Technological Aspects of Obtaining Fuel Composites Based on Fine-Grained Coal Waste

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Abstract The results of experimental research on the selection of binders for briquetting anthracite mines, coal and coke breeze, coal sludge, available in coal-mining regions are presented. It is developed an inexpensive, affordable binder for briquetting fine-grained coal waste. The influence of granulometric composition of coal components, binder content, moisture content of coal components, specific pressing pressure on the technical properties of fuel briquettes has been investigated. Methods of increasing moisture resistance and water resistance of fuel composites are proposed. The technical analysis of an experimental batch of fuel briquettes is presented. The mechanism of strengthening and formation of the structure and properties of fuel composites is considered.

Keywords Anthracite fines · Coal sludge · Fine coal and coke · Coal waste · Binder · Molasses · Carbide sludge · Bottoms of organic synthesis cracking · Briquetting · Fuel composite · Fuel briquette · Moisture resistance · Water resistance

1 Introduction

Significant amounts of coal waste have been accumulated in the coal-industrial regions: anthracite fines, fine coal and coke, coal sludge. The stocks of fine-grained coal materials are huge, and unused waste from the coal mining stored is dumps. They have a negative impact on the environment. The reserves of fine-grained coal

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materials are enormous. The study of such qualitative characteristics of these raw materials as ash content, sulfur content, heat of combustion, and the release of volatile substances made it possible to establish their prospects for use as a full-fledged household fuel after appropriate processing. This is a valuable carbon-containing raw material, but its use in a finely dispersed state is not effective due to the obstruction of transportation, dusting, and incomplete combustion. At the same time, due to the reduction in the output of high-quality coals for household needs and industrial energy, there is a need for additional types of solid fuel.

The problem of using screenings of coal and anthracite is increasingly attracting the attention of many researchers [1–6] in connection with the need to utilize coal fines and obtain additional conditioned fuel. Therefore, in the presence of a huge reserve of unused coal resources, it becomes necessary to develop a technology that ensures the efficient production of fuel products with specified quality indicators. It is possible to obtain a product with the required properties from substandard, but having a certain energy potential, raw materials, using the briquetting technology. The most reasonable technological direction, which can ensure the production of fuel with satisfactory consumer characteristics, is the briquetting of substandard carbon-containing waste with binders. This is a versatile way to obtain fuel briquettes from almost any material. This is especially true for anthracite fines, screenings and coal fines. Anthracite fines, coke, coal fines have a certain hardness and their mixtures are rigid, not plastic. A fuel briquette based on such carbon components can be obtained either with binders or with a very high compaction pressure. As follows from the analysis of the available domestic and foreign experience in the manufacture of briquettes, the most common binders are oil bitumen and coal tar pitch. However, these binders are classified as substances with increased carcinogenic properties. It is well-known the using inorganic binders such as lime, cement, water glass, gypsum. However, these binders increase ash content, impair combustion and the cost of briquettes. There are very few inexpensive, non-scarce binders that ensure the environmental safety of fuel briquettes, the manufacturability of their production process and the required quality indicators of briquettes. These are the main reasons why the production of briquettes from anthracite fines and coal fines has not received large-scale development.

Fuel briquettes are rightfully considered the fuel of the XXI century, the number of its consumers in various countries of the world is growing every year. The demand for solid fuel is steadily increasing, the fuel market is practically empty. Using the energy potential of substandard products by briquetting them and turning them into refined fuel will not only replenish the coal-raw material base, but also involve waste in production, and reduce the technogenic load on the environment.

1.1 Purpose of the Study

The purpose of this study is to develop a technology for briquetting fine-grained and fine-dispersed coal-containing waste with binders. When developing the technology, the following principles of constructing technological processes for producing coal composite materials were taken as a basis:

(i) selection of an adsorbent based on a set of properties that meet the requirements for finished products;
(ii) introduction of additional components into the composition of coal compositions to impart new consumer properties to the entire composition;
(iii) performing the necessary technological operations to obtain products with the specified technical quality indicators.

1.2 Research Objectives

The fuel briquette is a dispersed-granular composite consisting of a carbon-containing component and a binder. When forming the structure of the composite, it is necessary to create conditions for creating a structure that is most effective and optimal in terms of resistance to atmospheric influences during storage and thermal and mechanical loads during their use. The solution to this problem involves:

(i) to justify the requirements for the grain size composition of the carbon-containing component (large-scale composite structure criterion);
(ii) to determine the optimum moisture content of the carbon-containing component;
(iii) to establish the optimal ratio of the solid component and a binder;
(iv) to determine the optimal compaction force of the composition;
(v) to set the hardening mode of the dispersed-granular composite.

