

# Determination of composite fuel parameters in the operation of technogenic deposits of coal mining enterprises

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**Abstract.** The research provides the determining of the parameters for composite fuel in the operation of technogenic deposits at coal mining enterprises. The qualitative characteristics of technogenic raw materials are determined, and the parameters of technological processes to produce composite fuel are established: preparation (screening or grinding), physical and chemical influence on the state of raw materials, mixing, production, and drying (if necessary) to obtain suitable fuel. Based on the particle size distribution (as well as sedimentation analysis for waste fractions up to 50 µm) and chemical composition (with the determination of moisture, volatile matter, ash, and sulphur content) it was found that the physicochemical parameters for each type of industrial waste, when preparing them for use in the production of composite fuels, have been established. A technological classification of technogenic materials has been developed, which makes it possible to systematize technical issues in the implementation of preparation processes, physical and chemical influences, mixing, production, and drying to obtain suitable fuel.

## 1 Introduction

Coal industry is one of the most important sectors of the economy. The coal produced is used in many industrial enterprises in the country, most of which are in the energy, metallurgy, and chemical industries. In Ukraine, coal is an energy raw material that allows about half of the electricity to be produced from all possible energy sources. The electricity demand is growing every year, and the demand for coal is growing accordingly. However, the coal industry, like all other industries, is currently in a critical state. The main factors limiting the development of the coal industry, along with the war, are delays in payments for coal

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delivered and the lack of state funding for the modernisation of capital assets, which makes it impossible to purchase new equipment and repair old ones, as well as to maintain mine workings in accordance with operational requirements, which leads to a decrease in mine productivity [1, 2].

The extraction, beneficiation, and processing of mineral raw materials are associated with the generation and accumulation of waste. Mine and tailing dumps, ash and slag dumps of thermal power plants, and stored waste from metallurgical, chemical, and other industries occupy huge areas, degrade the ecology of regions, and reduce the quality of life of residents.

At the same time, the component composition and size of these formations make it possible to consider them as technogenic deposits that have real prospects for industrial utilization [3]. The development of technogenic deposits has at least two positive results: obtaining valuable mineral raw materials (including non-ferrous, rare, and even precious metals) and improving the environmental condition of the surrounding area.

The technogenic deposits also include places or objects of accumulation:

- products of mineral raw materials or fuel processing that resulted from their losses during transportation, storage, and utilization;
- substandard mineral raw materials that are not involved in the production process under current conditions, but in the future, when the technical and economic situation changes, may be involved in recycling [4 – 7].

Based on preliminary data, over the past decades, Ukraine has been accumulating about 1 billion tons of waste from various industries per year, and currently, it reaches more than 30 billion tons. These wastes occupy an area of more than 160 thousand hectares, most often on fertile land, poisoning the environment. However, these wastes contain significant amounts of mineral resources.

More than 200 years of industrial coal mining and processing in Ukraine have resulted in vast amounts of waste: the number of coal mine spoil tips and dumps is close to 1,300, they cover an area of about 6.500 hectares of fertile and buildable land, and the weight of waste per capita in Ukraine is about 4.000 tonnes [8 – 10].

Waste from the coal industry is a technogenic raw material for coal beneficiation plants, which accounts for 5 – 40% of the weight of processed raw materials. Both gravity and flotation methods of coal beneficiation produce lumpy and fine waste, respectively. The grain size in flotation beneficiation is less than 1 mm. In gravity beneficiation, half of the waste is in the 25 – 50 mm fraction, and about 30% of the waste is larger than 50 mm. The fine fraction (0 – 25 mm) accounts for approximately 20% of waste. Together with granulometric characteristics, this waste provides significant energy potential [8 – 13].

Implementing sustainable actions to diversify energy sources and utilize production wastes requires developing new technologies to produce alternative fuels and the recycling of technogenic waste.

The new technology for producing composite fuel from waste is directly related to the operation and interaction of fine dispersed materials with electrokinetic phenomena.

