

The present-day problem of the accumulation of carbon waste was considered in connection with the aggravating urgency. General tendencies and approximate rational compositions of unprepared polydisperse fractions of mixtures of potential raw materials during their compaction and subsequent thermolysis have been experimentally determined. It was found that with an increase in moisture or binder content, solid carbon waste becomes more plastic and viscous (from 0.6 to 0.4), the coefficient of internal friction decreases. The effect of moisture on the coefficient of external friction is less noticeable (up to a 25 % reduction). It has been determined that preheating of the charge to 80 °C contributes to a decrease in density of the resulting briquettes (on average by 5–6 %) and leads to an increase in the coefficient of elastic expansion. Briquettes, all other things being equal, are 5–10 % stronger but a 1 % increase in strength accounts for a 2 % increase in energy costs. Upon re-compaction, a noticeable change in compression properties occurs. The briquette density increases by an average of 7 %. With a lower binder content, a 14 % increase in density was obtained. In this case, the increase in strength is directly proportional to energy consumption. An increase in binder content in briquets and their re-compaction were recommended. It has been found that with the optimized operation of the boiler plants that incinerate the briquetted waste, the coefficient of expenditure per year is 32.9 % less than the value of this index when using the equipment for recovery of unprepared waste. At the same time, the coefficient of influence on the environment over a 15-year period was 28.89 % less than the value of this index when operating similar equipment. The results obtained reasonably indicate that the optimized technology of waste briquetting and subsequent incineration is characterized by a significant increase in the environmental and economic efficiency of the waste recovery process

**Keywords:** carbon waste, briquetting technology, mathematical modeling, Index-E program, environmental and economic efficiency

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## 1. Introduction

The rapid growth of population and production levels is closely linked with the increased use of natural resources many of which are non-renewable. Besides, imperfect production technologies can lead to the fact that most of the extracted raw materials are not used and become a waste.

Development of the level of technical equipment of the population also leads to the ecological problem of accumulation of millions of tons of household waste near settlements. Sanitary fills occupy colossal territories and pollute soil, soil water, and underground water [1].

The issue of complete destruction or partial recycling of household solid waste is relevant, first of all, from the stand-

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# IMPROVING THE EFFICIENCY OF EQUIPMENT AND TECHNOLOGY OF WASTE BRIQUETTING

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point of its negative impact on the environment. However, the accumulated waste is also an inexhaustible source of renewable secondary raw materials and energy resources, especially when it comes to carbon-containing combustible waste [2, 3]. Thus, the solution of this issue becomes not only an ecological but already an economic issue of resource conservation and alternative energy.

For example, it is indicative that according to various expert estimates, the total area of waste accumulation sites occupies from 2 % to 7 % of the territory of Ukraine and contains about 36 billion tons of cull. Analysis of the formation of present-day ecological, medical-ecological, and demographic problems (in particular, in connection with the problem of waste management being the main cause of the ecological crisis) and the world experience of improving systems for handling substandard materials is indicative. This analysis shows that there are no domestic technologies capable of processing accumulated waste on an industrial scale and, taking into account the abovementioned, argues the relevance of fundamental modernization of the waste management systems.

The waste management crisis has been an acute problem for a long time posing important scientific and practical problems. Analysis of statistical information on waste management in a number of developing countries proves that the level of annual waste formation is significantly higher than the average waste treatment level (disposal and recycling). This indicates a pronounced dynamics of cull accumulation even against the background of the decrease in annual growth of its quantity which indicates low efficiency of the waste management system and the need for its modernization.

Foreign experience in waste management illustratively shows, for example, the precedent of achieving maximum efficiency of the waste management system in Sweden where waste recycling degree reaches 99.1 %. This proves a practical possibility of solving this problem in developing countries and indicates the urgent, proved necessity of modernizing technical support of waste management systems within the framework of sanitary cleaning schemes for settlements.

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## 2. Literature review and problem statement

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Obtaining useful raw materials by extracting and recycling solid household waste (SHW) is considered in world practice as a promising option for returning material and energy resources to the production cycle. Today, there are over 450,000 unsanitary landfills in 28 EU countries indicating a great potential for resource recovery. Besides, the need to rehabilitate land and reduce pollution effects is an important motive in the issues of landfill reclamation and recycling the stored waste [4].

Studies [4, 5] are devoted to features of thermal recycling of carbon-containing waste, including small fractions of stored waste. Thermal recycling of waste was studied using the example of gasification and pyrolysis. The study results have shown that the raw materials based on fine waste fractions have higher reactivity compared to other investigated mixtures due to the high content of catalytic metal elements (K, Ca, Na, Mg, and Fe) and high ash content. However, at a high scientific value [5] of the study including a detailed analysis of thermogravimetry of stored household waste, the authors practically did not take into consideration

the effect of mechanical properties of the recycled material on this process efficiency.

It was noted in [2, 3] that waste recycling can proceed in various technological directions depending on morphological, fractional, and quality indices of the raw material which in general can be divided into:

- waste that cannot be recovered by standard methods (unsorted household waste, medical waste, etc.);
- large-sized and large-tonnage industrial waste (waste from metallurgical and mining industries, etc.) mainly used to produce building materials;
- waste with a high content of valuable components (plastic, paper, chemical industry waste, etc.) which when disposed of separately, can give a significant ecological and economic effect.

At the same time, it should be noted that the studies analyzed paid insufficient attention to the issue of processing heterogeneous and unsorted household waste which represents the main environmental hazard at present.

It was pointed out in [6] that the following methods of storage, processing, and reprocessing household waste are widely used in the current world practice: sorting, earth filling, open burning, biothermal composting, low-temperature, and high-temperature pyrolysis.

The authors of study [7] also note that incineration and pyrolysis are the main thermal methods for neutralizing solid waste used today. The main advantages of various methods of thermal processing depending on morphological composition and specific heat capacity of raw materials were analyzed in this study. However, along with a detailed analysis of variations in morphological composition and assessment of waste hazard classes, their influence on the choice of processing technology, the study practically did not mention the specific rheological properties of household waste which also significantly affect the efficiency of subsequent thermal recycling and require careful study.