2 Research Methods

Analytical and laboratory studies were carried out in order to obtain information on the technical properties and composition of the initial components for briquetting. The research results make it possible to determine the main technological aspects of coal waste briquetting. Further technological studies were carried out, according to which a complete assessment of the quality of raw materials was given in accordance with the requirements of regulatory and technical documentation. Rational combinations of research methods make it possible to develop optimal parameters for briquetting fine-grained coal waste and obtain efficient fuel composites.

The main technological operations during briquetting included preliminary preparation of coal raw materials: crushing and classification. Next, the prepared components: anthracite fines, coal sludge and coke fine, taken in a certain ratio, were thoroughly mixed until the components were evenly distributed (visual assessment). A binder was previously prepared. The solid components were mixed with a certain amount of binder. The mixture was thoroughly mixed until a homogeneous mass was obtained. Briquettes were manufactured on a hydraulic press in a cylindrical matrix with a lenticular shape of the upper and lower working surfaces of the punches with a pressing load of 25–40 MPa. Testing of briquettes for compressive strength was carried out on specimens-cylinders with a height and a diameter of 50 mm. The hardening of briquettes took place, as a rule, during natural drying.

3 Results and Discussion

Environmental stress in the coal-mining regions of the country is largely determined by the high level of waste from coal mining and processing. In terms of its quality characteristics, coal waste is not inferior to mined coals, but it is almost impossible to use their energy potential due to their fine dispersion and dustiness. The objects of the study were coal-containing raw materials from coal-processing factories of the Rostov region. Binders were made from wastes from the sugar-beet industry of the Krasnodar region and wastes from chemical industries in the Rostov region.

The following components were used as raw coal for research:

(i) anthracite fines are the anthracite screenings and waste from coal preparation plants, with a fraction of 0-6 mm; carbon content in organic matter is 93.0–95.0% and density is 1.4–1.8 g/cm^3.
(ii) coal fines are the coal screenings and waste from coal preparation plants; carbon content is 76–90%; density is 1.2–1.8 g/cm^3.
(iii) coal sludge are the wastes from coal preparation plants, fine grades of anthracite and coal with particle size of 0 – 1 mm.
(iv) coke fine is the coke screenings, contains 82–88% carbon, density is 1.4–1.95 g/cm^3.

The technical characteristics of the coal components are given in Table 1.

Molasses, a by-product of sugar beet production, was used as the basis of the binder for briquetting the carbonaceous raw materials. Refers to the group of disaccharides. The molasses contains up to 45–50% beet sugar $C_{12}H_{22}O_{11}$. Soluble polysaccharides easily swell in water and form viscous colloidal solutions in it. Molasses is a thick,

Table 1 Technical properties of coal technogenic raw materials

Type of raw material	Indicators				
	Ash content, %	Sulfur content, %	Volatile matter release, %	Humidity, %	Calorific value, MJ/kg
Anthracite fines	5.0–30.0	0.9 – 1.2	3.0–9.0	9.0–12.0	18.8–33.2
Coal fines	14.6–32.0	1.4–1.8	11.0–43.5	4.0–12.8	12.4–17.2
Coal sludge	26.0–45.0	1.2 – 1.7	5.0–9.0	8.0–28.0	14.9–18.5
Coke fine	10.0–12.0	2.1 – 2.4	21.0–28.0	4.0–16.0	15.2–36.4

syrupy, opaque, viscous liquid from brown to dark brown in color. Molasses has a specific smell from sucrose caramelization products and a sweet taste with a bitter aftertaste. Its relative density, depending on the content of dry substances, is 1.30–1.52 g/cm^3. The chemical composition of molasses is very complex. In its most general form, molasses contains up to 20% water, 45–50% sugar, 20–25% organic matter, and 10% non-sugar mineral substances.

Molasses is a concentrated solution of various organic and mineral substances, some of which are in a colloidal state. The colloids contained in the molasses have significant surface activity and therefore are well adsorbed on the surface of the particles to be glued.

The molasses is delivered to the place of use by road transport in tank trucks or metal closed containers. Molasses is stored in closed metal tanks. The guaranteed shelf life of molasses is at least 9 months from the date of acceptance of the molasses by the consumer. The storage time of molasses does not affect its adhesive (binding) ability.

