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PRODUCTION OF AGGLOMERATED COKE FROM INDUSTRIAL WASTE AND CHARACTERIZATION OF COKING PRODUCTS

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coke, coal, spent anode residue, coal pitch, Fourier transform infrared (FTIR), man-made waste.

ABSTRACT
The relevance of the work is due to the need to conserve resources and involve man-made waste from the coal and aluminum industries in the production of carbonaceous materials for metallurgy. The aim of the study was to obtain agglomerated coke from the coal fines of the Ekibastuz basin and the spent anode residue of aluminum production with an assessment of its mechanical, structural and chemical properties. The study employed briquetting, coking at 1150 °C in a reducing atmosphere, chemical analysis, strength testing, and FTIR spectroscopy. It was found that the optimal composition of the charge (50% coal, 20% anode cinder and 30% coal pitch) provides compressive strength up to 3.2 MPa, impact resistance of up to 8 drops without fracture. FTIR analysis showed the formation of a predominantly aromatic carbon structure with a high degree of carbonization. The practical significance of the work lies in the possibility of using the obtained coke in sintering production, and the theoretical one is to expand the understanding of the structural transformations of carbon-containing compositions during coking.

INTRODUCTION

Currently, ferrous metallurgy is showing rapid development due to the high demand for cast iron and steel in various sectors of the economy. The main task of the industry is to provide the domestic and foreign markets with metal products of the required range, quality and volume, using the best available technologies in the implementation of the State Industrial Policy and sustainable provision of raw materials resources (Sun W. et al., 2020; He K. et al., 2020; Holappa L. 2021).

Coke is the main fuel for ferrous metallurgy. Prospects for the development of the coke industry and forecasts of coke production are directly related to the expansion of metallurgical production focused on domestic and foreign markets. The increase in the demand for coke is due to an increase in production rates, as well as an increase in the price of raw materials, which, in turn, leads to an increase in the price of coke on the world market (Babich A. et al., 2019; Persistence Market Research. Metallurgical Coke Market Size & Growth Analysis, 2031. Persist. Mark. Res. 2023).

The problem of resource conservation is highly relevant, as it is necessary to develop and implement technologies that ensure the production of products with minimal consumption of energy and material resources, rational use of mineral raw materials, and the search for alternative carbon reducing agents. Such reducing agents should meet the technological requirements of metal and alloy production while reducing production costs through the use of secondary carbon resources. In this regard, research in this area is of particular importance and requires efficient approaches to the utilization of secondary carbon resources (Kuatbay, Y. et al., 2024; Aubakirov, A. et al., 2020; Holappa, L., 2023). In Kazakhstan, the accumulation of industrial waste remains an important environmental and technological issue related to the sustainable use of mineral resources. According to national environmental statistics, the total volume of accumulated industrial waste in the country exceeds 29 billion tons, while approximately 0.8 billion tons of new waste are generated annually. The largest share is associated with mining and mineral-processing activities (about 65%), whereas manufacturing industries account for roughly 12%, and the remaining portion is formed by energy production and other industrial sectors. Coal mining and beneficiation processes generate significant amounts of coal fines, slurry materials, and carbon-containing residues, which can be considered secondary raw materials for producing carbon products. The thermochemical processing of such technogenic materials, including agglomeration followed by coking, provides opportunities for obtaining carbon materials suitable for metallurgical applications such as sintering fuel (Bureau of National Statistics of the Republic of Kazakhstan, 2023; UNECE, 2022; Aubakirov et al., 2023).

Thus, the processing of coal industry waste into coke will not only reduce the environmental burden, but also provide an additional source of valuable products for the metallurgical industry of Kazakhstan.

In this regard, the development of advanced thermal processing technologies for coal treatment is of great practical importance for producing environmentally friendly, energy-efficient coke and reducing agents for industrial use (Nurgaliyev, N., et al., 2024). The need for further improvement of these methods determined the implementation of a complex of research, experimental and experimental-industrial work on the development of scientific foundations and the development of new technological solutions in the field of heat treatment of coal, ensuring the receipt of high-quality products for technological and energy purposes.

The paper presents the results of theoretical and experimental studies aimed at determining the optimal technological parameters for producing metallurgical coke for sintering production from man-made waste, such as coal fines from coal waste from Bogatyr Coal LLP (Ekibastuz, Kazakhstan) and waste from the anode production of the electrolysis plant of Kazakhstan Electrolysis Plant JSC.

In the course of research and analysis of Ekibastuz coal, we found that about 17% of the main volume of coal produced is coal fines with a particle size of 0–3 mm, which is a by-product of crushing coal is significantly cheaper, since in conventional use such fine material requires additional preparation (briquetting/granulating), which reduces its market price. In our process, a fine grain of Ekibastuz coal (0–3 mm) is used "as is" without additional crushing, which further reduces energy costs and operating costs and facilitates dosing and granulation. Previous studies demonstrated that the addition of coal fines to the ore, coke charge is possible through the use of ignition additives in order to improve its agglomeration (Nonaka H., et al. 2023; Guo Z. et al. 2023).

Adding spent anode residue to Ekibastuz coal during coke production leads to a significant increase in the amount of carbon in the final product. Spent anode residue is a carbon-rich by-product of aluminium electrolysis and contains up to 95–98% carbon, mainly in graphitized form (Li, B., et al. 2021; Bhardwaj S. et al. 2025).

