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Investigation on characterization of some high rank coals from Mongolia and preparation of coal derived activated carbon on their bases

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Abstract. *Mongolia possesses substantial coal resources (173 billion tons), which include high-rank bituminous coals, subbituminous coals, and brown coals. Based on these coal types, a manufacturer of activated carbon can be developed using comparatively simple technology. The consumption of activated carbon is continuously increasing due to its use in waste and drinking water treatments, atmospheric pollution control, gas mixture separation, and solvent recovery. Currently, Mongolia imports 700–800 tons of activated carbon annually at a price of 700–900 USD per ton. For this study, we have selected several high-rank coals from Mongolia, including Tavan Tolgoi IV and Nariin Sukhait (both bituminous coking coals from Southern Mongolia), as well as the Saikhan-Ovoo deposit (a high-rank stone coal from Northern Mongolia). The selected coals were enriched with a zinc chloride solution and subjected to semicoking (carbonization) to produce the primary raw material for activated carbon production. Activated carbon was obtained from the carbonized coal by activation with preheated water steam within 120 minutes. The main technical characteristics of the initial coal samples and activated carbons, along with their microporous properties such as iodine number, methylene blue adsorption, and surface area (BET), have been determined. Additionally, a technological scheme for activated carbon production from high-rank coal has been proposed.*

Keywords: *high rank coal, bituminous coal, stone coal, activated carbon, surface area*

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ХИМИЧЕСКАЯ ТЕХНОЛОГИЯ

Научная статья
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Исследование характеристик некоторых высокосортных углей Монголии и получение активированного угля на их основе

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Аннотация. *Известно, что в Монголии сосредоточены большие запасы угля (173 млрд т), в том числе страна богата высокосортным битуминозным углем, суббитуминозным углем и бурым углем. На основе данных видов*

углей можно организовать производство активированного угля по сравнительно простой технологии. Потребление активированного угля постоянно увеличивается, поскольку он используется в таких важных областях, как очистка сточных вод и питьевой воды, контроль загрязнения атмосферы, разделение газовых смесей, рекуперация растворителей и т.д. К сожалению, на данный момент активированный уголь в Монголии не производится, поэтому Монголия импортирует 700–800 т активированного угля в год по цене 700–900 долл. США за тонну. Для проведения исследования нами были выбраны несколько образцов высокосортного угля из Монголии, включая угли Таван Толгой IV, Нарийн Сухаит (оба являются битуминозными коксующимися углями из южной части Монголии), а также угли месторождения Сайхан-Овоо (высокосортный каменный уголь из северной части Монголии). Данные угли были обогащены раствором хлористого цинка и подвергнуты полукоксованию (карбонизации) с целью получения основного сырья для производства активированного угля. Активированный уголь был получен на основе этих карбонизированных углей путем их активации предварительно нагретым водяным паром в течение 120 мин. В результате работы были определены основные технические характеристики исходных образцов угля и полученных образцов активированного угля, а также их микропористые свойства, такие как йодное число, адсорбционная способность по метиленовому синему и удельная площадь поверхности. Предложена технологическая схема получения активированного угля из рассмотренных видов угля.

Ключевые слова: *высокосортный уголь, битуминозный уголь, каменный уголь, активированный уголь, площадь поверхности*

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INTRODUCTION

Mongolia has a total resource of 173 billion tons of different kinds of coal. They include high-ranking bituminous, stone sub-bituminous coal, brown coals of lignite type, which are distributed throughout the territory of Mongolia. Mongolia is one of the 10 coal-rich countries in the world and already has 28 billion tons of confirmed resources [1–9] of coal.

In Mongolia, there are several rich deposits of high rank coals such as Tavan Tolgoi IV, Nariin Sukhait, Saikhan-Ovoo deposits, and a huge resource of low coals, such as stone sub-bituminous and brown coal in the central region, which are in exploration. We have chosen these 3 previously investigated high rank coals, including Tavan Tolgoi IV [10, 11], Nariin Sukhait [12], and Saikhan-Ovoo coal [13, 14], for thermal processing investigation and preparation of activated carbons with highly developed porous structure and adsorption property [15–18].

Activated carbon consumption is continuously increasing due to its use in critical areas such as waste and drinking water treatments, atmospheric pollution control, gas mixture separation, and solvent recovery. Conversely, activated carbons are not produced in Mongolia, which results in the country importing 700–800 tons of activated carbon per year at a cost of 700–900 USD/ton. For this reason, we have decided to evaluate the feasibility of producing activated carbons here in Mongolia.

MATERIALS AND METHODS

Location data, type, resource, and other information of the investigated coal samples are given in Table 1.

The analytical coal samples from these three deposits were prepared in accordance with Mongolian National Standards (MNS) and the main technical specifications, including moisture (MNS 656-79), ash (MNS 652-79), volatile matter (MNS 654-79), caloric value (MNS 669-87), and sulfur content (MNS 895-79).