The authors of [8, 9] assert that recycling, that is the re-use of valuable waste components in production processes is the main direction of waste management in European countries. However, in the works cited, the authors do not offer effective solutions for the reprocessing of household waste in conditions where sorting and separate disposal of solid waste is impossible. This method requires mandatory preliminary sorting of raw materials and is difficult to carry out in conditions of indivisible collection and storage of waste.

It was noted in [10, 11] that the main solution to the problem of cost-effective and environmentally sound recycling of accumulated unsorted SHW implies its involvement in industrial reprocessing. To optimize expensive industrial recycling as the final technological operation in the general scheme of integrated SHW management, a stage of its preliminary preparation to reprocessing is essential [12]. However, technical aspects of preliminary preparation and processing of unsorted solid waste were insufficiently covered in these studies, the process parameters and properties of the final product were not evaluated. This does not allow to fully assess the efficiency of using results of the analyzed scientific studies and choose optimal conditions and reprocessing technologies for concrete conditions.

The main methods of preliminary pre-recovery processing of waste mostly include compaction and mechanical or manual sorting with picking-out valuable components. Various combinations of such technologies are also possible. Criteria influencing the choice of a waste processing technology

are considered in [13]. Also, a model for choosing an optimal technology for pre-recycling waste based on the described criteria was proposed. However, the authors did not disclose the relevance of stabilizing physical and mechanical properties of heterogeneous waste with variable morphological composition for effective subsequent recycling. Moreover, environmental and economic assessment of the methods for pre-recycling processing of solid waste described in [13] does not take into consideration basic factors of emission of polluting emission from specialized technological equipment during its long-term operation taking into consideration possible and predicted dynamics against the background of external technological, social, environmental and economic factors.

A detailed approach to the ecological and economic assessment of various methods of processing household organic waste was disclosed in [14]. Composting, incineration, storage, landfilling, gasification, and other methods were compared using indices of long-term payback, environmental impact, productivity, amount of energy consumed and produced. Such a comparative assessment using a variety of adjustable indices makes it possible to define with high accuracy the most effective waste management method in a particular case. At the same time, the authors left the opportunity for subsequent development of evaluative mathematical models of this type but did not touch the aspects of economic evaluation and occupational danger for workers in various waste management technologies.

According to [15], the use of solid carbon waste as fuel at small thermal power plants is the most rational in terms of the situation formed in the management of household waste in the post-Soviet space. In order to achieve the greatest ecological and economic effect, it is important to subject such waste to a preliminary preparation stage with briquetting to ensure the required moisture content and fractional composition. Conformity with moisture content requirements during briquetting is achieved by squeezing out excess moisture by compression of the combustible raw material. The fractional composition of the raw material during its briquetting is averaged by mixing and compaction of the material particles. Thus, briquetting contributes to an increase in the energy and calorific value of combustible carbon-containing waste.

The authors of [16] also note that accumulated solid combustible waste that occupies large areas and has a negative impact on the environment can serve as a base for high-quality fuel for household needs. The article considers the existing technologies and equipment for briquetting, compares compaction pressure indices for briquetting presses of various designs. At the same time, the issue of strength of final briquettes and the influence of pressing on them is not touched upon, especially for the case of using raw materials with a variable morphological and granulometric composition.

The need to assess particle size distribution in solid waste is considered in [17]. The particle size distribution in such waste as polymers, sawdust, unsorted residues, etc. is proposed to be determined using an innovative method of dynamic particle size control using a new model developed in the MATLAB® environment. This approach opens up new possibilities for assessing granulometry of processed solid waste. However, this study did not pay enough attention to the role of particle size distribution in processed raw materials when choosing the technology and process parameters for subsequent processing of dispersed waste.

Authors of studies [18, 19] note that solid waste briquetting as the most promising method of processing heterogeneous raw materials is a complex physical and mechanical process of interaction of dissimilar solid material particles. The briquette structure is formed by direct contacts of variously dispersed fractions with each other or through interlayers of binding solutions and moisture by applying pressing forces. It should be noted that when briquetting dispersed materials with a flat punch face in a closed chamber, pressure in the briquette decreases from the punch to the matrix bottom because of external contact friction. Despite detailed analysis of the briquetting process itself, the above studies did not sufficiently illustrate the features of double-action and multi-stage compaction (briquetting) which significantly affect the property of final briquettes.

Research work [20] also broadly touches upon features of preliminary mechanical processing by compacting unsorted organic mixtures. The study materials provide a detailed analysis of the influence of various binders on the compacting process and properties of the final product and the possibility of applying heating is considered. Justification of rationality of using briquetting equipment based on a cylinder-piston system for compacting biomass is also an important aspect of the study. However, along with a detailed study of the scientific issue of preparing unsorted organic raw materials by briquetting for subsequent thermal recycling, the authors ignored the issue of assessing the splitting strength of briquettes which is important for the preservation of briquettes at the stages of storage and transportation. Also, insufficient attention was paid to justifying the choice of effective technology for subsequent thermal recycling of final briquettes.

A preliminary analysis of a number of settlements having different levels of infrastructure development and belonging to different climatic zones has shown that the content of energy-carrying waste in the total mass of accumulated waste comes to 35–48 %. The moisture content of the energy-carrying part of the solid waste is 20–40 % and ash content can fluctuate within 10–20 % [1].

Yet, despite the significant moisture content in the raw materials, binders are often used to form strong and usable briquettes. Briquette structure formation with the introduction of binders is considered in the literature as one of the ways of providing bonding of the SHW fractions with the help of adhesives. The analysis of the use of binders in the industry made in [21, 22] has shown the possibility of using a variety of substances, for example, liquid glass, various glues, latex, bitumen, tar, etc. for each individual morphological fraction of energy-carrying waste. However, this study's authors have also paid insufficient attention to studying the compression and splitting strength of the final briquettes that have a limited scope of the study results.

Choice of the binder as well as careful selection of compaction parameters significantly affects the mechanical strength of briquettes which in turn provides them with the possibility of transportation, unloading, storage, and use. To this end, it is generally accepted that to obtain durable briquettes of solid waste, the content of a fine fraction up to 10 mm in the raw material composition should not exceed 15–20 % [1]. Thus, the required strength will be achieved with no impact on the energy-carrying properties of the resulting product.