In the case of mixing with ekibastuz coal, which itself has a high ash content and relatively low carbon content (about 70–75% carbon in the form of dry ash-free basis), the addition of spent anode residue allows you to significantly improve the quality composition of the charge. For example, with the introduction of a 10% spent anode residue, the carbon content of the mixture can increase by about 2–4% in absolute terms, depending on the initial Ash of coal and the ratio of other components. With a further increase in the composition of spent anode residue, carbon growth can reach 6–10%, but at the same time, due to non-carbon waste components (oxides, fluorides, salts), there may be negative technological effects such as bond destruction, deterioration of mechanical properties and ash growth (Kai, Y. et al. 2020; Biao, K. 2022).

Purposes of adding anode residue:

1) to increase the carbon content of the charge. It is important in metallurgical processes (reduction of oxides, reduction processes) to obtain coke with a high fixed carbon content, which improves its reactivity.

2) to disposal of man-made waste. Spent anode residue is a byproduct of the aluminum industry, and its reuse can reduce the environmental burden and save resources.

3) to reduce the need for expensive primary carbon materials. Partial replacement of expensive primary carbon materials with spent anode residue reduces the cost of coke.

4) to improve heat resistance and electrical conductivity. Partially graphitized carbon improves the conductive and heat-resistant properties of coke, which can be useful in special sintering options, especially in the presence of current-conducting or induction systems.

Previous studies by the authors have already demonstrated the possibility of producing carbon materials from coal fines and spent anode residue using briquetting and subsequent heat treatment, with evaluation of the physicomechanical properties of the resulting coke products (Tolymbekova et al., 2025). These results showed that technogenic carbon-containing materials can partially replace traditional carbon raw materials in metallurgical processes. The present work continues this research direction and focuses on the structural and chemical characteristics of coke obtained from real charge compositions containing coal fines, spent anode residue, and coal pitch.

The purpose of this work is to obtain coke from man-made waste that meets the requirements for use in the sintering process with an assessment of its mechanical and structural-chemical properties. As part of this study, the main attention is paid to the structural and chemical characteristics of the coke obtained using IR-Fourier spectroscopy methods and the mechanical properties of the obtained samples.

The scientific novelty of this work lies in the FTIR analysis of coke obtained from real technogenic waste compositions containing coal fines, spent anode residue, and coal pitch.

In recent years, FTIR spectroscopy has been widely used to study the structure of carbon-containing materials, including coal, semi-coke, and coke, in order to detect chemical changes occurring in the heat treatment process. Studies have shown that this method is effective in identifying functional groups, assessing the degree of aromaticity, residual content of binders, as well as in studying the transformation of hydrocarbon structures during coking. In particular, FTIR analysis was used to determine the amount of carbonyl, hydroxyl and aromatic fragments in coal of different degrees of enrichment and to identify microstructural differences between the primary and heat-treated material. This made it possible to establish a correlation between the chemical composition and quality of the resulting coke (Mishra, S. 2023; Wang 2023; Yang L. 2025).

MATERIALS AND METHODS

Laboratory experiments on coke production were carried out in the laboratory of the Department of Metallurgy of the NJSC Toraighyrov University (Tolymbekova et al., 2025).

Table 1 and Table 2 show, respectively, the content of the components and their chemical composition.

Table 1. The composition of the components in the charge, %

Samples	The composition of the components in the charge, %		
	Ekibastuz coal	Spent anode residue	Coal pitch
1	50	10	40
2	50	20	30
3	50	30	20
4	50	40	10
Note – compiled by the authors based on their own research			

Table 2. Chemical composition of charge materials

Indicator	Ekibastuz Coal	Spent anode residue	Coal pitch
Carbon (C), %	70–75	98	92–93
Hydrogen (H), %	5.2	–	4.3–4.7
Oxygen (O), %	9.2	–	0.8–1.0
Nitrogen (N), %	1.6	–	1.7–1.8
Sulfur (S), %	0.4–1.0 (avr. 0.7)	2.0	0.3–0.5
Humidity (Wr), %	3.8–7.0 (avr. 5.4)	–	–
Ash (Ad), %	37–41 (avr. 39)	0.3–0.4	0.2–0.3
Volatile substances (Vdaf), %	24–40 (avr. 32)	–	–
Qi^r, kcal/kg	3800–4200 (avr. 4000)	–	–
Melting point of ash, °C	1490–1500	–	–
SiO_2, %	56.9–67.3 (avr. 62.1)	–	–
Al_2O_3, %	24.4–31.6 (avr. 28.0)	–	–
Fe_2O_3, %	4.4–7.26 (avr. 5.83)	–	–
CaO, %	0.68–3.29 (avr. 1.98)	–	–
MgO, %	0.19–1.26 (avr. 0.72)	–	–
TiO_2, %	1.09–1.65 (avr. 1.37)	–	–
SO_3, %	0.55–2.31 (avr. 1.43)	–	–
Density, g / cm^3	–	1.56	1.2–1.3
Softening temperature, °C	–	–	110–125
Note – compiled by the authors based on their own research			

The charge with a fraction of 0–3 mm was weighed on Techprom electronic scales, mixed with heating up to 150 °C in a laboratory mixer LS-AB-10, the duration of heating was determined by the physico-chemical properties of the binder and the mixing intensity. Heat transfer to the mixed volume provided heating of the mixture particles, melting of coal pitch particles and coating of coal particles and spent anode residue. The consistency of the mass was controlled according to technological features: the absence of fineness, a viscous, but not liquid structure, the formation of a lump of a specific shape when compressed. The mixing time was 10 minutes, and the coal pitch softened and bound the charge into a homogeneous mass. Coal pitch is characterized by a relatively high coking value and good binding properties, the resulting coke binds the carbon graphite product into a single monolith, at the same time the mass subjected to molding acquires the necessary elasticity. The resulting mass was pressed in a hydraulic press.