Activated carbon samples derived from coal were prepared using the following procedure:

1. Purification of initial coal samples in $ZnCl_2$ solution aimed to decrease the content of ash.

2. Carbonization of purified coal by pyrolysis.

Table 1. Some information about the investigated coal deposits

Таблица 1. Некоторые сведения о разведанных угольных месторождениях

Coal deposit	Location	Coal type and reserves	Year of discovery
Tavan Tolgoi IV	Tsogttsetsi village of Southgobi aimak, 14 km from the Tsogttsetsi sum to the south and 600 km from Ulaanbaatar to the South Gobi	High rank bituminous and coking coal, geological reserves 6.4 billion tons	1966
Nariin Sukhait	Gurvantes village of Southgobi aimak, 296 km from the Dalanzadgad town and 849 km from Ulaanbaatar to the South Gobi	High rank bituminous coal, geological reserves 125.5 million tons	1994
Saikhan-Ovoo	Saikhan village of Bulgan aimak, 22 km from the village to the north west	High rank stone coal, geological reserves 34.7 million tons	1965

3. Activation of carbonized hard residues with pre-heated water steam.

Purification of initial coal samples in $ZnCl_2$ solution involves several steps. First, the coal samples were milled and sieved, with the 1.0–1.5 mm fraction selected for further processing. Water solutions of $ZnCl_2$ with varying densities (1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000) g/cm^3 were utilized for purifying the sieved coal samples. It was found that the $ZnCl_2$ solution with a density of 1300 g/cm^3 reduced the ash content by more than two times. The coal sample was submerged in the $ZnCl_2$ solution in a glass cylinder, mixed thoroughly for 5 minutes, and allowed to settle for 24 hours, resulting in the formation of top and bottom fractions (Figure 1). Both fractions were filtered separately, and their yields were recorded.

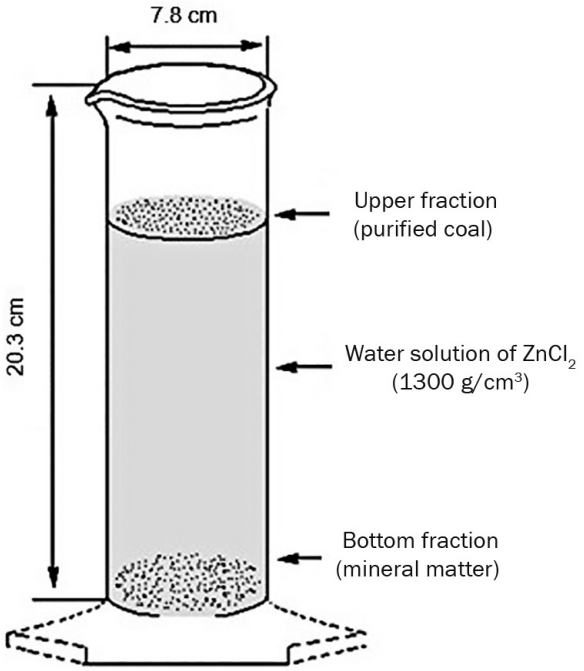

Fig. 1. Scheme of initial coal samples purification in $ZnCl_2$ solution

Рис. 1. Схема очистки исходных образцов угля в растворе $ZnCl_2$

Carbonization of purified coal. The pyrolysis of coal samples was conducted in a vertical cylindrical retort made of stainless steel, capable of holding 1000 g of sample (Figure 2). The retort was positioned in an electric furnace (model SNOL) with a maximum temperature of 950 °C. A chromel-alumel thermocouple was immersed in the coal bed to measure the actual heating temperature and was complemented with temperature control equipment (potentiometer). The retort was connected to an air-cooled iron tube and a water-cooled laboratory glass condenser, along with a collection vessel for the liquid products (pitch and pyrolysis water). The uncondensed gases exiting the water-cooled condenser left the system through a thin glass tube. The experiments were conducted at a temperature of 700 °C, with a heating rate of 20 °C×min^{-1}. The yields of products, including solid residue (coal char), tar, and pyrolysis water, were determined by weighing, while the yield of gases was calculated by difference.

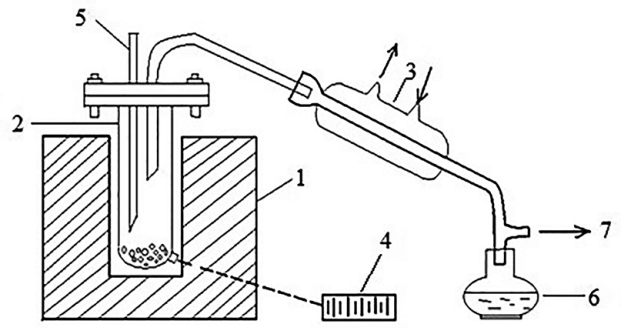

Fig. 2. Scheme of the equipment set for the pyrolysis (carbonization) of coal: 1 – electric furnace (model SNOL, Russia); 2 – retort; 3 – laboratory glass condenser (cooler); 4 – millivoltmeter; 5 – thermometer; 6 – vessel for tar; 7 – exit for uncondensed gas

Рис. 2. Схема установки для пиролиза (карбонизации) угля: 1 – электрическая печь (модель SNOL, Россия); 2 – реакционный сосуд; 3 – стеклянный холодильник; 4 – милливольтметр; 5 – термометр; 6 – сосуд для смолы; 7 – выход несконденсированных газов

Activation of carbonized coal samples. The carbonized coal samples (10–15 g) are placed in a quartz tube and flushed with nitrogen to eliminate oxygen, heated to 800 °C, and activated with heated water steam for 120 minutes (Figure 3).