## **2 The choice of object to study**

The properties of high molecular weight compounds, which include the main waste products of coal beneficiation, namely coal sludge, are determined by both the chemical structure of macromolecules and the forces of intermolecular interaction. There are various types of bonds between coal macromolecules of different levels of metamorphism: from valence and hydrogen bonds to intermolecular forces caused by orientation, induction, and dispersion effects [14, 15].

The structural chemistry of the carbon formation at the peat, lignite, and coal stages is the most complex and least investigated. One of the most important properties of technogenic raw

materials (sludge) is moisture content, which means the total mass of water contained by carbon particles. Many physicochemical properties and technological features are associated with the moisture content, mainly porosity, swelling, shrinkage, plasticity, compressibility, compression strength, and the ability to stamp or form.

When using other selected materials, the physical and chemical properties, and technological characteristics, not only moisture, should be considered for the processes of producing composite fuels from waste. Accordingly, the technological classification of technogenic materials from which composite fuels can be produced is necessary [10, 16].

When compacting weakly-structured coal sludge without binders, a certain moisture content in the carbon is an essential condition for the intermolecular interaction of the coal substance, both in the grain volume (which causes its strengthening) and on the surfaces of the grains in contact [17 – 20]. The contradictions of numerous hypotheses of briquetting and granulation are included in the different estimates of the forms of moisture bonding in the pressed solid fuel and its compression behaviour.

Solids and liquids have almost identical cohesive forces and low compressibility, as the average distance between particles is approximately the same. Therefore, concerning all-round compression (or all-round tension), unlike gases, liquids, and solids are almost equally difficult to compress and have a strong resistance to volume change. Only shear deformation determines the real strength, elastic and plastic properties of solids, and the viscosity (fluidity) of liquids. However, only solids have hardness, namely static elasticity of form. The elasticity of the form of solids is determined by the presence of a regular spatial lattice in crystals and polycrystalline aggregates or a disordered structural grid (“skeleton”) in gels and glassy bodies.

Following the reasoning of effective production of composite fuels, it is necessary to add various adhesives and, accordingly, binding materials to mixtures of technogenic materials to improve physical and mechanical properties. Liquid glass, cement, and clay will be the most effective materials. However, such binders significantly reduce the quality properties of the product – decrease the lower and higher calorific value, increase ash for the as-received and dry state of the fuel, and increase the abrasive effect on the equipment involved in the processing of technogenic waste into fuel [21].

Therefore, it was proposed to use materials containing carbon as binders. These materials are also representatives of technogenic waste. They can be components of composite fuels that can improve the technological characteristics of production processes and contribute to obtaining a better product in terms of the above quality indicators. This waste is lignin, a residue of the chemical industry [22, 23].

Annually, the global production of technical lignins is about 70 million tons, a valuable chemical raw material source. Unfortunately, this raw material is currently not widely available regarding organisational, economic, and technical conditions. Lignin decomposition into simpler chemical compounds (phenol, benzene, etc.) is more expensive than their synthesis from oil or gas when compared to the quality of the products obtained. According to the International Lignin Institute, no more than 2% of technical lignins are used worldwide for industrial, agricultural, and other purposes. The rest are burned in power plants or stored in landfills.

The complexity of the industrial processing of lignin is due to its nature, the multivariability of structural chains and bonds between them, and the instability of this natural polymer, which irreversibly changes its properties under chemical or thermal effects. Industrial wastes do not contain natural protolignin but rather significantly modified lignin-containing substances or mixtures of substances with high chemical and biological activity. Additionally, they are contaminated with other substances. This makes it difficult to recycle it in various processes [24 – 26]. Lignin storage areas have an unpleasant property of

spontaneous combustion, emitting sulphurous, nitrogenous, and other substances. Fig. 1 shows technogenic lignin deposits: a) “lignin storage” and b) burning lignin.



**Fig. 1.** Technogenic lignin deposits: (a) “lignin storage”, (b) burning lignin.

Another alternative to possible binders of composite fuels is waste from the pulp and paper industry (Fig. 2). The use of these wastes could solve the issue of replacing the binder by volume with the bulk of the composition in fuel production [27 – 31]. In addition, this will provide an opportunity to release the territories where this technogenic resource is stored.