The resulting coal briquettes are shown in Figure 1.

Figure 1. Coal briquettes

Note – compiled by the authors based on their own research

The strength of the briquettes was tested in accordance with GOST 24707–81, "Solid Fuel. Method for Determining the Drop Strength of Briquettes," and according to the laboratory procedures used at Toraighyrov University.

Equipment:

- Hydraulic Laboratory Press PGL–25 to determine the strength limit during compression (maximum force of 25 MPa);
- Impact test apparatus with a fall height of 2 m (Fall method);
- Techprom analytical scale (error ± 0.01 g).
- Digital Mitutoyo caliper (accuracy ± 0.02 mm) to control the geometry of the samples.

Briquettes had a diameter of 50 mm and a height of 50 mm. Before testing, the samples were conditioned for 24 h at a temperature (20 ± 2) °C and humidity no more than 60%.

Further, briquette samples were subjected to the determination of compressive strength.

The compressive strength was calculated by the formula σ (1):

$$\sigma = \frac{P}{S}\ , \tag{1}$$

where: P is load at sample failure, N;

S is cross-sectional area, m².

For a cylindrical briquette, the cross-sectional area was calculated as follows: $S = \pi \cdot \frac{d^2}{4}$.

The test results are presented in the table.

Also, samples of coal briquettes were subjected to the determination of impact strength. The impact strength was assessed by lowering the samples from a height of 2 m onto a steel plate. Impact resistance was expressed as the number of drops sustained before failure.

The resulting briquettes were then placed in a coking container with a split tube with a rubber nipple valve for the release of gases (Figure 2).

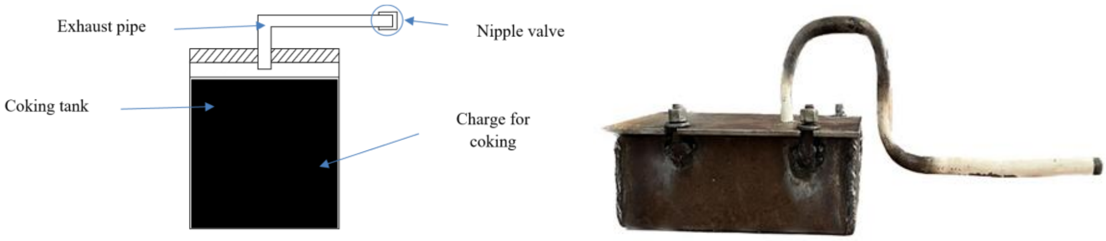

Figure 2. Laboratory coking vessel

Note – compiled by the authors based on their own research

The coking vessel was made of heat-resistant steel and is designed to operate at high temperatures in a reducing atmosphere without access to oxygen. The prepared charge batch is placed inside, the top cover is tightly fixed with bolted connections, ensuring the tightness of the volume. The lid has a fitting to which a curved metal tube is attached – an outlet line for gases and vapors formed during the coking process. At its end, a rubber nipple valve is installed, which allows volatile products to escape, but prevents air from entering the vessel.

When heated in an electric muffle furnace to the required temperature, the process of thermal decomposition of the organic components of the mixture occurs, which releases gaseous and liquid products in the container. Volatile products are discharged through the exhaust tube, and a solid carbon residue remains in the volume – coke.

This design simulates the industrial coking process on a reduced scale, ensures the stability of the heating mode, prevents the entry of oxygen and ensures the safe release of pyrolysis gases. The coking vessel was placed in a SNOL electric muffle furnace and heated according to a programmed schedule up to 1150 °C. After reaching the required temperature and subsequent cooling, the vessel was removed from the furnace.

The resulting coke has a porous structure, has sufficient strength, the average size is 3-5 mm, which meets the requirements of coke for sintering production.

Coke samples with different percentages of the resulting components were studied in detail using FTIR spectroscopy.

The FTIR method was used to analyze functional groups in the resulting coke structure. The main purpose of this analysis is to determine the degree of destruction of organic compounds and binder residues during the coking process.

Infrared spectroscopy (IR) is an analytical method that uses light from the infrared part of the spectrum to analyze a sample. Peaks in the IR spectrum represent the selective absorption of a part of the radiation that coincides in frequency with the oscillations of atoms in the molecule, that is, it corresponds to the oscillation frequencies of chemical bonds in the sample. Spectra can be recorded in transmittance or absorbance mode; in transmittance, absorption bands appear as minima, while in absorbance they appear as peaks (Al-Amin, K., Rahman, M., & others, 2024; Shimadzu Corporation, 2020)

The Shimadzu IRTracer-100 Fourier transform infrared spectrometer is designed to measure the optical spectra of full internal reflection, conduction, absorption, diffusion and mirror reflection in the infrared (IR) range; determination of the concentration of various organic and inorganic substances in solid, liquid and gaseous states (Figure 3).

