Liquid hydrocarbons in raw gas	Charcoal recirculation	High amount of usable heat in raw gas

Analysing the properties of CBF, it can be observed that the fractions from the Panewnicka dump (Haldex1 and Haldex2) are characterized by a high calorific value, indicating their significant energy potential. Compared to other fractions, such as Karvina2 (18.19 MJ/kg), this is a much more efficient fuel for gasification processes, as a higher calorific value means a greater amount of heat generated during thermochemical reactions.

The content of elements such as sulfur, nitrogen, and chlorine is crucial in the context of pollutant emissions and the protection of technological installations. The presence of sulfur (0.72–0.77%) requires the use of effective flue gas cleaning methods to prevent corrosion of installations and catalyst poisoning in the further processing of syngas. Similarly, the chlorine content of 0.081% may pose a challenge in terms of erosion and corrosion of structural materials, especially in high-temperature gasification reactors, where the formation of acidic gaseous compounds such as HCl can impact the longevity of equipment.

The ash melting temperature is an important factor affecting the gasification process, as too low a temperature can cause it to become plastic and lead to the formation of soot in the installation, while too high a temperature may reduce the process efficiency. In an oxidizing atmosphere, the deformation temperature of the ash for the Haldex1, Haldex2, and Karvina2 carbon fractions is 1360°C, 1390°C, and 1330°C, respectively, while in a reducing atmosphere,



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these values are lower, ranging from 1210°C to 1290°C. In the context of gasification, where a reducing atmosphere is used, it is essential for the process to proceed in a controlled manner to avoid issues related to slagging.

Data analysis indicates that the Haldex1 and Haldex2 fractions have very good parameters for use in the gasification process, due to their high calorific value and favorable chemical composition. However, attention should be paid to the sulfur and chlorine content, which may require additional syngas cleaning systems, as well as the need to carefully control process conditions to avoid issues related to the ash melting temperature. Additionally, gasification involves high capital expenditures, which may limit its application compared to conventional coal utilization methods. Despite these challenges, gasification of this fraction represents an efficient and low-emission alternative to traditional combustion, allowing for more flexible and environmentally friendly coal use.

8. Summary

The study explores the potential recovery of rare elements and other critical metals from post-mining heaps. Key elements identified include lithium (Li), nickel (Ni), gallium (Ga), scandium (Sc), and cobalt (Co), with lithium showing the highest concentrations. Given the growing global demand for these resources, their extraction from mining waste presents a promising opportunity. Magnetic separation has proven effective in increasing trace element concentration, enhancing recovery efficiency.

The research also examines the industrial applications of recovered elements. While Zn, Cr, Ni, and Cu are widely used in metallurgy and electronics, toxic elements such as Pb, Cd, and As require careful monitoring. REEs are crucial for high-tech industries, including electronics and nuclear energy. Both physical (e.g., flotation, magnetic separation) and chemical (e.g., leaching, solvent extraction) methods have been evaluated, with adsorption emerging as a promising technique due to its efficiency and simplicity.

The mineral fraction of mine waste shows significant potential for construction, road infrastructure, and environmental applications. Its high SiO₂ (56.97–58.69%) and Al₂O₃ (22.12–25.20%) content makes it suitable for cement, concrete, geopolymers, ceramics, and insulation materials. The high melting point (>1200°C) prevents agglomeration issues in fluidized bed reactors, while the presence of Fe₂O₃ affects cement hydration and coloration. Low SO₃ content (0.15%) ensures durability in cement applications. The material's composition also supports its use in lightweight aggregates, refractory materials, and sorbents for wastewater treatment.



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In terms of energy applications, the coal bearing fraction of mine waste exhibits properties suitable for both direct combustion and gasification. Samples from the Panewnicka dump (Haldex1, Haldex2) show a high calorific value (~26 MJ/kg), low moisture (~1.5%), and moderate ash content (~20%), making them compatible with various combustion technologies. However, sulfur (~0.7%) and ash fusion temperatures (1210–1360°C) must be managed to comply with environmental regulations. Gasification offers an alternative, producing syngas for energy and chemical industries, but requires advanced gas-cleaning technologies due to sulfur (~0.72–0.77%) and chlorine (~0.081%) content.

Overall, mine waste fractions can be utilized for raw material recovery, energy production, and construction applications. Future research should focus on optimizing separation and extraction methods to ensure economic feasibility and sustainable resource utilization.



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