**Fig. 2.** Technological waste from the pulp and paper industry that can be used to produce composite fuels.

Waste paper scrap is a dewatered sludge from the mechanical wastewater treatment from cardboard and paper production.

Preparation of the waste paper mass includes dissolving waste paper in pulverisers. The waste paper pulp then passes through a series of cleaning equipment, grinding and reaching the required concentration before being delivered to the cardboard and paper machines. The machines use the waste paper pulp to produce and dry cardboard and paper stock.

Wastewater from the cardboard and paper machines is treated (settled). After settling, clarified water and wastewater sludge are formed. The clarified water is returned to the production process and reused.

Wastewater sludge formed from settling contains a significant amount of cellulose fibre, which is not included in the finished product due to its small size. The small particle size and carbon component are interesting from the point of view of processing this waste. In addition, using this waste can reduce the abrasive component and improve the viscous plasticity of the fuel mixture. Additionally, cellulose can be effectively used as a component of mixtures with coal and other hydrocarbons for pyrolysis and coking [32 – 36].

To develop a complete view of the possibility of using waste from coal beneficiation, chemical, and pulp and paper industries, it is necessary to systematize all their characteristics, namely the technological classification of technogenic sources from which composite fuels can be produced. An important component of the properties of technogenic materials is the mineral part of waste, which directly affects the selection and reasoning of fuel production processes.

The electrification of solid fuel materials can be caused by electric fields and mechanical, physical, and chemical processes. When analyzing the data on the natural electrical properties of crushed coal, it should be noted that coal is charged bipolarly and asymmetrically during grinding [6, 7].

The fundamental difference from traditional granulation or briquetting is that electrokinetic (adhesion-chemical) processes do not require significant pressure at the level of 1 – 5 MPa/m<sup>2</sup> with binders and 10 – 30 MPa/m<sup>2</sup> without binders, or heating of raw materials to 100 – 120 °C.

Electrokinetic compaction of industrial waste is a complex physical and chemical interaction process between separated solid particles. The structure of the pieces is formed by direct contact of the particles with each other or through a layer of components and water due to mechanical activation. Dispersed waste, represented by coal and rock particles, is a substance that can combine separated solids and maintain their strong contact under conditions of significant external influences. It should meet the properties of adhesives. The strength of any multiphase system formed due to the adhesion and bonding of an adhesive and a substrate is characterized by adhesion, autogelation, and cohesion [4, 37, 38].

Adhesion characterises the molecular interactions between the surfaces of two dissimilar liquid or solid bodies that are brought into contact.

The energy balance of forces in the interfacial zone is described by

$$E_{wet} = E_{ss} + E_{as} + E_{ss-as}, \quad (1)$$

where  $E_{wet}$  is the wetting energy;  $E_{ss}$  is the substrate surface energy;  $E_{as}$  is the adhesive surface energy;  $E_{ss-as}$  is the energy of the substrate-adhesive interface.

It is common to use the values of surface tension and the contact angle to determine the wetting of a liquid by a solid. The contact angle determines the energy at the interface, i.e., the adhesive energy. The adhesive crosses the surface of the substrate along a line called the wetting perimeter.

Based on this and the equilibrium conditions, the contact angle is determined by:

$$\cos \theta = \frac{\sigma_{ss} - \sigma_{ss-as}}{\sigma_{as}} + \frac{f}{\sigma_{as}}, \quad (2)$$

where  $f$  is the coefficient that accounts for the friction force on the rough surface of the substrate.

### 3 Research methods

In the study of the properties of technogenic raw materials, analytical and experimental analysis of the granulometric composition – sieve, and sedimentation [5], as well as a comprehensive one, including analysis and summarisation of scientific and technical achievements in the field of physical and chemical effects on disperse systems – electrokinetic and surface properties, were used [39, 40].

## 4 Research results

The particles in technogenic waste also have a rough surface and different forms. To account for the particles' form, it was examined them at the microscopic scale and systematised them according to the ranges of particle size distribution.