Carbide sludge is used as a structuring additive for molasses. It is a lime containing product. Formed as a waste product in the production of acetylene from calcium carbide. According to the state of aggregation, carbide sludge is a finely dispersed gray-blue paste. This is lime of the 2nd grade, bluish tint. Mass fraction of calcium hydroxide [$Ca (OH)_2$] is not less than 35%. Carbide sludge is not a scarce product, accumulates in dumps of chemical plants, has a low cost.

As a hydrophobizing additive to molasses, we used the bottoms of organic synthesis cracking, namely wastes of synthetic products factories with a melting temperature of 35–38 °C, a pour point of 46–48 °C and an ash content of 0.016–0.018%.

The ability of coals to be briquetted depends on the coal belonging to one class or another. There are no strict criteria for evaluating the briquetting of coal and carbonaceous materials. As a rule, the ability to briquetting is associated with the ability of coal to plastically deform when it is pressed under certain conditions [7, 8]. A qualitative rapid assessment of the briquetting capacity of coal can be the simplest way: determination of the briquetting capacity of the charge by establishing the minimum amount of binder that is required to be introduced into the charge, for obtaining a mechanically strong briquette with a minimum pressing pressure. The main criterion for the formability of the coal-containing charge is the strength of the raw briquette. Evaluation of the briquetting ability of coal waste and the quality of the resulting product was determined by the strength of the briquettes for dropping and compression.

The efficiency of coal briquetting can be increased by activating the surface of the coal particles. One of the activation methods is grinding or mechanical activation. During crushing and grinding under the influence of mechanical forces, physico-chemical processes are intensified, leading to a change in the reactivity of coal. Under the influence of shock loads or friction, various structural defects accumulate in coal particles: cracks, roughness, unevenness. On the solid surface of the coal particles, the number of active centers increases, and the adsorption activity of the coal component in relation to the binder increases. The reactivity of coal changes.

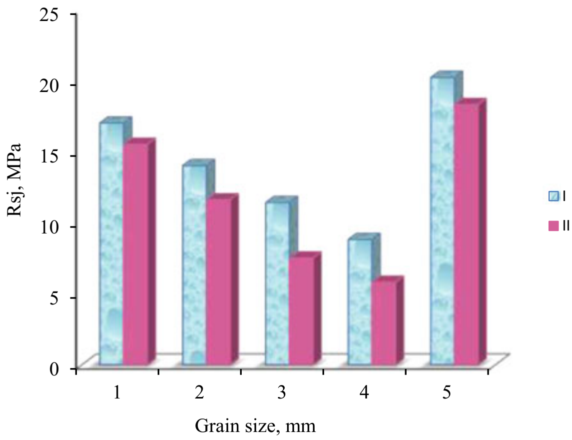

Fig. 1 Effect of coal grain size on the strength of fuel briquettes: (1) 0–1 mm; (2) 0–3 mm; (3) 1–3 mm; (4) 3–6 mm; (5) optimal grain size composition; I - binder: molasses; II - binder: molasses + carbide sludge

The processed material is stored with free energy. Moreover, mechanical fixation of the binder occurs on a rough surface.

One of the factors affecting the briquette ability and quality of fuel composites is the granulometric composition of the briquetted material. The granulometric composition of the briquetted material characterizes the ratio of particles of different sizes in the charge and affects the packing density of the particles. Polydisperse systems have a high specific surface area characterized by an excess of surface energy. This causes the particles to converge, i.e. transition of the system to a stable thermodynamic state. Such a system forms a denser packing of particles and a high briquette strength. Studies on the influence of the size of the initial carbon-containing raw material on the strength properties of briquettes have shown that the greatest value of the compressive strength was obtained in samples containing waste coal with a fraction of 0–1 mm (Fig. 1). This is due to the fact that fine coal particles on a solid surface have more active centers interacting with a binder. However, with such a grain size composition, the specific surface area of the particles increases and, accordingly, the consumption of the binder grows. Position 5 in Fig. 1 reflects the strength of briquettes with an optimal particle size distribution of the charge. With an optimal grain size composition of the charge, the time and energy consumption for brittle and elastic deformations of the composite during pressing decreases, and the share of energy and time for useful plastic deformations increases.