To study the processes occurring during the preparation and processing of mixtures in inclined thermolysis units, it is necessary to carry out a set of experimental and theoretical

studies. This will make it possible to optimally organize the process and take into consideration the nature of interactions occurring during processing the raw materials with a sufficient degree of accuracy when designing.

The issue of expanding the base of theoretical and practical data on technical parameters of various compositions of industrial and household waste remains unresolved, so, it is necessary to conduct experimental studies of SHW specimens. The ecological and economic efficiency of further recycling the fuel briquettes by various thermal methods in combustion devices for industrial, domestic, and local purposes can be assessed only with the help of large-scale computer modeling based on empirical indices.

### 3. The aim and objectives of the study

This study objective implied a comprehensive substantiation of improving the environmental and economic efficiency of equipment and technological processes used in the recovery of solid carbon waste (SCW) by experimental determination of general trends and approximating rational mixture compositions of potential raw materials.

To achieve this objective, it was necessary to solve the following tasks:

- experimentally substantiate recommendations for improving the efficiency of industrial production of fuel briquettes from carbon-containing waste based on the results of studying the properties of recyclable materials;
- substantiate the effectiveness of choice of technology and equipment (as well as the parameters of its long-term operation) for processing SCW by its briquetting in a comparative analysis of the ecological and economic effect of alternative reprocessing technologies.

### 4. Materials and methods used in studying the carbon waste properties

When considering the entire complex of the problems associated with the collection, transportation, neutralization, and recycling of the SHW, its composition and properties are the most important issues. To collect and transport SHW, information about its moisture content and density is quite enough. However, when choosing a method and technology for neutralization and subsequent recycling, it is necessary to have complete information about the SCW properties in order to optimize, for example, such process of waste management as briquetting.

A device for compression tests was used in experimental studies (Fig. 1). It was mounted on the basis of a mechanical press and included bed 1, a screw device with flywheel 2, movable platform 3 on which dynamometer 4, an upper and a lower pistons 5, 6, matrix 7, spring 8 were installed, and shell 9 for pressing out briquettes.

The principle of compression tests consisted in that when pressing the charge by rotating the flywheel, screw device 2 simultaneously applied a load to the material and controlled deformations making

it possible to calculate parameters of the compression curve. The upper piston stroke was directly proportional to the angle of rotation of the flywheel minus shrinkage of compression dynamometer 4.

When carrying out compression tests, a matrix was installed on the spring and the charge was poured in it while the crossbar on the flywheel of the screw device should be directed along or perpendicular to the cross-piece. The dynamometer readings were recorded every 90° and when the specified pressure was reached, the rotation was stopped and the angle of the flywheel rotation was recorded. To determine elastic aftereffect, the flywheel was turned in the opposite direction until the load is completely removed and the reverse angle was recorded. The resulting briquette was pressed out using shell 9, its height was measured and weighed. The data entered into the log and the results were processed using the software.

Next, parameters of the curve of limiting equilibrium in terms of compressive and tensile strength were determined using a device mounted on the basis of a UP-5 lever press (Fig. 2). The device consisted of bed 1, shifting mechanism 2, lever system 3 with counterweight 4, and loading system 6. The lever system was connected to the upper and lower plates 7, 8 between which the test specimen was placed.

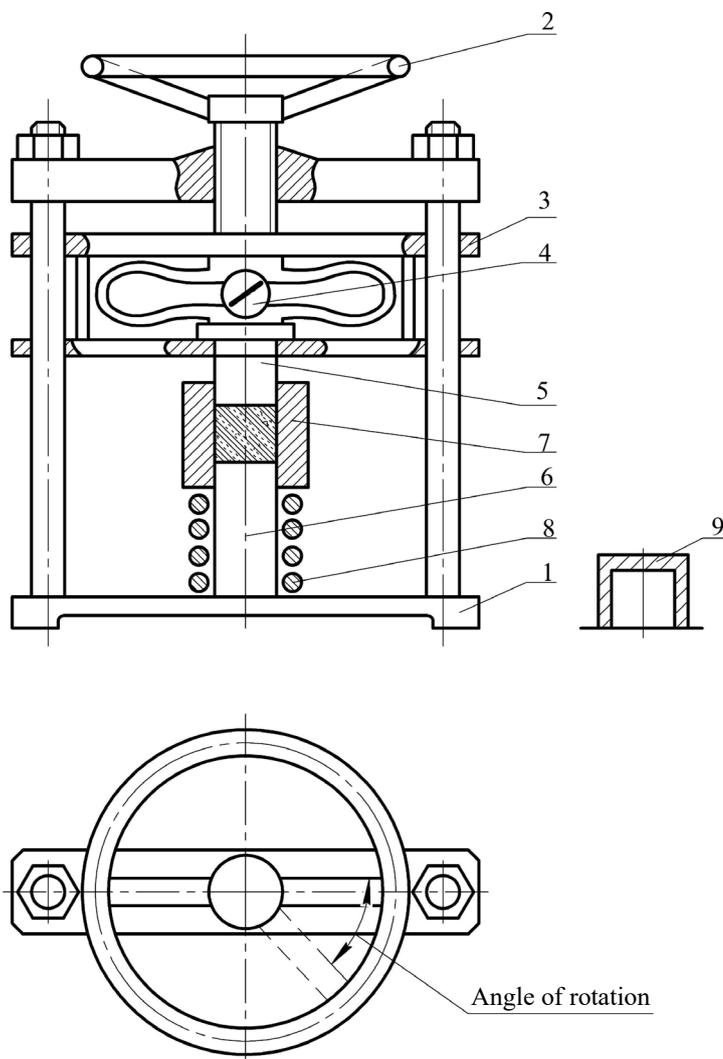


Fig. 1. The device for compression tests

When testing, the specimen was placed between plates 7 and 8, and a gap was selected using shifting mechanism 2. Also, preloading was carried out until control mark 5 on the lever coincides with the control mark on the bed. Then, using weights 6, a breaking load was applied. Before carrying out the experiments, it was necessary to balance the lever system using counterweight 4.