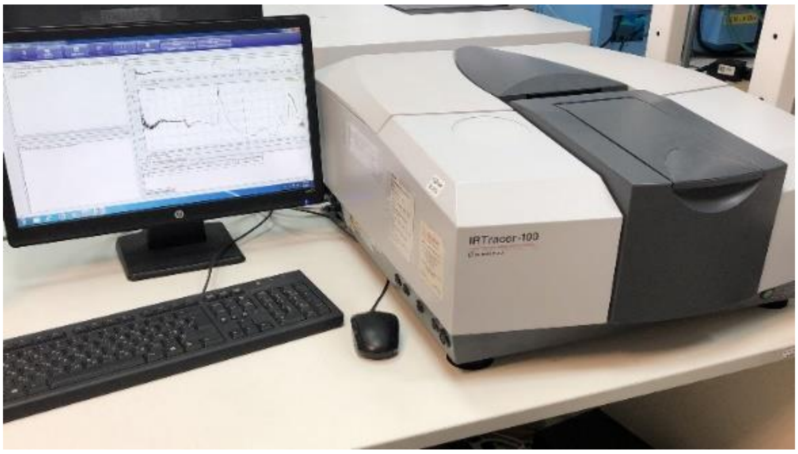

Figure 3. Shimadzu irtracer-100 Fourier spectrometer

Note – compiled by the authors based on (Shimadzu Corporation, 2020)

The principle of action of spectrophotometers is based on determining the stroke difference between the interference rays when moving mirrors in a two-beam interferometer. At the heart of the spectrophotometer is the Michelson interferometer (LibreTexts, 2023)

RESULTS AND DISCUSSION

This section presents and analyzes the results of experimental studies on the production and characterization of coke samples.

The chemical composition of the resulting coke is presented in Table 3.

Table 3. Chemical composition of coke

Carbon (C), %	Sulfur (S), %	Ash composition (Ash), %	Volatile substances, %	Humidity (Wr), %
85	0.9–1.1	19.0	1.5–2.5	≤ 1
Note – compiled by the authors based on their own research				

The resulting coke is characterized by high carbon content (85%) and low humidity (<1%), which confirms its suitability as a fuel. Despite the increased content of ash (19%) and sulfur (0.9–1.1%), this composition is suitable for use in sintering production. The increased ash and sulfur content is associated with the use of high-ash Ekibastuz coal and spent anode residue as waste from electrolysis production of aluminum (spent anode residue) containing sulfur compounds.

Table 4. Strength of compression briquettes

№ sample	Charge composition (coal : spent anode residue : coal pitch,%)	Average diameter, mm	Destructive load, N	Strength σ, MPa
1	50 : 10 : 40	50	5200	2.8
2	50 : 20 : 30	50	5700	3.2
3	50 : 30 : 20	50	5100	2.9
4	50 : 40 : 10	50	4710	2.4
Note – compiled by the authors based on their own research				

As the coal pitch content decreased, increasing the proportion of spent anode residue to 20% improved the strength of the briquettes due to the formation of a stable contact network and enhanced carbonization. However, a further increase in the spent anode residue content, accompanied by a decrease in coal pitch, reduced the strength because of insufficient binder content.

Table 5. Results of impact tests

№ sample	Composition of the charge	Number of falls before breaking	Fracture character
1	50 : 10 : 40	6	Cracks on the sides, broken edges
2	50 : 20 : 30	8	Small traces without destruction
3	50 : 30 : 20	7	Small cracks, without separation
4	50 : 40 : 10	5	Separation of the edge, division into fragments
Note – compiled by the authors based on their own research			

Briquettes containing 20% spent anode residue showed the highest impact resistance and a stable structure.

The results indicate that the optimal charge composition is 50% coal, 20% spent anode residue, and 30% coal pitch. This ratio provides sufficient plasticity, uniform particle bonding, and relatively low porosity.

The compressive strength reached 3.2 MPa, which meets the requirements for metallurgical briquettes intended for further coking.

Thus, increasing the proportion of spent anode residue to 20% was found to improve the strength of the briquettes by 15–20%.

Coal-tar pitch supplied by Kazakhstan Electrolysis Plant JSC proved to be an effective binder due to its high coke yield and suitable softening temperature.

The FTIR spectra of the coke samples prepared according to the compositions listed in Table 1 are presented below.

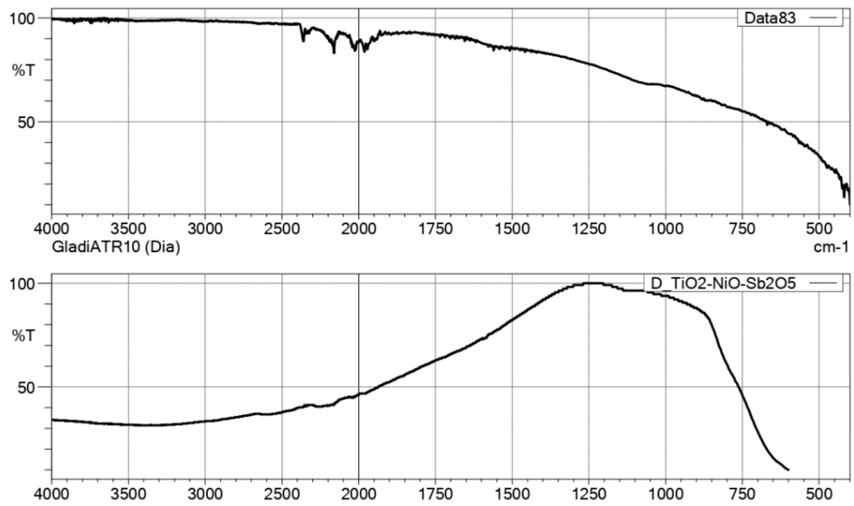

Figure 4. 1st sample

Note – compiled by the authors based on their own research

FTIR analysis of the coke spectrum of Sample 1 (Figure 4) made it possible to identify the following main functional groups:

1. Aromatic compounds (C=C, ~1600 cm^{-1}): a pronounced absorption band was observed in the region of 1580–1620 cm^{-1}, indicating the presence of aromatic carbon structures. These signals are characteristic of graphite-like structures and confirm the high degree of aromatization of the product.
2. Hydroxyl groups (O–H, 3200–3600 cm^{-1}): a broad band in the region of 3200–3600 cm^{-1} indicates the presence of hydroxyl or phenolic groups. The intensity of this band suggests the presence of residual moisture or oxygen-containing compounds after coking.
3. Carbonyl compounds (C=O, 1700–1750 cm^{-1}): the absorption peak in this region indicates the presence of carbonyl fragments, such as ketones or carboxylic acids, which may result from incomplete thermal decomposition of oxygen-containing compounds.
4. Aliphatic C–H bonds (2800–3000 cm^{-1}): weak peaks corresponding to C–H stretching vibrations in aliphatic fragments indicate a low content of volatile hydrocarbons, confirming a high degree of carbonization.
5. Ether and phenolic groups (C–O, 1050–1150 cm^{-1}): the presence of a signal corresponding to C–O vibrations indicates the presence of oxygen-containing fragments, including phenols and esters.

6. Mineral components (500–900 cm^{-1}): peaks in this region are characteristic of bending vibrations associated with metal oxides, including TiO_2, Fe_2O_3, and Al_2O_3, originating from ash components.

Sample 1 demonstrates a high degree of aromatization and a low content of volatile substances. The moderate amount of oxygen-containing functional groups indicates a sufficient level of coking. However, due to the relatively low proportion of spent anode residue, the degree of carbonization is lower than that of the other samples. Therefore, this composition can be considered acceptable, but not optimal for metallurgical applications. In addition, the increased content of ash components requires further control when the material is used in metallurgical processes.

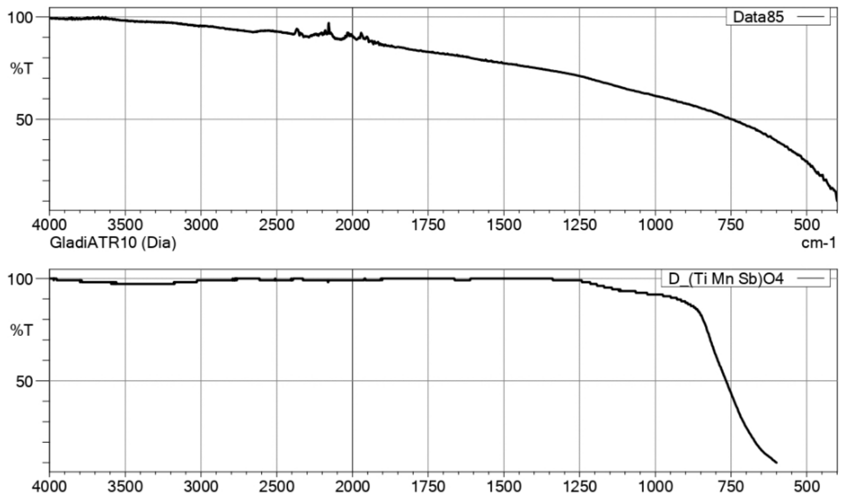

Figure 5. 2nd sample

Note – compiled by the authors based on their own research

FTIR analysis of the coke spectrum of Sample 2 revealed the following spectral features:

1. Aromatic compounds (C=C, ~1600 cm^{-1}): an intense peak in this region indicates the presence of aromatic carbon structures, confirming a high degree of aromatization.

2. Hydroxyl groups (O–H, 3200–3600 cm^{-1}): a broad high-intensity band indicates the presence of hydroxyl or phenolic groups, which may be associated with residual moisture or incomplete decomposition of oxygen-containing compounds.

3. Carbonyl compounds (C=O, 1700–1750 cm^{-1}): compared with Sample 1, a more pronounced band in this region indicates the presence of carbonyl compounds, such as quinones or residual acids, which may be associated with the oxidation of residual organic fragments.

4. Aliphatic C–H bonds (2800–3000 cm^{-1}): very weak peaks confirm a high degree of carbonization and the decomposition of volatile compounds during heat treatment.

5. Ether and phenolic groups (C–O, 1050–1150 cm^{-1}): peaks in this range are more intense than those observed in Sample 1, which may indicate a higher proportion of residual resinous substances due to the increased content of spent anode residue.

6. Mineral components (500–900 cm^{-1}): more pronounced peaks indicate the presence of metal oxides, including Fe_2O_3 and TiO_2.