It has been experimentally established that when anthracite fines with a size of 0–6 mm are included in the briquette, their particle size distribution should be following: (i) 5–7% > 6 mm; (ii) 25–30% with sizes of 3–6 mm; (iii) 30–33% with sizes of 1-3 mm; (iv) 35–45% with sizes of 0 – 1 mm. In the result of the studies performed, the optimal granulometric composition of the charge for briquetting was determined: the content of the 6 mm class is 2–3%; 3 – 6 mm is 24–28%; 1–3 mm is 27–35%; 0 – 1 mm is 38 – 45%.

To increase the plasticity, manufacturability and improve the grain size composition of the charge, finely dispersed coal sludge was introduced. In the grain composition of coal sludge with a particle size of 0–3 mm, the content of fractions was 1–3 and for 0–1 mm, it was 40–45% each, for particles over 3 mm, it was no more than 10%. Dusty fractions of coal sludge fill the voids of the frame, which creates larger fractions. The stabilization of large particles by small ones is based on the ability of the latter to be fixed due to long-range intermolecular forces near large particles. This provides a tighter packing of the dispersed phase particles. This particle packing is characterized by a large grain contact area. This provides the briquettes with sufficient strength to resist external destructive influences to which the briquettes are exposed during storage, loading and transportation.

Both the strength of the raw briquette and the final technical characteristics of the fuel composition significantly depend on the initial moisture content of the coal waste intended for briquetting. A change in the moisture content in coal waste affects the adhesion forces between particles [9]. The presence of a water film allows particles to bind at distances greater than the van der Waals radius of interaction of two particles in the absence of a liquid phase and favors the mobility of particles relative to each other when the specific pressing pressure is applied. The increased moisture content in coal is accompanied by a thickening of water films, accompanied by the separation of solid particles from each other and a decrease in the action of molecular forces. From domestic and foreign experience, it follows that the optimal moisture content of fine coal, intended for briquetting, is estimated as 2–3% [10].

With such a moisture content of the anthracite fines, it is possible to obtain a strong raw briquette with a minimum consumption of binder. Satisfactory results can also be obtained when the initial moisture of anthracite fines the 5–6% [11]. The strength properties of the raw briquette are influenced by the moisture content of the charge. With a lack of moisture, a continuous hydration film on the surface of the particles is not provided, that affects the adhesive strength of the binder with the carbon component. There are no conditions for maximum manifestation of adhesion forces. With an excess of moisture, the thickness of the hydration film increases, preventing the adsorption contact of the particles, the wetting ability of the binder decreases and the strength of the briquette composition decreases.

Figure 2 shows the effect of the moisture content of the charge for briquetting on the strength of fuel briquettes at various consumptions of molasses. It follows from the figure that the nature of the dependence is approximately identical for all consumption of the binder.

With an increase in the moisture content of the charge, the strength of the raw briquette decreases. It follows from the experiment carried out, which shows the lower the binder content, the narrower the range of moisture content of the charge to obtain sufficient strength of the raw briquette. The optimum value of the moisture content of the charge is established from the values of the compressive strength of the specimens at the minimum and maximum pressing load. The highest values of strength are noted with a binder content of 6–10% in the range of moisture content of the charge 4–7%. This conclusion is also confirmed by the experimental data presented in Fig. 3. It has been found that at a molasses consumption from 6 to 7%, the

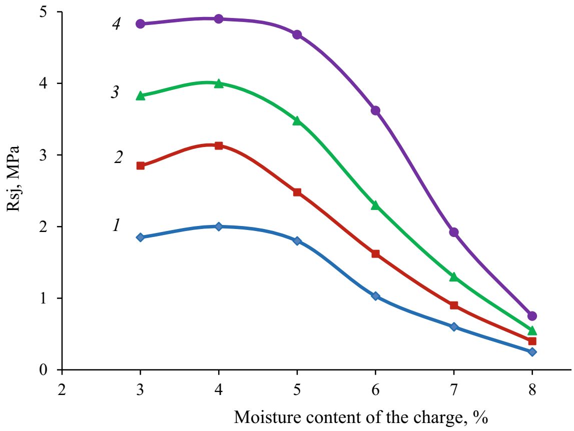

Fig. 2 Dependence of the strength of the raw briquette on the moisture content of the charge; binder consumption (%): (1) 4.0; (2) 6.0; (3) 8.0; (4) 10.0