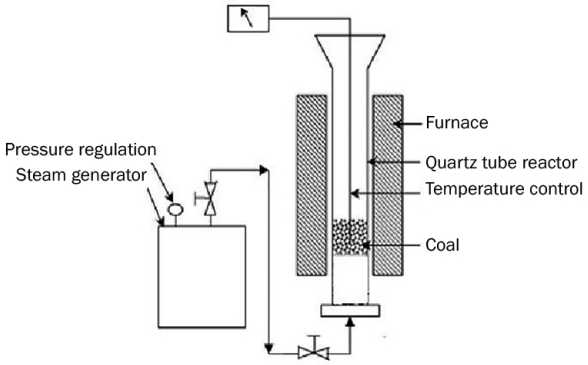

Fig. 3. Scheme of the equipment set for the activation of carbonized coal

Рис. 3. Схема установки для активации карбонизированного угля

Characterization of activated carbon samples. The iodine number is defined as the number of milligrams of iodine adsorbed from an aqueous solution by 1 g of activated carbon when the iodine concentration in the residual filtrate is 0.02 N. Granular activated carbon was pulverized (<0.1 mm) and then dried at 150 °C to a constant weight. A weighed carbon sample (1 g) was placed into a 250 ml stoppered dry glass flask, and then 50 ml of 0.10 N iodine solution was added by pipette. The flask was stopped immediately and then shaken vigorously for 30 seconds, filtered by gravity through filter paper immediately after the 30-second shaking period. The filtrate was stirred in the beaker with a glass rod, and then 50 ml was transferred by pipette into a 250 ml flask. A 50 ml sample was titrated with 0.10 N sodium thiosulfate solution until the yellow

color had almost disappeared. Then about 1 ml of starch solution was added, and titration continued until the blue indicator color just disappeared. The volume of sodium thiosulfate solution used was recorded.

The iodine number *X*, %, of the carbon was calculated using Equation 1.

$$X = \frac{(V_0 - V_1) \times 0.0127 \times 100 \times 50}{m \times 10}, \quad (1)$$

where V_1 – volume of sodium thiosulphate solution, ml; *m* – mass of activated carbon, g; 50 – iodine solution of 0.10 N added into weighed sample, ml.

The methylene blue value is defined as the number of milliliters of standard methylene blue solution decolorized by 0.1 g of activated carbon (dry basis). Granular activated carbon is pulverized (<0.1 mm) and then dried at 150 °C to constant weight. Exactly 0.1 g of the carbon sample is contacted with 25 (5) ml of the methylene blue test solution in a glass stoppered flask. The flask is shaken until decolorization occurs. Then a further 5 (1) ml of the methylene blue test solution is added, and the flask is shaken until decolorization. The addition of methylene blue test solution in 5 (1) ml portions is repeated as long as decolorization occurs within five minutes. The volume of methylene blue test solution in ml that is just decolorized is the methylene blue value of the activated carbon.

RESULTS AND DISCUSSION

The results of ultimate and proximate analysis of the studied initial coal samples from Tavan Tolgoi IV, Nariin Sukhait, and Saikhan-Ovoo deposits are shown in Table 2.

The technical characteristics in Table 2 show that Tavan Tolgoi IV, Nariin Sukhait, and Saikhan-Ovoo coals have low ash content. The sulfur content is less than 1 in all coals, which is beneficial from an environmental perspective. Additionally, the volatile matter is lower in Tavan Tolgoi and Nariin Sukhait coals, which is characteristic of high-rank coking coal. The volatile matter content is lowest in Saikhan-Ovoo coal, as it is of the anthracite type.

The carbon content in Table 2 is higher and the oxygen content is lower in Tavan Tolgoi IV and Saikhan-Ovoo coals, which are characteristics of high-rank coals. The oxygen content in Nariin Sukhait coal is higher because this coal is closer to subbituminous coal. The hydrogen content in the Saikhan-Ovoo deposit coal is lower because this coal is a hard stone coal of anthracite type. The results of FTIR analysis of coal samples are shown in Figure 4.

In the FTIR spectra of initial coal samples from all deposits, the following absorption frequency regions can be recognized: 700–900 cm^{-1} for Car-H; 1000–1300 cm^{-1} for the vibration of bonds in various oxygen-containing groups; 1350–1470 cm^{-1} for vibrations of –CH, $-CH_2$, and $-CH_3$ groups; 1500–1630 cm^{-1} for skeletal vibrations of aromatic rings and >C=O bonds in ketones, aldehydes, and quinones; 2800–2950 cm^{-1} for stretching vibrations of –CH, $-CH_2$,

Table 2. Ultimate and proximate analysis of coal samples from Mongolia, %

Таблица 2. Техническая характеристика и элементный состав образцов угля из Монголии, %

Samples	W^a	A^d	V^{daf}	S^d_t	C	O	N	H
Tavan Tolgoi IV	0.95	1.70	28.00	0.90	76.40	0.60	2.30	4.50
Nariin Sukhait	3.65	11.10	34.00	0.80	68.60	9.10	0.90	4.30
Saikhan-Ovoo	2.54	8.70	7.60	0.59	80.00	0.80	1.60	2.00

Note. W^a – moisture; A^d – ash; V^{daf} – volatile matter; S^d_t – sulfur.