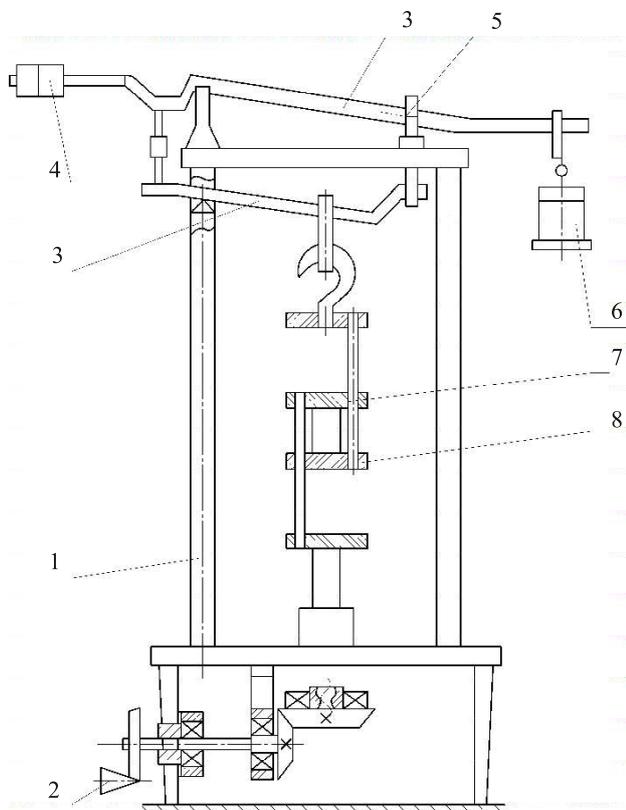


Fig. 2. The device for testing specimens for strength

To determine the ultimate compressive strength  $\sigma_{com}$ , the press was balanced, the specimen was placed flat on lower plate 8 and upper plate 7 was brought in contact with the specimen using shifting mechanism 2. Then, load on bowl 6 was gradually increased while simultaneously controlling the coincidence of the control marks using shifting mechanism 2.

The moment of the specimen destruction point is considered to be reached when shifting mechanism 2 fails to superimpose control risk 5 with the risk on the press bed. The results of specimen destruction were processed using the author's software packages created in the Microsoft Excel software environment in the Visual BASIC programming language (VBA). Step-by-step solutions of the basic equation system in bulk materials mechanics describing the change in density and strength properties of discrete materials under pressure as well as the equation system of the pressing process energy intensity were applied.

Tensile strength  $\sigma_t$  was determined in the same way with the difference that the specimen was installed on the cylinder generatrix.

The complex stress state at any point of the tested material can be represented as a set of three plane stress states in corresponding coordinate planes.

According to Mohr's theory, material destruction occurs at a certain state between the highest and lowest main normal stresses.

Magnitudes of the tangential and normal stresses acting on any area selected within a certain volume can be determined using Mohr's circles.

The information about the SCW compositions obtained during the tests according to the described methodology has made it possible to optimize the process of their processing by briquetting. However, scientific substantiation of practical significance of modernization of the technology of production of fuel briquettes to improve the ecological and economic efficiency of waste management systems as such, in general, requires a comprehensive experimental and mathematical forecasting. It is necessary to model the main parameters of long-term implementation of the project of industrial use of the obtained fuel in conditions of technical support of thermal power plants, in a comparative analysis of the operation of the plants for incineration of unprepared waste and compacted polydisperse fractions.

In order to carry out mathematical modeling of efficiency of the selected technological processes of waste management, the Index-E program was developed and applied [23]. This application is intended to determine optimal technical support for the waste processing system on an industrial scale and increase the capacity of such enterprises as the Avdiyivka Coke Plant (Avdiyivka, Donetsk oblast, Ukraine). A specially developed simulation mathematical model was used as the basis for the operation of the selected program [24–26].

## 5. The results of studying properties of carbon waste and characteristics of the technology of its briquetting

### 5.1. Experimental substantiation of recommendations for improving the efficiency of production of fuel briquettes from carbon waste

Insufficient attention to the experimental determination of material characteristics leads to a wrong choice of their processing parameters and the design of units, a growth of energy consumption, and, ultimately, unsatisfactory equipment operation.

The SCW characteristics obtained in the course of shear tests are given in Table 1.

It should be noted that for the reference charge, coefficients of internal and external friction, initial shear resistance, and adhesion to the metal surface were obtained with similar and low values. With the addition of any of the studied binders, a 30–50% increase in these values was observed.

This allows us to conclude that the mixtures with a binder proposed for briquetting in the considered modes are not prone to arching, sticking, etc. However, one should expect a significant deterioration of flowability at low (less than 5 °C) temperatures caused by an increase in viscosity of moisture-containing and resinous binders (materials with moisture content more than 8% are prone to freezing at negative temperatures).

For the numerical solution of the mathematical model of the waste compaction process, strength, and tribomechanical characteristics of the processed material were experimentally determined. Mechanical conditions of the process of waste compaction in presses were simulated in experimental studies.

Since properties of such specific materials are influenced by a large number of various external factors and the values determined experimentally have a certain scatter, the root-mean-square value was determined when processing the experimental results.

Table 1

Initial shear resistance  $\sigma_0$  and coefficients of internal  $f_0$  and external  $f$  friction of the SCW at various binder ( $S$ ) and moisture ( $W$ ) contents

Composition	$S$ , %	$W$ , %	Internal friction		External friction			
					on metal		on concrete	
			$\sigma_0$ , kPa	$f_0$	$\sigma_0$ , kPa	$f$	$\sigma_0$ , kPa	$f$
anthracite			0.26	0.36	0.08	0.34		
coal G		8	0.25	0.48	0.21	0.32		
sludge and rock PP (80/20)		10	0.45	0.30	0.20	0.34		
sludge and SHW (80/20)		8	0.34	0.75	0.12	0.41		
sludge and SHW (80/20)		13	0.41	0.48	0.09	0.47		
coal G	6	8	0.10	0.41	0.13	0.37		
coal G	9	8	0.24	0.44	0.22	0.41		
sludge	7	7	0.34	0.39	0.30	0.36	0.09	0.54
sludge	7	12	0.31	0.57	0.31	0.45	0.37	0.51
sludge	9	7	0.73	0.36	0.22	0.40	0.26	0.58
sludge	9	11	0.95	0.38	0.45	0.42	0.49	0.44
sludge and SHW (80/20)	7	11	0.74	0.45	0.32	0.51		
sludge and SHW (80/20)	7	20	0.63	0.41	0.50	0.48		
sludge and SHW (80/20)	9	8	0.66	0.62	0.33	0.53	0.37	0.50
sludge and SHW (80/20)	9	17	0.50	0.48	0.10	0.50	0.46	0.55
sludge, SHW and binder	10	7	0.70	0.86	0.44	0.75	0.27	0.68
sludge, SHW and binder	10	16	0.25	0.45	0.33	0.51	0.51	0.44

To determine each value, at least three experiments were carried out and the “drop-out” points were not sifted in order to take into consideration all possible features of the facility under study.