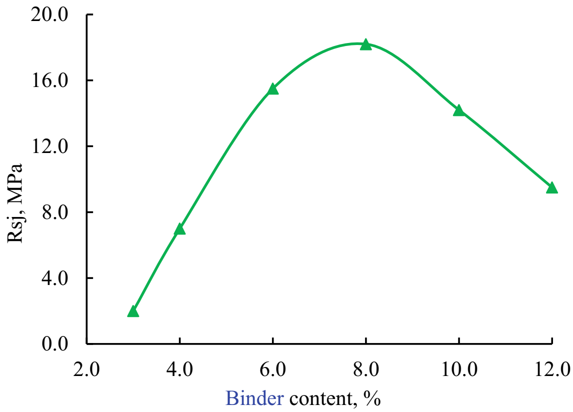

Fig. 3 Dependence of the strength of fuel briquettes on the consumption of the binder

molded briquettes have a strength sufficient to prevent the briquette from collapsing during transportation to the place of strengthening and storage. Low binder content does not provide the required strength of the fuel briquette. Excess binder is squeezed out of the mold during pressing. For a specific consumption of molasses, there is an optimum moisture content of the initial components, at which the maximum strength of the raw briquette is achieved. By forming a fuel composite, it is necessary to create a structure that is stable in terms of resistance to weathering. One of the important characteristics of the quality of fuel briquettes is the indicator of their mechanical strength. Moisture resistance of briquettes is the ability not to collapse under the influence of high humidity. This property of briquettes can be estimated by the residual mechanical strength. Under high humidity conditions, structural bonds in molasses-based fuel briquettes can be weakened to the point of destruction. This is due to the hygroscopicity of molasses.

At constant parameters of temperature and relative humidity of the environment, the system undergoes structural changes to a lesser extent. In natural climatic conditions, when the temperature and humidity of the environment change cyclically and repeatedly, additional factors of destruction appear, expressed in the weakening of structural bonds under the action of repeated heating–cooling, humidification-drying, freezing–thawing. The resulting shrinkage and swelling deformations lead to the appearance of cracks in the samples, which turns out to be a very strong factor in the process of structure formation, contributing to the destruction of the composite.

To stabilize the structure of neoplasms and prevent a decrease in the strength of briquettes during storage under high humidity conditions due to the hygroscopicity of compounds based on molasses, various methods were used. For example, a special additive–hardener was introduced into fuel composition to block the sugars contained in molasses and negatively affect the properties of briquettes during long-term storage in high humidity conditions. Of the tested substances, the greatest effect is achieved when using finely dispersed carbide sludge. The action of this component in the composition is multifunctional. Carbide sludge is used as a structuring agent and activator in a system containing hard coal particles and molasses. The advantage of using this waste is that it does not require preliminary preparation, is mixed with molasses in any ratio, and lowers the viscosity of molasses. The resulting mixing mixture is evenly distributed on the surface of the particles, enveloping all the components, gives plasticity to the molded charge and ensures good formability and high strength of the raw briquette after pressing. Carbide sludge contributes to the formation of calcium saccharates, resistant to moisture changes.

The assessment of the moisture resistance of briquettes containing carbide sludge as an additive to molasses was carried out according to the strength and moisture content of the samples stored for a year in a climatic chamber at a humidity of 98% and a temperature of 20 °C. The moisture content and strength were monitored monthly.

As follows from the data obtained, when the briquettes are found during the year under high humidity conditions, their strength decreases within 2.6–9.3%, the increase in moisture in the briquettes was 3.3–4.7%. A slight decrease in strength and an increase in moisture content did not affect the quality of the briquettes. This is confirmed by a drop test of briquettes according to the standard method [12]. The dumping strength of briquettes kept in a climatic chamber under conditions of high humidity is 85–92%. Thus, the addition of carbide sludge stabilizes the strength of briquettes in high humidity conditions.

Another technique for stabilizing the structure of the fuel composition is heat treatment. Thus, the manufactured briquettes were subjected to heat treatment at various temperature and time conditions. Figure 4 shows the nature of the change in the strength of the samples depending on the temperature and time of treatment. The highest strength is observed in the samples hardening at elevated temperatures (170, 200 °C). At such temperatures, the largest number of irreversible bonds is formed, which give the composition water resistance and moisture resistance.