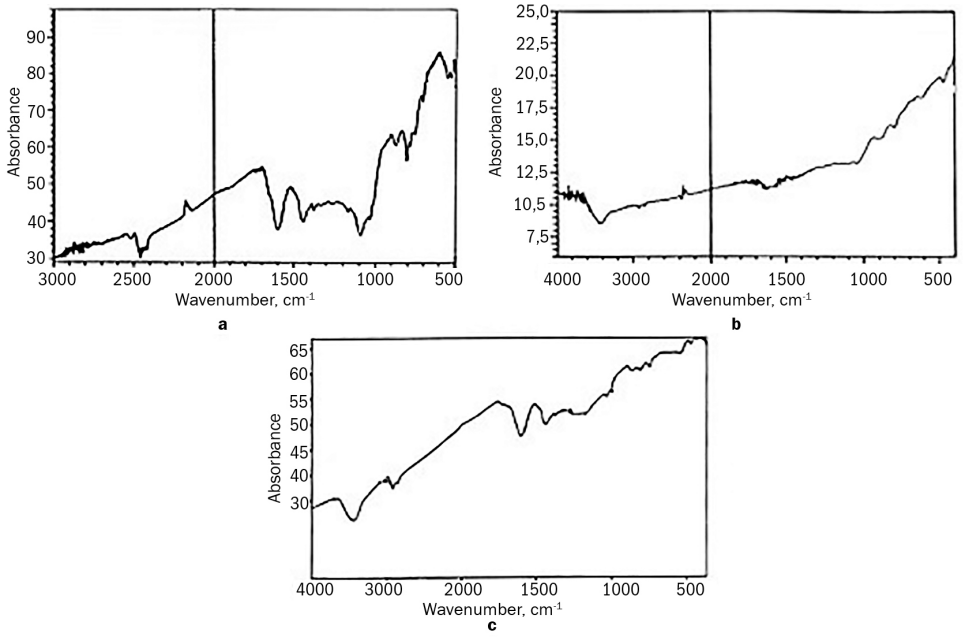

Fig. 4. FTIR spectrum of initial coal samples: Tavan Tolgoi IV (a), Saikhan-Ovoo (b), and Nariin Sukhait (c)

Рис. 4. ИК-спектры исходных образцов угля: Таван Толгой IV (a), Сайхан-Овоо (b) и Нарийн Сухаит (c)

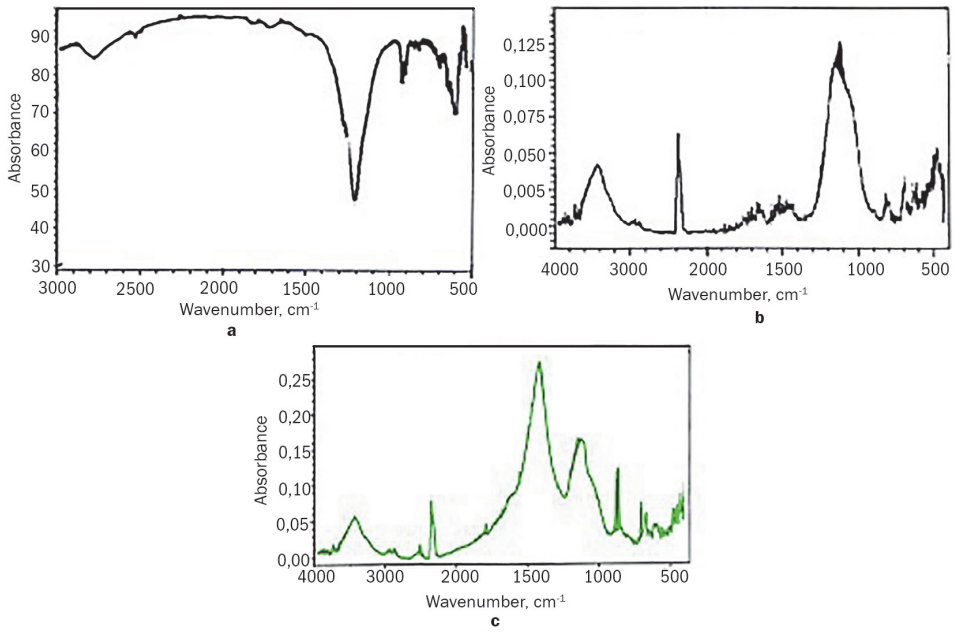

Fig. 5. FTIR spectrum of ash of initial coal samples: Tavan Tolgoi IV (a), Saikhan-Ovoo (b), and Nariin Sukhait (c)

Рис. 5. ИК-спектры золы исходных образцов угля: Таван Толгой IV (a), Сайхан-Овоо (b) и Нарийн Сухаит (c)

and –CH_3 groups in saturated aliphatic structures; and 3030–3350 cm^{-1} for stretching associated vibrations of –OH groups in aromatic rings and aliphatic structures. Coals from the Tavan Tolgoi IV, Nariin Sukhait, and Sakhan Ovoo deposits are high-rank and more polymerized coals with lower reactivity. Therefore, the FTIR spectra of coal samples from these deposits have very weak, indistinct, and continuous absorption bands.

Table 3. Mineral composition of coal ashes from examined coal deposits, %

Таблица 3. Минеральный состав золы угля исследованных месторождений, %

Compound	Deposit		
	Tavan Tolgoi IV	Nariin Sukhait	Saikhan-Ovoo
Na_2O	–	–	–
MgO	–	2.50	2.53
AL_2O_3	15.75	17.05	8.20
SiO_2	77.61	22.80	17.07
SO_3	1.93	7.30	2.15
K_2O	0.52	3.00	0.44
CaO	1.89	14.80	4.82
TiO_2	0.92	2.70	0.50
V_2O_5	–	–	–
Mn_2O_3	–	0.60	0.43
Fe_2O_3	0.72	27.50	60.21
CuO	0.01	0.07	0.03
SrO	0.03	–	0.28
NiO	0.01	0.09	–
ZrO_2	–	0.08	–
PbO	–	0.90	0.04
P_2O_5	0.58	0.40	3.06
ZnO	–	0.20	–

Note. (Fe_2O_3 + CaO + MgO + Na_2O + K_2O) / (SiO_2 + Al_2O_3 + TiO_2) acidic < 1 < alkaline.

To investigate the mineral composition of coal samples, the ash from the complete combustion of each coal sample at 950 °C was obtained. The FTIR spectra of the coal ash samples are presented in Figure 5. The mineral oxide composition of the ash, determined by the X-Ray Fluorescence method, is given in Table 3.