Sample 2 demonstrates a high degree of aromatization and carbonization while retaining a moderate amount of functional groups that contribute to structural integrity. Although oxygen-containing compounds and ash components may adversely affect coke quality, the balance between graphitization and structural bonding makes this sample promising for further application.

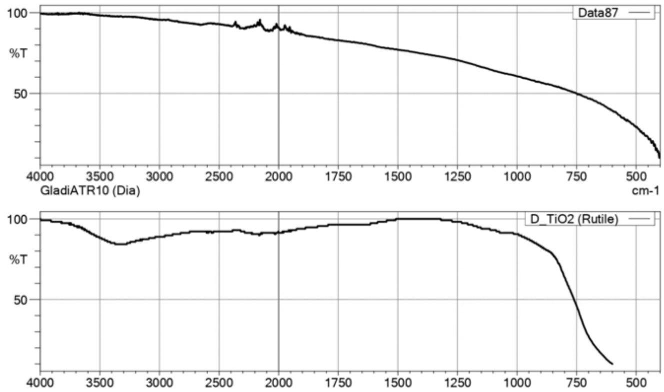

Figure 6. 3rd sample

Note – compiled by the authors based on their own research

FTIR analysis of the coke spectrum of Sample 3 revealed the following main functional groups:

1. Aromatic compounds (C=C, ~1600 cm⁻¹): an intense absorption band was observed in the range of 1580–1620 cm⁻¹, indicating the presence of aromatic structures characteristic of graphitized carbon. This confirms a high degree of aromatic structure formation.
2. Hydroxyl groups (O–H, 3200–3600 cm⁻¹): a broad absorption band in this region indicates the presence of hydroxyl or phenolic groups. This may be associated with residual moisture and the partial decomposition of oxygen-containing compounds during the coking process.
3. Carbonyl compounds (C=O, 1700–1750 cm⁻¹): the presence of carbonyl groups, such as ketones or carboxylic acids, is confirmed by an intense peak in this region, which may indicate residual organic fragments and oxidative transformations.
4. Aliphatic C–H bonds (2800–3000 cm⁻¹): weak bands corresponding to C–H stretching vibrations indicate a small amount of aliphatic fragments, confirming an advanced stage of carbonization.
5. Ether and phenolic groups (C–O, 1050–1150 cm⁻¹): the presence of a C–O signal indicates residual oxygen-containing compounds.
6. Mineral components (500–900 cm⁻¹): peaks in this range are associated with spent anode residue and ash compounds characteristic of Ekibastuz coal, including Fe_2O_3, TiO_2, CaO, and Al_2O_3.

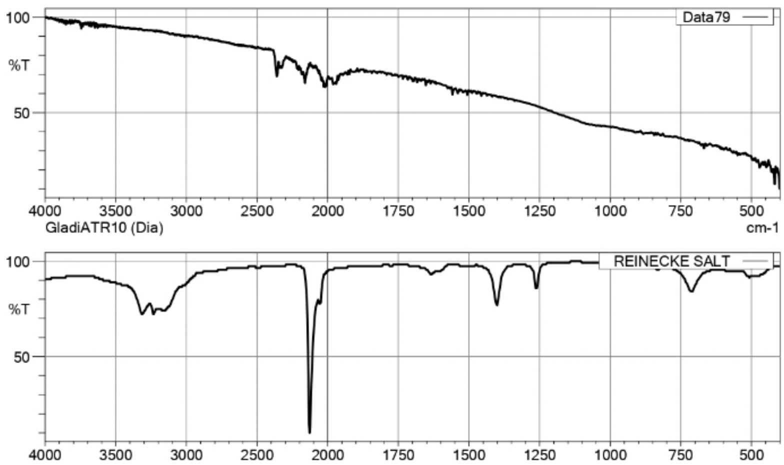

Figure 7. 4th sample

Note – compiled by the authors based on their own research

Sample 3 is characterized by a pronounced aromatic structure, good thermal stability, and a relatively high degree of carbonization. However, the reduced coal pitch content may limit the structural stability of the coke compared with Sample 2.

FTIR analysis of the coke spectrum of Sample 4 revealed the following characteristic features:

1. Aromatic compounds (C=C, ~1600 cm^{-1}): the intense absorption band indicates the presence of aromatic carbon structures, including graphite-like structures, confirming a high degree of carbonization.

2. Hydroxyl groups (O–H, 3200–3600 cm^{-1}): a broad absorption band in this region indicates the presence of hydroxyl and/or phenolic groups, as well as residual moisture associated with the spent anode residue.

3. Carbonyl compounds (C=O, 1700–1750 cm^{-1}): a distinct peak in this region indicates the presence of carbonyl compounds, possibly quinones or oxidation products.

4. Aliphatic C–H bonds (2800–3000 cm^{-1}): weakly defined peaks indicate the partial preservation of aliphatic structures, possibly originating from coal pitch.

5. Ether and phenolic groups (C–O, 1050–1150 cm^{-1}): the intensity of the bands in this range confirms the presence of oxygen-containing functional groups, such as esters and phenols.

6. Mineral components (500–900 cm^{-1}): the spectrum shows distinct peaks characteristic of metal oxides, including Fe_2O_3, TiO_2, and Al_2O_3, which indicates a relatively high content of ash impurities.