The tests were first carried out for two-component mixtures of sludge and SHW. When pressing briquettes, material structuring was observed implying the orientation of lamellar particles of solid waste perpendicular to the direction of action of the active pressing force (main stresses).

After removing the load, local bulging of the briquette surfaces was observed associated with the presence of solid waste particles with significant elastic deformation in surface layers.

The height of the elastic bulging of particles above the surface did not exceed 30 % of the maximum solid waste particle size. Besides bulging, the formation of shallow 3–4 mm deep annular cracks along the middle part of the briquette was also observed. As a rule, the interface passed through the solid waste particles with their surface poorly adhered to the sludge particles. Sludge adhesion was often observed on the rod and die surface.

The compacted briquettes were subjected to compressive static and tensile strength tests. Dependences of compressive strength on compaction pressures for two-component mixtures are shown in Fig. 3.

The data obtained have shown that the use of two-component mixtures in the future will be connected with difficulties: mixtures are not a homogeneous medium, so it is difficult to predict the material behavior during their processing.

An increase in cohesion of the components, and, consequently, the degree of mixture homogeneity, can be achieved by adding finely dispersed material to the charge which will ensure a more durable bond between the solid waste particles and the sludge.

This material can be silt formed in sufficient quantities at the processing plants.

When pressing three-component mixtures consisting of sludge, SHW, and silt fractions, there was an increase in plasticity and cohesion of the mixture, bulk density, and, as a consequence, a decrease in compactness at almost the same final briquette densities. This reduction makes it possible to use hydraulic cylinders with a shorter stroke when briquetting in the designed unit which will have a positive effect on the reliability of the device and its cost. Strength values for the final briquettes are shown in Fig. 3, *b*.

During thermolysis of the briquettes produced from a three-component mixture, a significant volume of gases was released.

The resulting sintered briquettes had few deep cracks in random directions obviously caused by shrinkage during sintering.

At the same time, the sintered cleavages had significant strength which can have an adverse effect during further processing.

To deplete the mixture in order to control the strength of thermolysis residue, a depleting material (rock) was added to the charge.

When pressing four-component mixtures, the similarity of their properties with those of three-component mixtures was observed. At the same time, the density of the resulting briquettes slightly increased from 1,200 to 1,400 kg/m<sup>3</sup>. The number of cracks in briquettes in comparison with briquettes made of two- and three-component mixtures has significantly decreased (because of enveloping the SHW particles with well-wetted fine-dispersed rock fractions). At a compaction pressure of 4 MPa, the strength of such briquettes reached 0.12 MPa (Fig. 3, *c*).

Briquettes of 4-component mixtures subjected to thermolysis did not experience significant thermal deformations. Uniform volumetric fracturing was visually noted. The nature of fracturing in briquettes of the carbonaceous residue makes it possible to estimate the shape of a piece in the form of a tetrahedron with side dimensions not exceeding 25×30×30 mm.

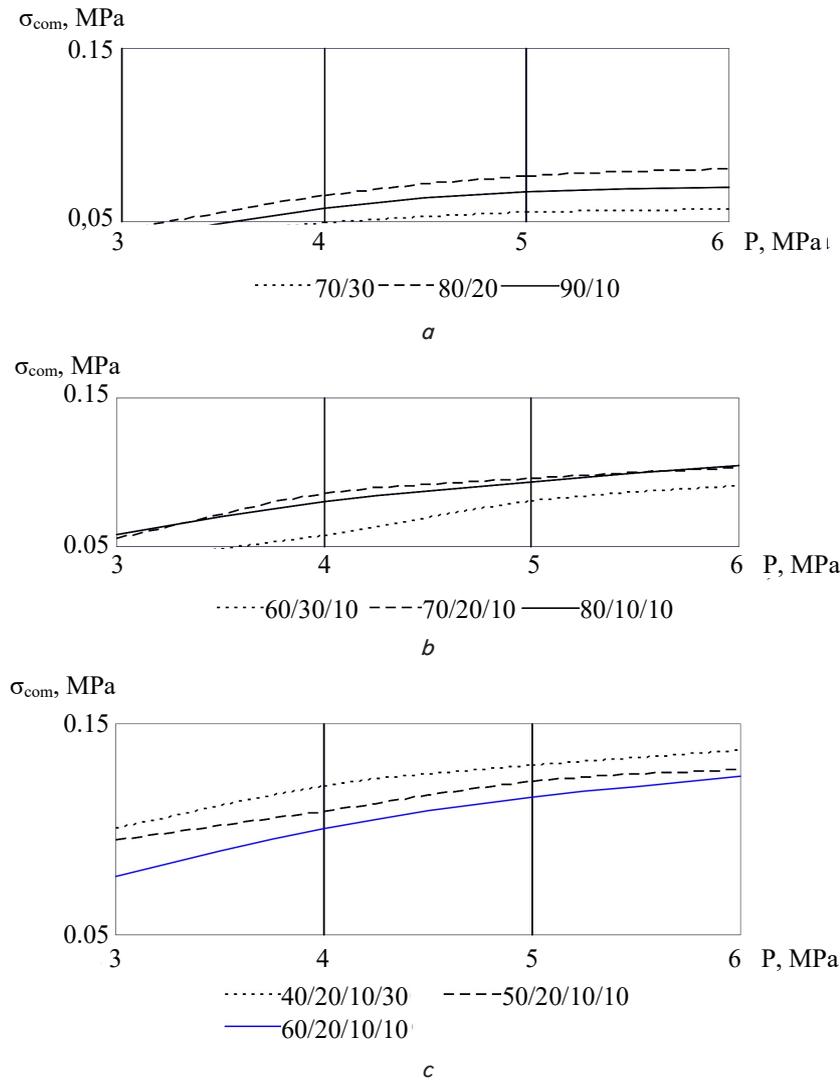


Fig. 3. Dependence of compressive strength  $\sigma_{com}$  of briquettes on composition and compaction pressure  $P$  (the figures show the percentage of this or that component in the mixture: the first for the amount of sludge, the second for SHW, the third for silt fractions, the fourth for rocks): *a* – two-component mixtures; *b* – three-component mixtures; *c* – four-component mixtures