The most intensive and broadest adsorption bands in each FTIR spectrum of coal ash (Figure 5) are as follows: 1060 cm^{-1} for Si-O- bonds in silicates (Saikhan-Ovoo), 1091 cm^{-1} for Si-O- bonds in silicates (Tavan Tolgoi IV), and 1410 cm^{-1} for Ca-O- bonds in carbonates (Nariin Sukhait). Additionally, some other peaks with lower intensity are observed, including at 3400 cm^{-1} for –OH groups in different minerals, 1000 cm^{-1} for Al-O-, 900–1000 cm^{-1} for Si-O-, 765 cm^{-1} for Si-O-Si, 1145 cm^{-1} for Si-O, 1020 cm^{-1} for Si (Al)-O-, 730 cm^{-1} for Si-O-Al, 610 cm^{-1} for –O-Si(Al) –O- and Ca-O-, and 400-500 cm^{-1} for Si-O-Mg; Si-O-Fe; Si-O-Al bonds in various minerals.

The data in Table 3 show that the main components of ash are SiO_2, Al_2O_3, CaO, and Fe_2O_3 in all coal samples. The content of CaO and Fe_2O_3 is lowest in the ash of Tavan Tolgoi coal. The content of Al_2O_3 is lower in the ash of Sakhan-Ovoo coal, and the content of CaO is also lower in the ash of Saikhan-Ovoo coal. The content of SiO_2 is highest in the ash of Tavan Tolgoi coal, while the content of Fe_2O_3 is highest in the ash of Sakhan-Ovoo coal. To confirm the presence of Fe_2O_3 in the coal ash samples, photographs of the ash have been taken. The red color of Saikhan-Ovoo coal ash indicates the highest content of Fe_2O_3.

The ratio of (Fe_2O_3 + CaO + MgO + Na_2O + K_2O) to (SiO_2 + Al_2O_3 + TiO_2) has been calculated using the data from Table 3, and the results of the X-ray fluorescence spectrum are provided in Table 4.

The calculated values of the ratio between (Fe_2O_3 + CaO + MgO + Na_2O + K_2O) and (SiO_2 + Al_2O_3 + TiO_2) indicate that the ash of Tavan Tolgoi IV coal exhibits an acidic character, while the ash of Nariin Sukhat coal and Saikhan-Ovoo coal displays an alkaline character.

Table 4. Values calculated for the ratio of (Fe_2O_3 + CaO + MgO + Na_2O + K_2O) to (SiO_2 + Al_2O_3 + TiO_2)

Таблица 4. Расчетные значения соотношения между (Fe_2O_3 + CaO + MgO + Na_2O + K_2O) и (SiO_2 + Al_2O_3 + TiO_2)

Samples	Value of the ratio	Type of ash
Tavan Tolgoi IV	0.03	Acidic
Nariin Sukhait	1.12	Alkaline
Saikhan-Ovoo	2.63	Alkaline

X-ray diffraction analysis of coal ashes indicates that the most important minerals in all ashes are quartz, anhydrite, akermanite, and albite. The chemical formulas of these minerals are provided in Table 5.

Table 5. Key minerals found in coal ash

Таблица 5. Преобладающие минералы в золе исследованных углей

Most determined minerals in the coal ash	Chemical formule
Quartz	SiO_2
Anhydrite	$CaSO_4$
Akermanite	$Ca_2(Mg_{0.75}Al_{0.25})$ $(S_{4.75}Al_{0.25})O_7$
Albite	$Na(S_3Al)O_8$

It is widely recognized that the concentrations of radioactive elements such as Ra, Th, and U in natural coals are generally lower than international standards and tend to increase if the coal deposits are located in regions with uranium deposits. Naturally, the concentration of radioactive elements in activated carbons should be kept as low as possible. Therefore, the levels of radioactive elements in coal samples and their ashes have been measured. The results are presented in Table 6.