Six samples of technogenic raw materials were examined, namely:

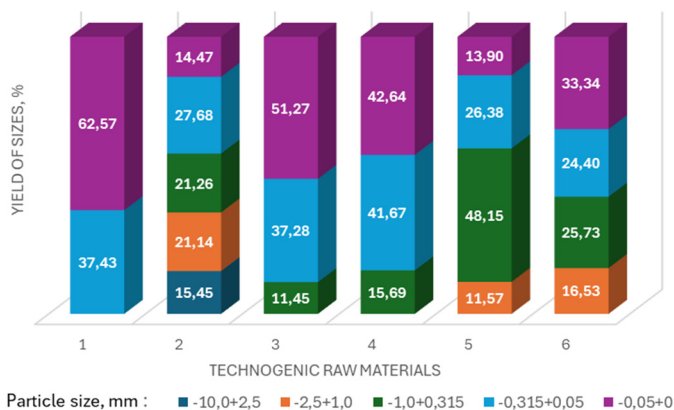
- 1 – lignin 1;
- 2 – lignin 2;
- 3 – lignin 3;
- 4 – pulp and paper mill sludge;
- 5 – coal sludge of mark G;
- 6 – coal sludge of mark D.

The results of the research are presented in Table 1.

**Table 1.** Results of sieve analysis.

Size range, mm	Technogenic material (lignin)											
	1		2		3		4		5		6	
	$\gamma$	$\Sigma\gamma$	$\gamma$	$\Sigma\gamma$	$\gamma$	$\Sigma\gamma$	$\gamma$	$\Sigma\gamma$	$\gamma$	$\Sigma\gamma$	$\gamma$	$\Sigma\gamma$
-10.0+2.5	–	–	15.45	15.45	–	–	–	–	–	–	–	–
-2.5+1.0	–	–	21.14	36.59	–	–	–	–	11.57	11.57	16.53	16.53
-1.0+0.315	–	–	21.26	57.85	11.45	11.45	15.69	15.69	48.15	59.72	25.73	42.26
-0.315+0.05	37.43	37.43	27.68	85.53	37.28	48.73	41.67	57.36	26.38	86.10	24.40	66.66
-0.05+0	62.57	100	14.47	100	51.27	100	42.64	100	13.90	100	33.34	100

The particle size distribution of the studied technogenic materials is presented in the diagram (Fig. 3).



**Fig. 3.** Particle size distribution of the technogenic raw materials.

The subsequent more precise and detailed analysis for studying the particle size distribution is sedimentation. Since the technogenic raw materials in most of their masses represent complex dispersed systems, sedimentation will characterise the physical and mechanical properties of the waste components to the maximum possible level.

Sedimentation analysis (SA) is a combination of methods for determining the particle size in dispersed systems and the molecular weight of macromolecules in polymer solutions by the sedimentation rate under conditions of sedimentation-diffusion equilibrium [8, 41, 42].

SA allows for determining both the average dispersion characteristics and the size or weight distribution of dispersed phase particles. The main methods of SA are constant sedimentation rate and sedimentation diffusion or sedimentation equilibrium; methods of approximation to sedimentation equilibrium and sedimentation in a density gradient are also used. Gravity-field SA is used for coarse systems (suspensions, emulsions, dust) with a particle size of  $10^{-2} - 10^{-4}$  cm. Usually, the method of constant sedimentation rate is used, and the searching values are found by changing the rate of sediment (cream) accumulation, the density of the suspension (emulsion) column, and the particle concentration at a certain level. Equipment for this method, based on the principles of weighing (e.g., sedimentation) or hydrostatic pressure measurement, is called a sedimentation device. Sedimentation Analysis (SA) for highly dispersed systems, where particle sizes are less than  $10 - 4$  cm and typically sedimentation stable, is conducted under centrifugal forces. A.V. Dumanskiy first suggested utilizing centrifuges for the sedimentation of such systems [43]. Further advancements in SA methods within centrifugal forces were pioneered by T. Svedberg, the inventor of the ultracentrifuge [44, 45]. The ultracentrifuge generates centrifugal accelerations tens and hundreds of thousands of times greater than Earth's gravity, facilitating the sedimentation not only of small colloidal particles but also high molecular weight compounds. During Centrifugal Analysis (CA) in an ultracentrifuge, the sedimentation constant can characterize dispersed phase particles or dissolved polymer molecules. This constant, measured in Svedbergs (1 Svedberg =  $10^{-13}$  s), depends on the mass and shape of the particle or macromolecule. Optical measurements, such as changes in refractive index or light transmission, are employed to calculate sedimentation rates, equilibrium, constants, particle sizes, masses, and polydispersity in the analyzed system. While gravity-based SA is common for determining dispersed composition in materials like crushed substances, soils, and industrial dust, centrifugal SA is instrumental in evaluating molecular weight and uniformity of polymers, including biopolymers. In disciplines like biochemistry and molecular biology, SA aids in identifying cellular structures, sizing viruses, and separating lipoproteins based on lipid-protein ratios [21, 46].