Sample 4 is characterized by a high degree of aromatization, as well as an increased amount of oxygen-containing groups. This may affect the reactivity of coke and deteriorate its mechanical properties, thereby reducing its technological suitability for sintering production.

Comparative analysis based on FTIR spectroscopy showed that all samples contained the main functional groups characteristic of carbon-containing and oxygen-containing compounds: aromatic C=C bonds (~1600 cm^{-1}), alkyl C–H bonds (~2850–2950 cm^{-1}), hydroxyl O–H groups (~3200–3600 cm^{-1}), carbonyl C=O groups (~1700 cm^{-1}), as well as ether and phenolic C–O and C–O–C groups (~1000–1300 cm^{-1}). The intensity of the bands associated with aliphatic groups generally decreased as the proportion of spent anode residue increased and the coal pitch content decreased, whereas the intensity of oxygen-containing groups varied depending on the ash content and residue composition.

This indicates a high degree of carbonization and the formation of graphite-like structures in coke with an increased proportion of spent anode residue in the charge, especially in Sample 4. In addition, samples with a lower coal pitch content showed a decrease in the functional groups involved in the formation of bonds between carbon fragments, which may reduce the mechanical strength of the resulting coke.

Samples 2 and 3, containing 50% Ekibastuz coal, 20–30% spent anode residue, and 20–30% coal pitch, showed an optimal balance between the high degree of carbonization required for the formation of a strong carbon structure and the preservation of a sufficient amount of oxygen-containing functional groups. Therefore, these samples can be considered promising compositions for metallurgical applications.

Despite its maximum degree of carbonization, Sample 4, containing 40% spent anode residue and 10% coal pitch, showed signs of excessive destruction of binding functional groups. This may lead to a decrease in coke strength during handling, transportation, and use in sintering production.

Thus, Samples 2 and 3 can be considered the most promising compositions. However, Sample 2 demonstrated the best balance between carbonization and mechanical strength. Based on the results obtained, these samples can be recommended for further investigation regarding their application in sintering production.

Comparison with industrial sintering coke

A comparative analysis of the obtained coke and typical industrial sintering coke was carried out to assess the suitability of the developed material for sintering production (Table 6).

The obtained coke demonstrates physicochemical characteristics generally comparable to those of industrial sintering coke. The carbon and sulfur contents fall within the typical ranges reported for industrial applications, whereas the ash content remains relatively high due to the use of high-ash Ekibastuz coal. Nevertheless, the obtained mechanical strength and degree of carbonization indicate the potential suitability of the produced coke for use in sintering production.

Table 6. Comparison of the obtained coke properties with typical industrial sintering coke characteristics

Parameter	Obtained coke	Industrial sintering coke*
Carbon content, %	85	80–90
Ash content, %	19	10–18
Sulfur content, %	0.9–1.1	0.5–1.2
Compressive strength, MPa	3.2	comparable range
Note – compiled by the authors based on Babich and Senk (2019), Wang et al. (2023), and own experimental data		

*Typical values according to published data for industrial sintering coke.

CONCLUSION

The study demonstrated the feasibility of producing sintering coke from technogenic waste generated by the coal and aluminum industries without relying on scarce primary carbon resources. The use of Ekibastuz Basin coal fines with a particle size of 0–3 mm without additional crushing made it possible to reduce energy consumption and improve the resource efficiency of the process. The introduction of high-carbon spent anode residue with a carbon content of 98% increased the carbon content of the charge and promoted carbonization during coking.

The optimal charge composition was 50% coal, 20% spent anode residue, and 30% coal pitch. For this composition, the compressive strength of the briquettes reached 3.2 MPa, and the impact resistance was up to 8 drop cycles without failure, which meets the requirements for carbon materials intended for sintering production. With a simultaneous decrease in coal pitch content, increasing the proportion of spent anode residue above 30% led to a deterioration in mechanical properties due to insufficient binder content and disruption of structural bonding.

Chemical analysis of the obtained coke showed a carbon content of 85%, an ash content of about 19%, and a sulfur content of 0.9–1.1%, which are acceptable for use in the sintering process, taking into account the initial ash content of Ekibastuz coal. FTIR spectroscopy revealed the predominance of aromatic carbon structures and a decrease in the intensity of aliphatic and oxygen-containing functional groups with an increase in the proportion of spent anode residue, indicating a high degree of carbonization and the formation of graphite-like structures in the material.

Thus, the results obtained confirm the feasibility of involving spent anode residue and coal fines in the technology for producing sintering coke. The proposed approach provides a simultaneous solution to the tasks of resource conservation, technogenic waste utilization, and production of a carbon material with the required mechanical, structural, and chemical characteristics for use in metallurgical production.