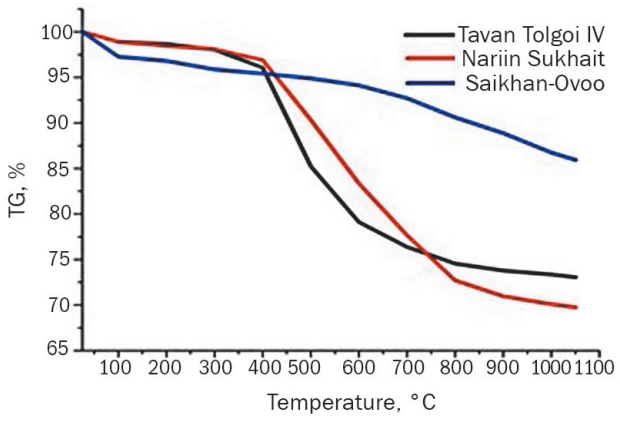

Fig. 6. Thermogravimetric curve of coal samples

Рис. 6. Кривая термогравиметрии образцов угля

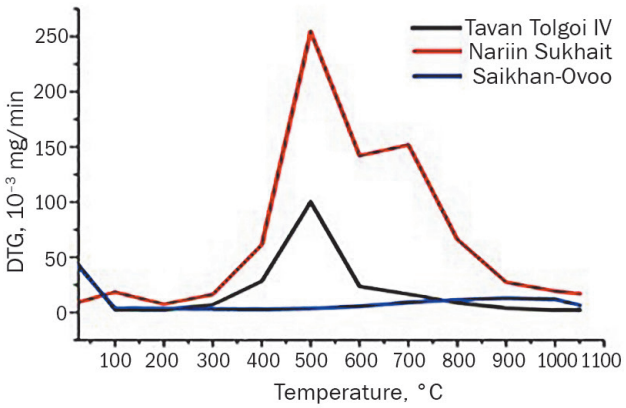

Fig. 7. Derivative thermogravimetric curve for coal samples

Рис. 7. Кривая производной термогравиметрии образцов угля

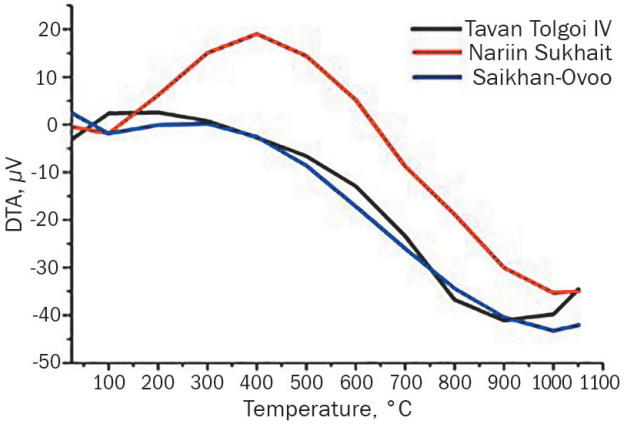

Fig. 8. Differential thermal analysis curve of coal samples

Рис. 8. Кривая дифференциального термического анализа образцов угля

The data in Table 6 show that the content of radioactive elements such as Ra, Th, and U in the studied coals is below international standards for concentrations. However, the concentration of radioactive elements such as Ra (Bq/kg), Th (Bq/kg), and U (g/ton) in the coal ash has increased. For example, the concentration of Ra (Bq/kg) in all samples increased by 3 to 6 times.

The thermogravimetric analysis is a highly useful method for investigating thermal decomposition (in an argon atmosphere using the Hitachi TG/DTA7300) and the

Table 6. Content of radioactive elements in coal and coal ash

Таблица 6. Содержание радиоактивных элементов в углях и золе углей

Samples	Isotope activity, Bq/кг			Elemental content			Radium equivalent, Bq/кг
	Ra-226	Th-232	K-40	U, г/тон	Th, г/тон	K, %	
Tavan Tolgoi IV coal	13.4	6.0	460.2	1.1	1.5	1.5	60.38
Tavan Tolgoi IV coal ash	78.3	75.2	1203.0	6.4	18.4	4.0	278.96
Nariin Sukhait coal	54.6	16.9	595.0	4.5	4.1	2.0	127.31
Nariin Sukhait coal ash	219.8	75.3	2097.0	18.0	18.4	7.0	496.69
Saikhan-Ovoo coal	67.4	4.3	259.1	5.5	1.1	0.9	95.6
Saikhan-Ovoo coal ash	393.8	53.8	1036.4	31.88	13.25	3.34	332.71

thermal stability of natural organic resources, including coals. Therefore, the selected high-rank coals have been examined using this method. The thermogravimetric (TG) curve is presented in Figure 6, the derivative thermogravimetric (DTG) curve is shown in Figure 7, and the differential thermal analysis (DTA) curve is depicted in Figure 8.

Figure 6 shows that the coals of Tavan Tolgoi IV and Nariin Sukhait have a similar thermogravimetric curve to that of Saikhan-Ovoo coal, which is completely different. Based on the aforementioned proximate and ultimate analyses of the coals, it has been confirmed that the coals of Tavan Tolgoi IV and Nariin Sukhait are high-quality bituminous coking coals, while the coal of Nariin Sukhait is a non-bituminous hard stone coal of anthracite type.

The thermal stability indices of coals ($T_{5\%}$, $T_{15\%}$, and $T_{25\%}$) were determined from the thermogravimetric curves (Table 7).

Table 7. Thermal stability indices of coals

Таблица 7. Показатели термической устойчивости углей

Samples	Thermal stability indices, °C		
	$T_{5\%}$	$T_{15\%}$	$T_{25\%}$
Tavan Tolgoi IV	422.85	501.74	768.46
Nariin Sukhait	425.30	455.50	620.00
Saikhan-Ovoo	483.81	1050.00	–

The data in Table 7 indicate that the studied coals exhibit very high thermal stability, with the Saikhan-Ovoo deposit demonstrating greater thermal stability than the Tavan Tolgoi IV and Nariin Sukhait coals due to its hard, anthracite-type organic mass. For instance, $T_{15\%}$ = 1050 °C, which is twice as high as that of the Tavan Tolgoi IV and Nariin Sukhait coals.

The heating of Tavan Tolgoi IV and Nariin Sukhait bituminous coal at temperatures ranging from 25 to 1100 °C in an argon atmosphere indicates that the thermogravimetric curve in Figure 7 comprises different temperature intervals (steps), such as 25–425 °C, 425–825 °C, and 825–1100 °C. During the first step (25–425 °C), the weight loss occurs due to the release of absorbed gases and moisture from the coal sample. In the second step (425–825 °C), intensive thermal decomposition of the coal's organic matter takes place, leading to the formation of liquid products (tar and pyrolysis water) and gaseous products. In the third step (825–1100 °C), the weight loss declines significantly, indicating the end of thermal decomposition and the onset of carbonization of the coal. Following the intense thermal decomposition at 425–825 °C, a hard residue remains of 75% for Tavan Tolgoi IV and 65% for Nariin Sukhait.

Due to the hard stone and the lack of bituminous character in the Saikhan-Ovoo coal, the thermal decomposition rate is very low. Consequently, the yield of hard residue was 87.5%, which is significantly higher than that of the Tavan Tolgoi IV and Nariin Sukhait coals.

For this reason, three coal samples have been prepared for purification in a $ZnCl_2$ solution. The moisture and ash content (with the decrease in ash content being the most important) of these samples is provided in Table 8.