Sedimentation equilibrium:

Spherical dispersed particles are influenced by gravity proportional to the apparent mass:

$$P = \frac{4}{3} r^2 \pi g \Delta\rho, \quad (3)$$

where  $g$  is free-fall acceleration;  $\Delta\rho = \rho_2 - \rho_1$  is difference in the densities of the particle and the medium.

Under the action of a force  $P$ , the particles begin to move accelerated, but they are subject to a force of resistance  $F$  proportional to their velocity  $U$ , radius  $r$ , and viscosity of the medium (Stokes' law):

$$F = 6\pi U \eta r. \quad (4)$$

As the velocity of the particle increases, there comes a point where the force of resistance from the medium,  $F$ , counteracts the force of gravity,  $P$ , acting on the particle. Following this point, the particle moves at a constant sedimentation rate,  $U$ .

$$U = \frac{gV\Delta\rho}{6\pi\eta r}; \quad (5)$$

$$V = \frac{4}{3} \pi r^3, \quad (6)$$

where  $V$  is the volume of a spherical particle with radius  $r$ .

During the sedimentation of particles, a gradient of their concentration arises in the direction of gravity; such a gradient leads to the diffusion of particles in the direction of their lower

concentration, i.e., in the direction opposite to the direction of sedimentation. At the same time, a state is possible when sedimentation and diffusion flows are mutually balanced – sedimentation-diffusion equilibrium occurs, which is described by the barometric formula:

$$n_h = n_0 \exp \left[ -\frac{gV\Delta\rho}{KT} \right]. \quad (7)$$

The barometric formula defines the dependence of the pressure or density of a gas on the height in the field of gravity. For an ideal gas that has a constant temperature  $T$  and is in a homogeneous field of gravity, the barometric formula is as follows:

$$\rho = \rho_0 \exp \left[ -\frac{gm(h-h_0)}{RT} \right], \quad (8)$$

where  $p$  is the gas pressure in the layer located at a height  $h$ ;  $p_0$  is the pressure at zero ( $h = h_0$ );  $m$  is the molecular weight of the gas;  $R$  is the gas constant;  $T$  is the absolute temperature.

According to the barometric formula, the concentration of molecules, denoted as  $n$  (or gas density), decreases with altitude following the same principle:

$$n = n_0 \exp \left[ -\frac{mg(h-h_0)}{kT} \right], \quad (9)$$

where  $m$  is the mass of the molecule;  $k$  is the Boltzmann constant.