In the result of testing the properties of heat-treated fuel briquettes, the following was established. During heat treatment, physicochemical transformations occur in the

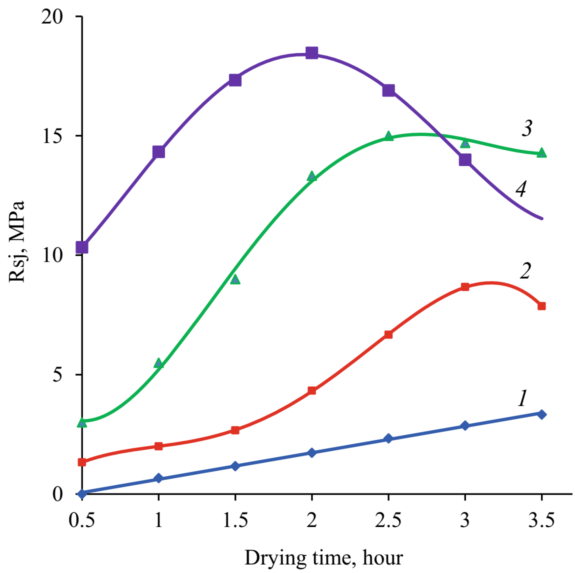

Fig. 4 Dependence of the strength of fuel composites on the temperature and duration of heat treatment: (1) 130 °C; (2) 150 °C; (3) 170 °C; (4) 200 °C

structure of the fuel composition, which entail a change in the structure of the material, the appearance of bonds of the condensation-crystallization type, forming insoluble solidification products and imparting water resistance and moisture resistance to the composition. However, at high processing temperatures, dehydration of neoplasms occurs, the probability of destructive changes increases, the density decreases and the porosity of the material structure increases. These factors reduce the water resistance and moisture resistance of briquettes. It has been experimentally established that briquettes that have undergone treatment at temperatures of 150 and 170 °C for at least 60 min can withstand tests for water resistance and moisture resistance. From an economic viewpoint, the optimal mode is heat treatment at 150 °C for 60 min.

According to the results of the studies carried out, it can be stated that for imparting moisture resistance to fuel briquettes, from an economic viewpoint, it is more attractive to use carbide sludge as a binder component. In this case, energy consumption for the manufacture of briquettes is significantly reduced, and material costs are also reduced: carbide sludge does not require costs for its extraction and the price of this waste is low.

To increase the water resistance of the fuel briquettes, a hydrophobizator (bottoms of thermal cracking of paraffins) was introduced. It was experimentally found that it is more expedient to mix the hydrophobizator with molasses at a temperature of 45–50 °C. Distillation residues combine well with molasses, forming a homogeneous solution. Distillation residues play not only the role of a hydrophobizing, but also a plasticizing additive. This mixture is a complex binder. The results of the study of water absorption of briquettes depending on the content of bottoms at different consumption of molasses, presented in Fig. 5, make it possible to determine the most

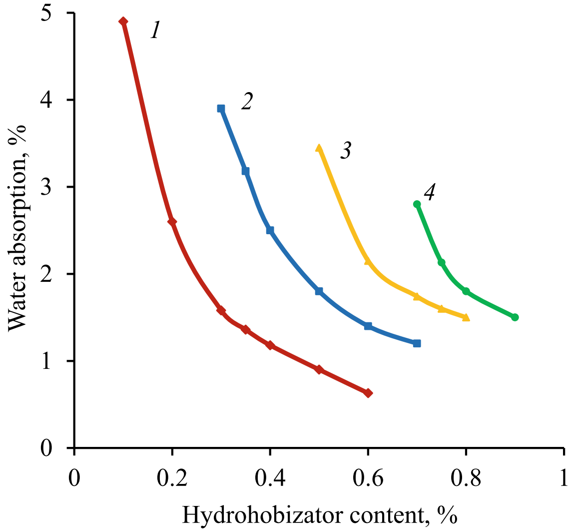

Fig. 5 Change in water absorption of briquettes from the content of hydrophobizator and molasses; molasses consumption: (1) 4.0%; (2) 6.0%; (3) 8.0%; (4) 10.0%

optimal range of consumption of molasses (6–8%) and water repellent (0.6–0.8%) to obtain briquettes with water absorption of no more than 2.0%.

The manufacture of briquettes using the bottoms of organic cracking of paraffins is as follows. The setting mixture (binder) is being prepared. For this, distillation residues are introduced into the heated to a fluid state, the mixture is heated (to the softening temperature of the distillation residues) and stirred until a homogeneous mass is obtained. The mixture prepared in this way is mixed with a heated carbon-containing component, namely anthracite waste and sludge, or coke fines. Stirring is carried out until the coal fines are completely wetted and a homogeneous mass is obtained. Briquettes are molded from a charge having a temperature of 40–45 °C, and a pressing load of 25–40 MPa, depending on the composition and moisture content of the charge. The molded samples have sufficient strength to be transported to the storage site. Hardening of briquettes is possible both under natural hardening conditions at an ambient temperature of 18–20 °C and a relative humidity of 55–60%, as well as with forced drying. When drying briquettes under the influence of molecular-surface forces, their structure changes. Natural drying makes it possible to obtain briquettes with a minimum number of defects, since this slows down the material. However, the intensity of the processes of structure formation and the number of crystalline phases that affect the properties of briquettes increase with their temperature treatment. Optimal heat treatment mode is a temperature of 105–110 °C, a holding time of 0.5 h and air cooling.