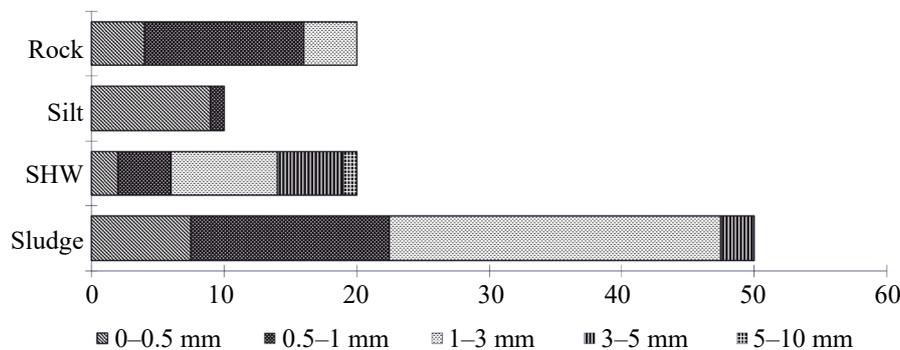


Fig. 4. Granulometric and component composition of the 50/20/10/20 mixture

Thus, four-component mixtures most fully meet the requirements of manufacturability of processing in LTF. From the condition of the presence of a sufficient amount of combustible components in the SOF, the 50/20/10/20 mixture was adopted as the base for further studies. The granulometric composition of each of the components of this

20 %) differs insignificantly which makes it possible to use a roller press with the same design parameters for compaction of the SCW with the given moisture content range.

When carrying out compression tests, values of the coefficient of elastic expansion of final briquettes were also established under various pressing conditions (Table 2).

mixture is shown in Fig. 4 and cumulative size curves are shown in Fig. 5.

Tensile strength tests of briquettes gave  $\sigma_t$  values for briquettes of various compositions and compaction pressures up to 9 kPa.

The investigated charge contained 25–35 % ash and 15–25 % moisture and had 750–800 kg/m<sup>3</sup> bulk density. Ligno-sulfonate, waste engine oil, liquid hydrocarbons, bitumen, and tar resins which in some cases are wastes from coke production plants were used as binders. SHW comprised shredded household waste in appropriate proportions as well as plastic and sawdust.

Investigation of the energy consumption for SCW pressing is associated with the determination of the most efficient conditions for conducting the process from the point of view of energy consumption. The range of studies on the density of the compacted charge was from 700 to 1,700 kg/m<sup>3</sup>. The value of specific energy consumption was calculated as a specific work consumed to obtain the current density of the SCW. Thus, the dependence of growth of specific energy consumption in the process of briquette compaction has been established (Fig. 6).

Analysis of energy consumption for compacting at pressures of 5, 10, and 15 MPa has shown a wide scatter of values: 0.094–0.8, 0.21–1.28, and 0.4–1.96 kJ/kg, respectively. The cause of fluctuation in values of energy consumption for compaction lies not in the different actual densities of the SHW and sludge or their ash content but in unequal elastoplastic properties and strength of the SHW components. In view of this fact, the strength of the specimens prepared from pure sludge and rock is higher than that of the briquette specimens with SHW in the entire pressure range.

It follows from the nature of variation of the SCW density and strength that the maximum compaction pressure should be 15 MPa since its further increase leads to a slight increase in density and strength but a sharp increase in energy consumption.

It should be noted that the specific energy consumption during compaction of the SCW with various moisture contents (from 10 to