Table 8. Content of moisture and ash in coal samples for purification, %

Таблица 8. Содержание влаги и золы в образцах угля для очистки, %

Samples	W^a	A^a	A^d
Tavan Tolgoi IV	0.77	8.21	8.30
Nariin Sukhait	3.08	7.46	7.70
Saikhan-Ovoo	2.98	8.34	8.60

The yield of fractions after the purification in $ZnCl_2$ solution is presented in Table 9.

Table 9. Results of enrichment of coals in $ZnCl_2$ solution

Таблица 9. Результаты обогащения углей в растворе $ZnCl_2$

Samples	Weight of coal sample, g	The yield of top fraction, %	The yield of bottom fraction, %	Loss, %
Tavan Tolgoi IV	753.10	82.60	12.00	5.40
Nariin Sukhait	741.70	77.40	14.90	7.65
Saikhan-Ovoo	750.40	53.40	46.60	–

The highest yield of the top fraction (purified coal) comes from Tavan Tolgoi coal. Typically, high-rank coals such as Tavan Tolgoi, Nariin Sukhait, and Saikhan-Ovoo have a high yield of the top fraction. The loss indicated in Table 9 suggests that some particles of coal and mineral matter are dispersed in the middle zone between the top and bottom fractions.

The moisture and ash content in purified coal samples (top fraction) are presented in Table 10.

Table 10. Technical characteristics of coals (top fraction) after enrichment, %

Таблица 10. Технические характеристики углей (верхняя фракция) после обогащения, %

Samples	W^a	A^a	A^d
Tavan Tolgoi IV	0.74	4.74	4.80 (8.30)
Nariin Sukhait	3.10	4.45	4.60 (7.70)
Saikhan-Ovoo	2.79	6.20	6.40 (8.60)

Note. In brackets the ash content of initial coal samples is given for comparison.

The data in Table 10 suggest that the mineral matter content in all coal samples decreased by nearly half after the enrichment.

The purified coal samples have been used for pyrolysis (carbonization) experiments in the authors' developed large-scale retort. The yields of pyrolysis products, including hard residue, condensed liquid (tar), and uncondensed gas, have been determined (Table 11).

The hard residue in Table 11 refers to the carbonized purified coal samples after pyrolysis (carbonization). The yields of pyrolysis hard residue have increased compared to the yields of pyrolysis hard residue from the initial coal samples (Table 11). We expected this result because the ash content of all initial coal samples was reduced by almost half through enrichment in $ZnCl_2$ solution.

To enhance the porosity of pyrolysis hard residue, it has been treated with preheated water steam, as described in the experimental section.

Table 11. Yields of pyrolysis products of purified coal samples, %

Таблица 11. Выходы продуктов пиролиза очищенных образцов угля, %

Samples	Hard residue	Tar + Pyrolysis water*	Gas
Tavan Tolgoi IV	82.70	4.77	12.53
Nariin Sukhait	79.60	8.10	13.30
Saikhan-Ovoo	95.20	2.17	2.63

Note. In this experiment, the yield of tar and pyrolysis water was determined together (not separated).

The technical characteristics of the activated carbon samples obtained are presented in Table 12.

The yield of activated carbon from Tavan Tolgoi IV, Saikhan-Ovoo coal is higher than that of other sources due to their greater degree of purification and enhanced thermal stability. The yield of activated carbon in Table 11 is lower than in Table 10 because the pyrolysis (carbonization) of purified coal samples was conducted at 700 °C (Table 11), while the activation of carbonized samples was performed at 800 °C. At this higher temperature, the organic matter in the carbonized hard residue can decompose, and some volatile materials that fill the pores can be released during activation with heated water steam.

The most crucial technical specification of activated carbons is their adsorption capacity, evaluated by iodine number and methylene blue adsorption.

For this reason, the prepared activated carbon samples and the pyrolysis hard residue of the initial coal samples, without activation (for comparison), have been tested for iodine and methylene blue adsorption analysis to evaluate the adsorption ability, and the results are presented in Table 13.

The iodine number of activated carbon derived from purified and carbonized coals increased by 5 to 17 times, and methylene blue adsorption also rose by 4 to 10 times compared to the pyrolysis hard residue of initial coal samples without purification and activation. The activated carbon samples prepared from Saikhan-Ovoo, Nariin Sukhait, and Tavan Tolgoi IV coals exhibit higher adsorption capabilities than those from Ereen, Shariingol, and Baganuur coals, as these coals are of a higher rank and quality than others, as previously mentioned [19].

The other important technical specification of activated carbons is the determination of surface area (BET). For this reason, the surface area (BET) of the prepared activated carbons and initial coal samples (appendix) has been determined to show how the purification, carbonization, and activation of the initial coal affect the development of the surface area of the prepared activated carbons (Table 14).

Table 14. Surface area (BET) of initial coal and corresponding activated carbon, m^2/g

Таблица 14. Площадь поверхности (по методу Брунауэра – Эммета – Теллера) исходного угля и соответствующего активированного угля, $м^2/г$

Samples	Initial coal	Activated carbon
Tavan Tolgoi IV	0.90	176.00
Nariin Sukhait	1.30	442.00
Saikhan-Ovoo	8.70	263.00

The surface area (BET) determination results of initial coal and its activated carbon samples from the Tavan Tolgoi IV coal deposit in Nariin Sakhait show that the surface area of the activated carbon is 195 times higher than that of the initial coal from the Tavan Tolgoi IV deposit.