In the conditions of a coal chemical laboratory, an experimental comparative combustion of an experimental batch of fuel briquettes and raw coal was carried out. The compositions of the fuel composites are shown in Table 2. The obtained results of combustion are presented in Table 3. The nature of combustion of fuel briquettes on a binder of molasses with additives and high-quality coal of AM grade is almost

Table 2 Compositions of a pilot batch of fuel briquettes, wt. %

Composition number	Anthracite fines	Coal sludge	Fine coal	Molasses	Carbide sludge
1	71.3	14.0	–	6.7	8.0
2	68.2	–	20.0	6.8	5.0

Table 3 Results of comparative combustion of fuel briquettes and coal

Type of fuel	Ash content, %	Mass moisture of working fuel, %	Total sulfur content, %	Volatile matter release, %	Amount of unburned fuel, %
Briquette composition 1	17.9	4.4	1.14	4.7	27.6
Briquette composition 2	16.8	4.7	1.16	6.8	27.9
Coal, grade AM	13.7	4.2	1.12	7.1	24.8

identical. Fuel briquettes were ignited by burning wood (like ordinary coal of large grades). Combustion of briquettes is good, it was not accompanied by cracking, sparks. After a day, the briquettes are red-hot, no cakes are formed, the ash residue is not caked, and is dusty in structure. Briquettes do not crumble during combustion, retain their shape, and withstand mechanical stress during combustion.

The heat resistance of the briquettes is characterized as "good". Experimental combustion of fuel briquettes has shown: the permeability of the bulk layer is better than that of ordinary coal. The ash residue during unloading does not generate dust, there is no caking in the layer, combustion proceeds without emitting odor. The combustion processes of briquettes of different composition and manufacture are almost identical.

Determination of the quality indicators of fuel briquettes was carried out according to the technical specifications and state standards for assessing the quality of coal [12]. Table 4 shows the quality indicators of briquettes intended for use as fuel in the domestic market, as an alternative to raw coal.

The theoretical basis of the complex method of strengthening the fuel composition is the principles of physical and chemical mechanics of dispersed systems [13, 14]. These principles are based on the creation of conditions for directed structure formation and the formation of desired properties of solidified compositions, namely fuel briquettes. The strength properties of the fuel dispersed-granular composite are largely determined by the structure of the contact between the carbonaceous material and the binder. Immediately after the binder has wetted the solid surface of the coal particles, complex processes of a different nature occur, the activity of which largely determines the quality of the fuel briquettes. One of the most important processes that determine the physical and mechanical properties of briquettes is the selective adsorption of the components of a complex binder on a solid surface of a

Table 4 Technical characteristics of pilot batches of fuel briquettes

Indicator	Indicator value
Drop mechanical strength (R_{sb}), %	99.5 – 100
Total moisture ($W_t{}^r$), %	4.0 – 4.7
Ash content ($A_t{}^d$), %	8.9 – 28.0
Mass fraction of total sulfur ($S_t{}^d$), %	0.9 – 1.34
Volatile matter release (V^{daf}), %	4.3 – 19.0
Net calorific value ($Q_i{}^r$), MJ/kg	21.87 – 27.81
Higher calorific value ($Q_s{}^{daf}$), MJ/kg	26.44 – 33,93
Chlorine mass fraction (Cl^d), %	0.027 – 0.031
Mass fraction of arsenic (As^d), %	0.0013 – 0.0015

carbon-containing material, which largely depends on the nature of the adsorbent, the chemical composition of the binder and subsequent technological operations that provide the required quality indicators of briquettes.