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REFERENCES

Sun, W., Wang, Q., Zhou, Y., & Wu, J. (2020). Material and energy flows of the iron and steel industry: Status quo, challenges and perspectives. Applied Energy, 268, 114946. https://doi.org/10.1016/j.apenergy.2020.114946

He, K., Wang, L., & Li, X. (2020). Review of the energy consumption and production structure of China's steel industry: Current situation and future development. Metals, 10(3), 302. https://doi.org/10.3390/met10030302

Holappa, L. (2021). Challenges and prospects of steelmaking towards the year 2050. Metals, 11(12), 1978. https://doi.org/10.3390/met11121978

Babich, A., & Senk, D. (2019). Coke in the iron and steel industry. In S. Suárez-Ruiz (Ed.), New trends in coal conversion: Combustion, gasification, emissions, and coking (pp. 367–404). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102201-6.00013-3

Persistence Market Research. (2023). Metallurgical coke market size & growth analysis, 2031. Retrieved December 10, 2025, from https://www.persistencemarketresearch.com/market-research/metallurgical-coke-market.asp

Kuatbay, Y., Kelamanov, B., Aitkenov, N., & Uakhitova, B. (2024). Thermodynamic and experimental studies on the influence of high-ash coal in the production of high-carbon ferrochrome. Acta Metallurgica Slovaca, 30, 178–182. https://doi.org/10.36547/ams.30.4.2088

Aubakirov, A., Kaliakparov, A., & Tolymbekova, L. (2023). Determination of the quality of special coke as a result of heat treatment of coal from the Shubarkolskoye field. Complex Use of Mineral Resources, 327, 96–106. https://doi.org/10.31643/2023/6445.33

Bureau of National Statistics of the Republic of Kazakhstan. (2023). Environmental statistics of Kazakhstan. Retrieved December 10, 2025, from https://stat.gov.kz

United Nations Economic Commission for Europe. (2022). Environmental performance reviews: Kazakhstan. Retrieved December 10, 2025, from https://unece.org/environmental-policy/environmental-performance-reviews/kazakhstan

Nurgaliyev, N., Kolpek, A., Iskakova, S., Glazyrin, R., Safarov, Zh., & Aibuldinov, Y. (2024). Low-temperature pyrolysis of coal with determination of physicochemical properties of coal and its thermal decomposition products. E3S Web of Conferences, 545, 03004. https://doi.org/10.1051/e3sconf/202454503004

Nonaka, H., et al. (2023). Preparation of formed coke for blast furnace using kraft lignin as a binder. ISIJ International, 63(9), 1515–1525. https://doi.org/10.2355/isijinternational.ISIJINT-2023-046

Guo, Z., et al. (2023). Clean preparation of formed coke from semi-coke by the hot briquetting method. ACS Omega, 8(26), 23504–23515. https://doi.org/10.1021/acsomega.3c02519

Li, B., et al. (2021). Advances in the safe disposal and comprehensive utilization of spent carbon anode from aluminum electrolysis: Prospects for extraction and application of carbon resources from hazardous waste. Frontiers in Energy Research, 9, 779476. https://doi.org/10.3389/fenrg.2021.779476

Bhardwaj, S., & Daniel, B. S. S. (2025). Green initiatives in aluminium production: Implementing sustainable processes and effective waste management. Journal of Material Cycles and Waste Management, 27(5), 3100–3120. https://doi.org/10.1007/s10163-025-02310-8

Tolymbekova, L. B., et al. (2025). Sustainable production of metallurgical coke from technogenic wastes: A circular approach to waste utilization. International Journal of Innovative Research and Scientific Studies, 8(4), 2763–2776. https://doi.org/10.53894/ijirss.v8i4.8554

Tolymbekova, L. B., et al. (2025). Optimization of charge composition for coke production with spent anode material and evaluation of agglomerate properties. International Journal of Innovative Research and Scientific Studies, 8(6), 2491–2501. https://doi.org/10.53894/ijirss.v8i6.10131

Kai, Y., et al. (2020). Purifying spent carbon anode (SCA) from aluminum reduction industry by alkali fusion method to apply for Li-ion batteries anodes: From waste to resource. Journal of the Taiwan Institute of Chemical Engineers, 116, 121–127. https://doi.org/10.1016/j.jtice.2020.10.034

Al-Amin, K., Rahman, M., et al. (2024). Fourier transform infrared spectroscopic technique for functional group analysis of carbon materials. Applied Spectroscopy Reviews. https://pmc.ncbi.nlm.nih.gov/articles/PMC12426772/

Shimadzu Corporation. (2020). IRTracer-100 Fourier transform infrared spectrophotometer. https://www.shimadzu.com/an/products/molecular-spectroscopy/ftir/ftir-spectroscopy/irtracer-100/index.html

LibreTexts. (2023). How an FTIR spectrometer operates. Chemistry LibreTexts. https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_%28Physical_and_Theoretical_Chemistry%29/Spectroscopy/Vibrational_Spectroscopy/Infrared_Spectroscopy/How_an_FTIR_Spectrometer_Operates

Biao, K., & Fengxia, Z. (2022). Co-treatment of spent carbon anode and copper slag for reuse and the solidification of the constituent fluorine and heavy metals. Journal of Cleaner Production, 135418. https://doi.org/10.1016/j.jclepro.2022.135418

Mishra, S., Prasad, A. K., Shukla, A., Vinod, A., Preety, K., & Varma, A. K. (2023). Estimation of carbon content in high-ash coal using mid-infrared Fourier-transform infrared spectroscopy. Minerals, 13(7), 938. https://doi.org/10.3390/min13070938

Wang, X., He, X., & Wang, X. (2023). FTIR analysis of the functional group composition of coal tar residue extracts and extractive residues. Applied Sciences, 13(8), 5162. https://doi.org/10.3390/app13085162

Yang, L., & Yuan, Y. (2025). Functional group characteristics of coal treated with clean biomass surfactant via FTIR spectroscopy. Scientific Reports, 15(1), 18676. https://doi.org/10.1038/s41598-025-03769-z

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