The barometric formula finds its roots in the law governing the distribution of ideal gas molecules concerning velocities and coordinates within a potential force field. Two essential conditions underpin this derivation: the stability of gas temperature and the uniformity of the force field. These conditions find analogous application to the tiniest solid particles suspended in either a liquid or gas medium. Leveraging this analogy, J. Perrin adapted the barometric formula to elucidate the height distribution of emulsion particles, thereby enabling a direct determination of Boltzmann's constant. Essentially, the barometric formula reveals that gas density experiences an exponential decrease with increasing altitude. The value  $-mg(h-h_0)/kT$ , which determines the rate of density reduction, is the ratio of the potential energy of particles to their average kinetic energy, proportional to  $kT$ . The higher the temperature  $T$ , the slower the density decreases with height. On the other hand, an increase in gravity  $mg$  leads to a much greater compaction of the lower layers and an increase in the density difference. The force of gravity  $mg$  acting on the particles can change due to two quantities: the acceleration  $g$  and the mass of the particles  $m$ . Hence, within a gas mixture under the influence of gravity, molecules of varying masses exhibit distinct distributions in altitude. The real distribution of air pressure and density within Earth's atmosphere deviates from the barometric formula due to variations in temperature and gravitational acceleration with altitude and geographical latitude. Furthermore, atmospheric pressure increases with water vapor concentration in the atmosphere. Barometric leveling relies on the barometric formula as its foundation, serving as a technique for calculating the disparity in height ( $Dh$ ) between two locations marked by distinct atmospheric pressures ( $p_1$  and  $p_2$ ). Given that atmospheric pressure is subject to weather variations, it's essential to minimize the time gap between measurements and ensure that the measurement sites are relatively close together.

In this case, the barometric formula is written in the form:

$$Dh = 18400(1 + at) \cdot \lg \frac{p_1}{p_2}, \quad (10)$$

where  $t$  is the average temperature of the air layer between the measurement points;  $a$  is the temperature coefficient of volumetric expansion of air.



Using this formula, the calculation error does not surpass 0.5% of the measured height. However, Laplace’s formula is more precise due to its consideration of factors like air humidity and fluctuations in free-fall acceleration [5].

For sedimentation analysis, it is necessary to calculate the time of particle sedimentation:

$$t_{dpp} = \frac{0.1835}{d^2 (\delta)}, \tag{11}$$

where  $\delta$  is the material density, g/cm<sup>3</sup>;  $d$  is the particle diameter of the material,  $\mu$ m.

Density calculation  $\delta$  by S.I. Mitrofanov [5]:

$$\delta = \frac{(A - B) \gamma_p}{(C - B) - (D - A)}, \tag{12}$$

where  $A$  is the dry flask weight with the material, g;  $B$  is the mass of the dry flask, g;  $\gamma_p$  is water density at the test temperature, g/cm<sup>3</sup>;  $C$  is the flask weight with water, g;  $D$  is the flask weight with water and material, g.

The results of the six most representative samples, which were analyzed using the granulometric (sieve) and sedimentation methods, are presented in Tables 2 and 3, respectively.

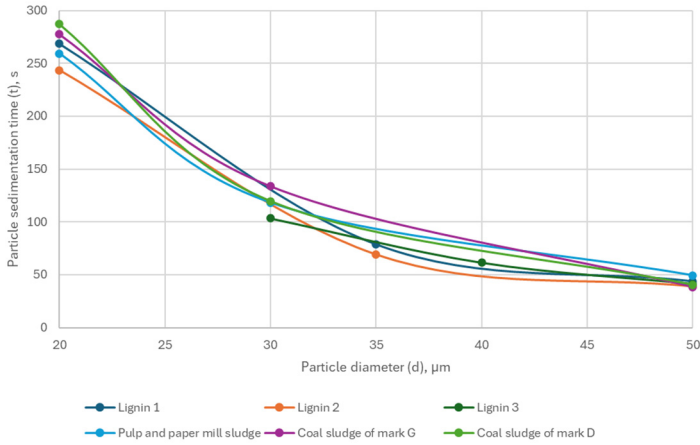
**Table 2.** Results of studying the particle size distribution of technogenic materials samples

Sample number	Sample name	Size range, mm				
		-10.0+2.5	-2.5+1.0	-1.0+0.315	-0.315+0.05	-0.05+0
Yield of sizes and total yield $\gamma$ and $\Sigma\gamma$ , respectively, %						
1	Lignin 1	–	–	–	38.36; 38.36	61.64; 100
2	Lignin 2	–	–	–	61.39; 61.39	38.61; 100
3	Lignin 3	–	–	13,16; 13.16	50.34; 63.50	36.50; 100
4	Pulp and paper mill sludge	–	4.72; 4.72	34.69; 39.41	43.45; 82.86	17.14; 100
5	Coal sludge of mark G	–	12.48; 12.48	46.67; 59.15	26.62; 85.77	14.23; 100
6	Coal sludge of mark D	–	8.23; 8.23	41.61; 49.84	22.63; 72.47	27.53; 100

**Table 3.** Results of studying the particle size distribution of technogenic materials samples less than 50  $\mu$ m fraction using sedimentation analysis.