The surface area (BET) determination results of initial coal and its activated carbon samples from the Nariin Sukhait coal deposit in Tavan Tolgoi IV show that the surface area of the activated carbon is 340 times higher than that of the initial coal from the Nariin Sukhait deposit. This result also shows that the initial coal has a relatively small surface area, and the method of preparation for the initial coal, including enrichment, carbonization, and activation for activated carbon, has a significant influence on the

Table 12. Technical analysis of activated carbon samples after activation of pyrolysis hard residue at 800 °C by preheated water steam

Таблица 12. Результаты технического анализа образцов активированного угля после активации твердого остатка пиролиза при 800 °C предварительно нагретым водяным паром

Activated carbon from the coal of the deposit	Time of activation, min	Yield, %	W^a, %	A^d, %	V^{daf}, %	Gas, %
Tavan Tolgoi IV	120	77.12	0.67	8.03	2.6	11.58
Nariin Sukhait	120	56.60	0.13	7.01	3.2	33.06
Saikhan-Ovoo	120	72.40	0.45	6.08	1.6	19.47

Table 13. Iodine number and methylene blue adsorption of activated carbon samples

Таблица 13. Йодное число и величина адсорбции метиленового синего образцами активированного угля

Samples	Type of sample	Iodine number, %	Methylene blue adsorption, mg/g
Tavan Tolgoi IV	Pyrolysis hard residue of initial coal sample	3.30	1.40
	Activated carbon of purified and carbonized coal	16.54	6.00
Nariin Sukhait	Pyrolysis hard residue of initial coal sample	2.60	1.00
	Activated carbon of purified and carbonized coal	18.50	6.30
Saikhan-Ovoo	Pyrolysis hard residue of initial coal sample	1.20	0.59
	Activated carbon of purified and carbonized coal	20.50	6.23

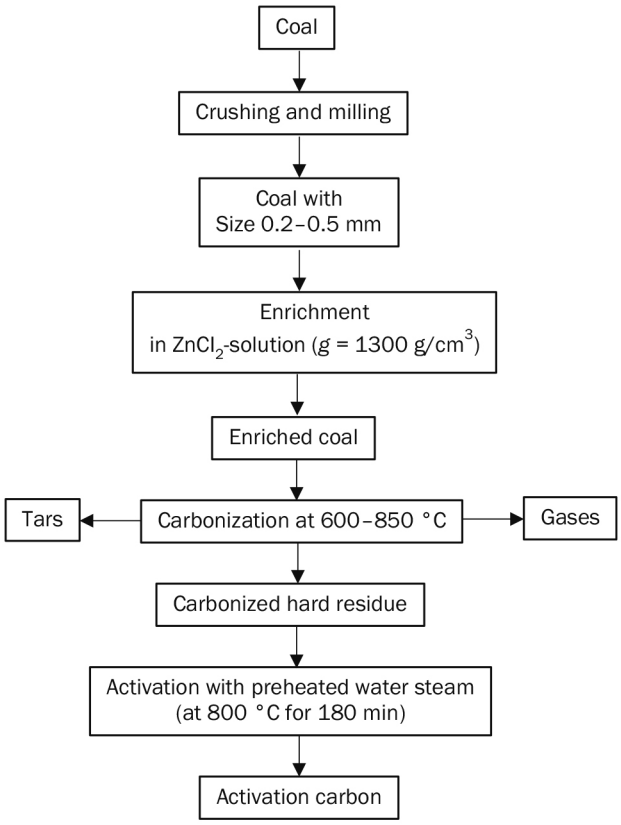

Fig. 9. Scheme for activated carbon preparation from some high rank Mongolian coals

Рис. 9. Схема получения активированного угля из некоторых высокосортных углей Монголии

development of the porosity structure and surface area.

The surface area (BET) determination results of the initial coal and its activated carbon samples from the Saikhav-Ovoo coal deposit in Nariin Saikhait show that the surface area of the activated carbon is 30 times higher than that of the initial coal from the Saikhav-Ovoo deposit.

Based on the research conducted, a reasonable technological scheme for the production of activated carbon from high-rank Mongolian coals has been developed (Figure 9).

The technological scheme for the production of coal-derived activated carbon consists of four main steps: crushing and milling, enrichment in heavy liquid, carbonization, and activation with preheated water steam.

CONCLUSIONS

1. The ultimate and proximate analyses of coal samples from the Tavan Tolgoi IV, Nariin Sukhait, and Saikhan-Ovoo deposits have been conducted in our laboratory in accordance with Mongolian national standards.

2. Based on ultimate and proximate analysis, the assessment of coals according to international classification has been conducted:

The Tavan Tolgoi IV coal is a high rank bituminous coking coal of KZh mark;

The Nariin Sukhait coal is a high rank bituminous coking coal of KZh mark;

The Saikhan-Ovoo coal is a high rank hard nonbituminous (anthracite) coal type of SS mark.

3. The yield of pyrolysis hard residue (carbonized coal) is high for the Saikhan-Ovoo, Tavan Tolgoi IV, and Nariin Sukhait coals, due to their high rank and greater thermostability of organic matter. The resulting hard residue (carbonized coal) takes the form of a porous material with meso and macro pores. Some pores may be filled with volatile substances that could not completely escape during pyrolysis. To achieve a high-quality adsorbent material with well-developed porosity, it is necessary to conduct additional processing, such as coal purification, carbonization, and activation of the resultant hard residue using heated water vapor.

4. The ash content of coals purified in a $ZnCl_2$ solution, compared to the ash of coals before purification, shows that the mineral matter content of the coals after enrichment is significantly decreased, nearly by half, in all samples.

5. Based on the carbonization, purification, and activation experiments of coal, a reasonable technological scheme for active carbon production has been developed.

6. The determined iodine number of activated carbons from purified and carbonized coals increases 5–17 times, and methylene blue adsorptions also increase 4–10 times compared to the pyrolysis hard residue of initial coal samples without purification and activation.

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