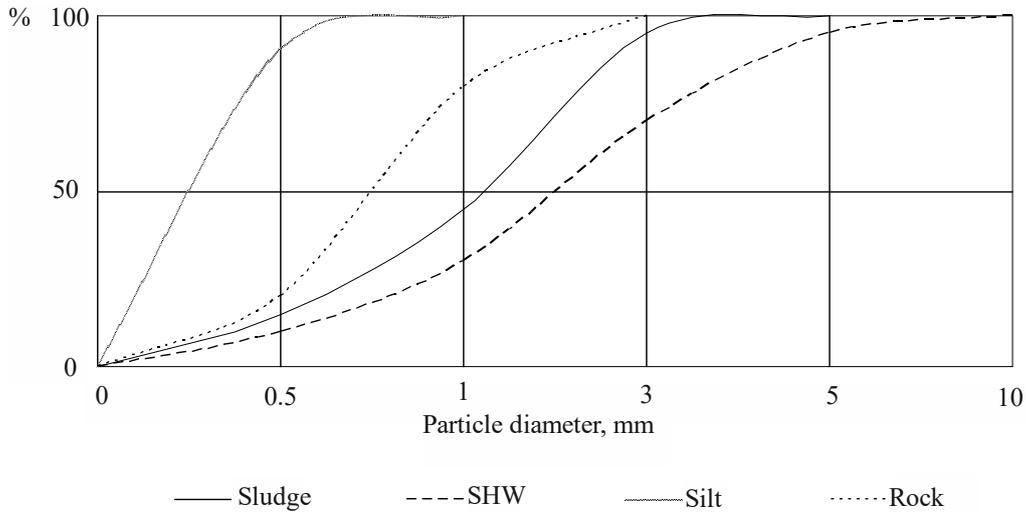


Fig. 5. Cumulative size curves of mixture components

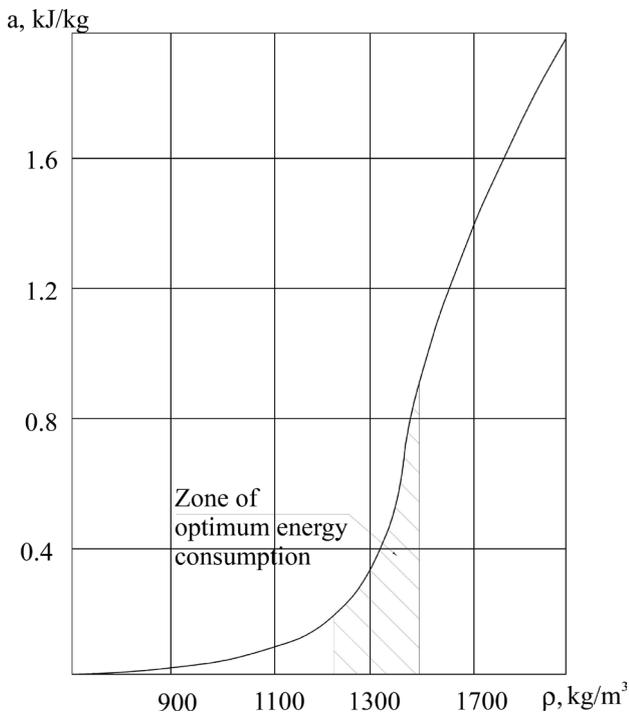


Fig. 6. Dependence of specific energy consumption on compaction density

mine the compressive and tensile strength of the compacted product, the above-described instruments and methods were used. Based on the experiments performed (Fig. 7, 8), it can be concluded that the strength of the compacted product increases with an increase in moisture content. This is due to the fact of additional interaction of soda with water in the compacted material with the addition of moisture to the dust.

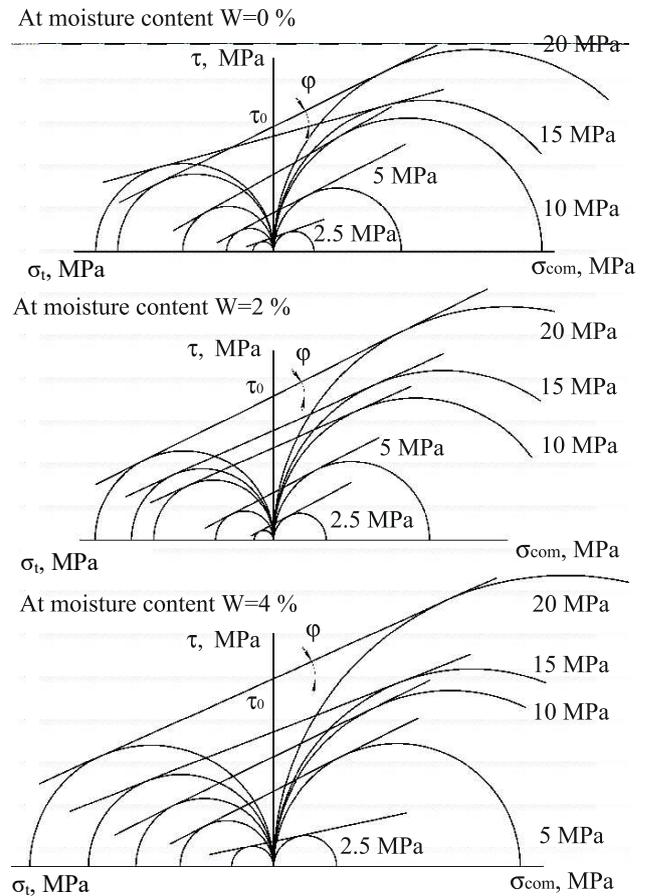


Fig. 7. Strength passport of the compacted products

Table 2  
Values of the coefficient of elastic expansion  $K_y$  at various final compaction pressures

Briquette composition	5 MPa	10 MPa	15 MPa
Sludge	1.001–1.015	1.005–1.022	1.015
Sludge and rock (80/20)	1.015–0.020	1.005–1.015	1.018
Sludge and binder (90/10)	1.015–1.025	1.010–1.025	1.006–1.020
Sludge and SHW (80/20)	1.030	1.025–1.030	1.024–1.027
Sludge, SHW and binder (70/20/10)	1.004–1.027	1.011–1.017	1.009–1.024

The strength of the resulting compacted product is the important characteristic of the SCW compaction. To deter-

Strength characteristics of briquetted mixtures depend on the mixture composition, binder content, and compaction pressure. After compaction of wet sludges with SHW

at a pressure of 5 MPa, values of  $\sigma_{com}=0.15-0.22$  MPa,  $\sigma_{com}=0.014-0.02$  MPa were obtained which allows us to consider the briquettes a brittle material.

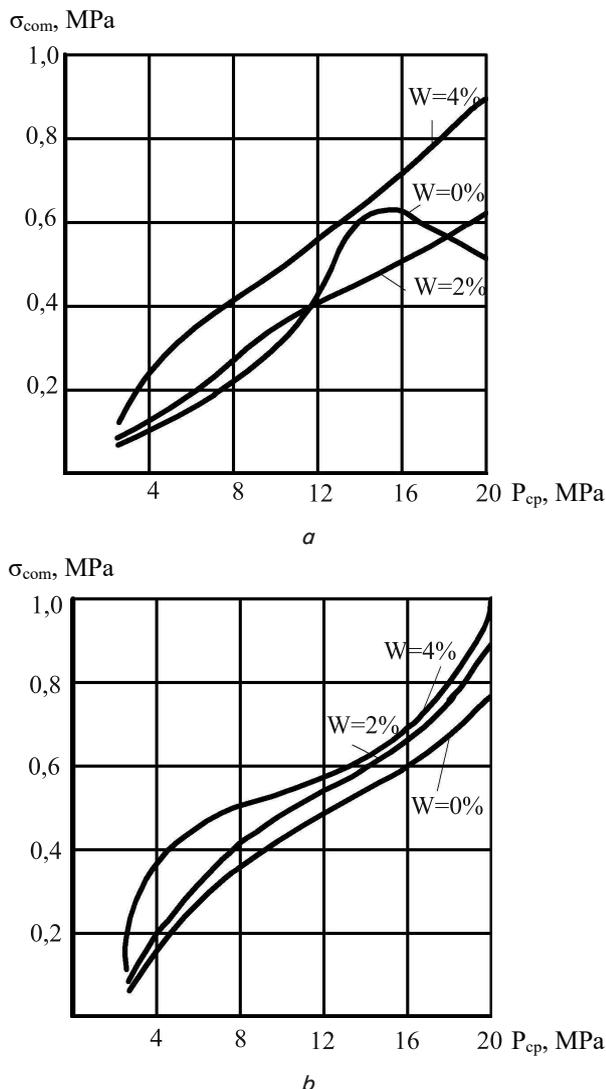


Fig. 8. Graphs of the dependence of ultimate strength of the compacted charge in tension  $\sigma$ , and compression  $\sigma_{com}$  on specific compaction pressure  $P_{cp}$ : *a* – graph of the ultimate tensile strength of specimens; *b* – graph of compressive strength of specimens

With an increase in compaction pressure to 15 MPa, no significant hardening of the material was observed ( $\sigma_{com}=0.15-0.25$  MPa) while compaction required 50 % more energy.