Sample number	Sample name	Diameter of the particles $d$ , $\mu$ m			Density, $\delta$ , g/cm <sup>3</sup>	Particle sedimentation time $t$ , s			Volumetric mass $\Delta$ , %		
		1	2	3		1	2	3	1	2	3
1	Lignin 1	50	35	20	0,92	43.8	78.7	268.5	36	39	25
2	Lignin 2	50	35	20	0,94	39.1	69,3	243.6	59	12	29
3	Lignin 3	50	40	30	0,89	41.2	61,4	103.5	39	23	38
4	Pulp and paper mill sludge	50	30	20	1.21	49.4	118.2	259.3	41	28	31
5	Coal sludge of mark G	50	30	20	1.67	38.5	133.6	277.4	31	26	43
6	Coal sludge of mark D	50	30	20	1.58	40.6	119.7	287.2	68	12	20

Fig. 4 provides a comparative graph of the dependence of the particle deposition time on their diameter for each type of sample.



**Fig. 4.** Dependence of particle sedimentation time on their diameter.

The decrease in the free energy of the system, which is characteristic of adhesive spreading, is expressed by the spreading coefficient:

$$K = \sigma_{ss} - \sigma_{as} - \sigma_{ss-as}. \quad (13)$$

The spreading coefficient is the difference between the adhesive's bonding energy to the substrate and the adhesive's cohesive energy. Cohesion characterizes the intensity of molecular interactions in the adhesive volume and is a criterion for assessing the strength of the substrate. A specific case of adhesion is autohesion, which is the adhesion of surfaces of the same substance, preventing their distribution at the place of contact. A required condition for autohesion interactions is the spontaneous fusion of adhesive films.

Pressure plays an important role in the structure formation process. When pressure is applied during the fuel production process, the mixture is transformed into a strong, lumpy product. Deformation of the coal-rock mixture during fuel production is a plasticity function. The following equation can describe plastic deformation:

$$\frac{F}{S} - N = \eta \frac{dv}{dh}, \quad (14)$$

where  $F$  is the deforming force,  $N$ ;  $S$  is the shear surface on which the deforming force acts,  $\text{cm}^2$ ;  $N$  is the maximum shear stress,  $\text{Pa}$ ;  $\eta$  is the viscosity,  $\text{Pa}\cdot\text{s}$ ;  $dv$  is the difference in velocities of two particles of material located at a distance  $dh$  perpendicular to the direction of movement;  $dv/dh$  is the velocity gradient.

Compounds containing raw materials can be of organic or inorganic origin and need to correspond to the following requirements:

- have high surface activity, maximally wetting the hard surface of the material, providing a strong bond;
- be resistant to precipitation, temperature, sunlight, oxidation, etc;
- not destroy the structure of the substrate in the finished solid fuel;
- have elastic and plastic properties, have high strength, but not stiffer than the material being bonded;
- have a high curing rate;
- not contain toxic volatile substances;

- contain a sufficient proportion of caking components that ensure thermal stability of the finished fuel during combustion;
- not to be in short supply and to be cheap;
- be stable during storage, well and safely transported.