According to the results of studies [15], anthracites are inert, since their structural basis consists of aromatic compounds of a high degree of condensation. The interaction of anthracites with binders is carried out through strong van der Waals bonds. A change in the surface of the coal particles affects the nature of the interaction with the binder. Thus, according to [16], grinding coal to 0–3 mm promotes an increase in the relative adhesion of long-flame coals by 59.0%, gas coals by 60.8%, lean coals by 63.7%, anthracites by 71.2%. According to [17], to improve the adsorption properties of the inactive surface, its modification is carried out, which promotes the hydrophilization of the surface. For this, surfactants are used. Improvement of wettability upon contact of a hydrophobic material with an aqueous surfactant solution is associated with hydrophilization of the material surface in the result of adsorption of surfactant molecules and water and with a decrease in surface tension at the liquid–gas interface. As the main binder in the developed technology, it is recommended to use colloidal-dispersed solutions of molasses, namely a by-product of sugar beet production. As follows, from the results of experimental works [18], molasses exhibits the properties of an anionic surfactant. The adsorption of molasses on the active centers of the low-polarity [15] coal surface changes its properties, contributing to the hydrophilization of the surface. On the positively charged surface of anthracite [19], the adsorption of the anionic surfactant (molasses) occurs according to the ion exchange mechanism [20]. Thus, the plasticizing effect of molasses in the composition for briquetting is associated with the hydrophilization of the surface, an increase in its potential, which occurs due to the adsorption of surfactants, which is predominantly ion-exchange in nature.

Under the influence of the processes occurring at the interface between the binder and the surface of the adsorbent, structuring layers are formed around the granular carbon-containing component, which determine the strength and other technical characteristics of fuel briquettes. To ensure a strong and stable adhesion of the binder to the surface of the coal particles, the latter should cover the surface of the coal particles with a continuous thin layer [21]. The adsorbed binder layer, depending on the shape of the particles, forms a film of different thickness on their surface. The presence of such a film favors the mobility of particles relative to each other when pressing load is applied, and an increase in the contact area of the particles. At the optimal thickness of the film layer, the maximum manifestation of capillary forces and an increase in the adhesive interaction between the particles and the binder take place. In thin layers (of the order of angstroms), the action of unsaturated molecular forces of the surface is manifested, contributing to the manifestation of physical adsorption processes, accompanied by an increase in the cohesion of the binder in this layer. The bond strength reaches its maximum when the adhesive layers at the contact points become equal to the thickness of the adsorption layer.

The added calcium-containing additives intensify the hardening process, block sugars and form compounds with molasses, which contribute to the compaction and hardening of the structure, the creation of the most durable bonds that are resistant to fluctuations in the humidity and temperature conditions of the environment. An increase in the number and area of contacts between the particles and the intensity of their adhesion increases with the application of pressing load, when there is maximum contact and the manifestation of the adhesive-cohesive properties of the binder to the surface of the particles of the constituent components of the charge. At the initial stage of structure formation, the strength of the system is associated with the appearance of dispersed structures of the coagulation structure. Further strengthening under conditions of normal humidity and ambient temperature is accompanied by the transformation of coagulation structures into condensation-crystallization structures, which provide the mechanical strength of the fuel compositions.

4 Conclusion

Fuel composites (fuel briquettes) are an economical, high-calorie, transportable and easy-to-use lump fuel for the needs of the population and industrial enterprises. According to studies [22], it was found that when burning in the same furnace of raw coal with a high content of fines, its coefficient efficiency is 0.467, coal concentrate with a particle size of more than 13 mm is 0.625, and aggregate fuel is 0.75.

The developed technology for briquetting fine-grained carbon-containing waste provides high uniformity and stability of quality indicators of fuel briquettes. This type of fuel in all respects is one of the most demanded materials. The scale of solving the problems of utilization of wastes with a certain energy potential and a shortage of coal makes it possible to recommend the developed technology for briquetting fine-grained carbon-containing materials and products based on them for widespread development in production and use in power plants for industrial and domestic purposes. The need for refined fuel is high, its production is promising.

Composite fuel from potentially combustible waste will replenish the coal-raw material base, reduce the shortage of solid fuel, and can be exported. The proposed briquetting technology can be used to produce fuel briquettes with high consumer properties, competitive in the domestic and world markets.

From an economic point of view, it is attractive to create briquette production at an existing processing plant or mine, with the maximum use of existing engineering structures and communications. In [23], the authors, taking into account modern technical solutions for briquetting, set out the basic principles of an approach to organizing the production of briquettes from coal fines and sludge. It is advisable to locate such an enterprise in close proximity to the places of accumulation of coal waste in order to reduce material costs for the delivery of raw materials with energy potential to the briquette manufacturing enterprise.

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