The rheological properties of compounds containing raw materials depend on molecular interactions, structure, and thermal motion of macromolecules. The main rheological constants of the raw material particles are the plastic viscosity  $\eta_{pl}$  and the maximum shear stress. The relationship between these quantities, which is expressed with the application of external forces, is described by the formula:

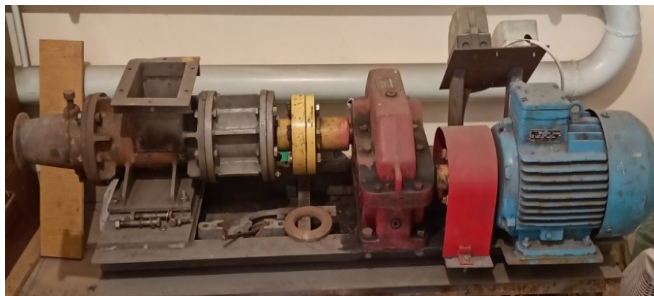
$$F = \eta_{pl} \frac{dv}{dr} + f', \quad (15)$$

where  $F$  is the force required for the surface of a certain area of the velocity gradient  $dv/dr$  to interact with an adjacent surface.

The activity of the surface is determined by the specific surface area and the particles that compose it and have certain charges. It has been experimentally found that the electrokinetic potential on the surface of particles increases by 2–2.5 times because of mechanical activation, which occurs when using the technology of development of technogenic waste from the coal industry. It was established that the increase in chargeability leads to an increase in strength and improvement of the structure formation of the resulting fuel.

Electrokinetic compacting, as a mechanism, consists of the following processes: grinding and compaction of sludge inside the equipment (in the mechanical activation unit), which compresses the material between the particles; then the particles themselves are compacted and deformed, with molecular bonding occurring between them. As a result of compacting, the elastic deformations of the particles are transformed into plastic deformations, which strengthen the structure of the fuel and keep the specified form.

The formation of the structure of composite fuel should be considered as one of the types of bonding of separated solid materials using adhesives. Structure formation is based on the processes of mutual arrangement and interconnection of individual contacting elements of the system. Aggregation is determined by adhesion and bonding. Adhesion, as the initial stage of the bonding process, is associated with forming an ordered adhesive film on the surface of a solid (substrate). Adhesion is characterized by the viscous-fluid (sometimes liquid) state of the composite. Subsequent processes lead to structuring. The production processes were modeled on the CFP-1 laboratory setup (Fig. 5).



**Fig. 5.** Laboratory setup for modeling the processes of composite fuel production from wastes (CFP-1).

The compounding process depends on many factors because of using the technology of production of composite fuel from waste (adhesion-chemical method) and may consist of several basic operations that are carried out sequentially:

- loading the charge into silos, dosing and loading into special vessels;

- removal of ferromagnetic objects from the raw material;
- screening (crushing or dispersing) - destruction of pieces from 5 – 6 to 25 mm and above to a particle size below 5 – 6 mm. In the case of coal sludge and composites with the largest class up to 1 – 2 mm and below, crushing is not required, and such material is ready for compaction;
- loading of raw materials into the bunker of the test setup (industrial unit);
- moisturizing (if required) and adding the composite;
- compacting in the facility. In this case, the compacting mechanism is realized as follows: when the fuel is compacted inside the test facility, a small pressure is formed, which causes the material to compress due to the voids between the particles. Then, the particles themselves are compacted and deformed; molecular bonding occurs between them. At the end of processing, the elastic deformations of the particles turn into plastic deformations, as a result of which the structure of the rods-briquettes is strengthened, and their specified form is preserved. The physical and chemical properties of the material strongly influence the character of the deformation;
- loading into the drying chamber;
- drying with hot air in the drying chamber;
- delivery of the composite fuel to the storage unit;
- drying fuel at the storage unit if needed.

## 5 Conclusions

The production of composite fuel from coal beneficiation products within the context of developing technogenic deposits involves a multifaceted physical and chemical process. This process revolves around the intricate interaction among separated solid particles. The composite fuel's structural composition arises from the direct contact of these particles with each other, or through interlayers of various components and water. This interaction is facilitated by the mechanoactivation forces present in the technogenic waste processing machinery.

Given the diverse range of technological methods and the inherent specificity of different types of raw mineral materials, a one-size-fits-all approach to producing composite fuel from waste is unattainable. Consequently, there exists no unified theory governing the production of finished composite fuel. Instead, the parameters and processes of the technology exhibit a lack of uniformity, necessitating a nuanced understanding and adaptation to the unique characteristics of each raw material and processing method employed.

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