Adding a binder to the charge improves strength properties by 2–3 times, namely:

- *tar pitch* increases the compressive and splitting strength by 3 times at pressures up to 15 MPa, however, the strength of the briquettes decreases after drying;

- *silt or wet residue of VHO with liquid hydrocarbons* increases compressive strength by 2 times while the splitting strength does not change significantly.

The most durable briquettes were obtained for mixtures of sludge and CPP rock.

To construct a passport, ultimate strength  $\sigma_{com}=0.1$  MPa of the material in compression and  $\sigma_t=0.01$  MPa in tension

were experimentally determined. Substituting the limit stress values, the following was obtained:

$$\sin\varphi=(0.1-0.01)/(0.1+0.01)=0.82,$$

then  $\varphi=55^\circ$ ;

$$\tau_o=0.5\cdot 0.1 ((1/0.82)-1) 1.42=0.016 \text{ MPa}.$$

Thus, in this particular case, the material strength passport has a form of dependence:

$$\tau=0,016+1.42\cdot\sigma.$$

When conducting experiments, the SCW properties cannot be determined unambiguously with all desire, therefore, along with the accuracy and volume of specimens, repeatability, and sampling method are important.

The following initial materials and their compositions were taken as test subjects.

The SHW composition included food waste (60 % by weight), compost (22 %), paper (13 %) and polyethylene (5 %). Polyethylene share, taking into consideration modern tendencies to its growth, was overestimated by 2–3 times.

Table 3 shows characteristics of the sludge from Avdiyivsky Coke Plant (ACP) concentrating works (Avdiyivka, Donetsk oblast, Ukraine). Acidic resin from ACP sulfate department was used as the SCW binder (a mixture of 80 % sludge and 20 % SHW). The resin characteristics are given in Table 4.

Table 3

Characteristics of ACP concentrating works sludge

Indicator	Value, %
Moisture content	18
Ash content	40
Fine size class (<3 mm) content	85

Table 4

Characteristics of acid resin (ACP sulfate department)

Indicator	Value
Density at 20 °C, g/cm <sup>3</sup>	1.1
Viscosity, CV units	20
Acidity (by weight), %	2
Composition, %:	
– substances insoluble in toluene;	50
– water;	15
– ammonium sulphate;	5
– ash	1.8

Structural characteristics are determined by material particle size distribution, particle shape, and repose angle.

The *granulometric composition* is a percentage of fractions of different sizes in the total mass of dry material.

Particle size is determined by the largest size (length) of a particle. It affects many parameters of processing, transporting, and storage devices for discrete materials.

The granulometric composition was determined by sieving the material through a series of sieves with holes of various sizes (1, 3, 5, 7, and 10 mm). After sieving, fractions were weighed and their percentage in the mixture was determined (Table 5).

The angles formed between the lateral surface of the material and the horizontal plane are formed by two methods: pouring and caving.

Table 5

Results of granulometric analysis of solid waste

Fraction	Share, %
>10 mm	47
7–10 mm	30
5–7 mm	10
3–5 mm	6
1–3 mm	5
<1 mm	2
Total	100

As a result of the experiment, repose angle  $\alpha_{rep}=32^\circ$  and inbreak angle  $\alpha_{inb}=81^\circ$  were determined.

Based on the data obtained and taking into consideration the fact that both angles are equal only for ideally free-flowing material, it can be concluded that solid waste is highly prone to caking, hanging, arching, etc. properties that are negative from the point of view of suitability for further processing.

Tests were carried out in the pressure range up to 0.01 MPa in order to determine coefficients of internal and external friction for each composition.

The device for shear tests and their procedure is described in [27]. The test results are shown in Table 6, 7.

Table 6

Values of normal and tangential stresses according to the results of shear tests, kPa

Composition	Stress	Friction					
		internal			external		
SHW	$\sigma$	0.64	1.23	1.77	0.59	1.18	1.62
	$\tau$	0.89	1.21	1.62	0.42	0.69	0.98
SCW: 5 % binder content 7 % binder content 10 % binder content	$\sigma$	0.32	1.30	2.45	0.32	1.30	2.45
		0.47	0.88	1.37	0.26	0.79	1.37
	$\tau$	0.41	0.87	1.28	0.71	0.71	1.13
		0.29	0.69	1.16	0.69	0.69	1.08

Table 7

Parameters of approximating lines

Friction	Composition	$\tau_0$ , kPa	$\varphi$ , deg.	$f, f_0$	Equation of approximating dependence
Internal	SHW	0.5	35	0.61	$\tau=0.50+0.61\sigma$
	SCW: 5 %	0.32	26.5	0.44	$\tau=0.32+0.44\sigma$
	7 %	0.28	25.5	0.42	$\tau=0.28+0.42\sigma$
	10 %	0.17	23.5	0.39	$\tau=0.17+0.39\sigma$
External	SHW	0.10	31	0.53	$\tau=0.10+0.53\sigma$
	SCW: 5 %	0.11	29.5	0.50	$\tau=0.11+0.50\sigma$
	7 %	0.12	26.5	0.44	$\tau=0.12+0.44\sigma$
	10 %	0.13	24	0.40	$\tau=0.13+0.40\sigma$

Compression properties characterize the ability of bulk material to change its density depending on the applied pressure.

Same SCW mixtures with different binder contents (5, 7, and 10 %) were prepared for the studies. Besides, experimen-

tal conditions were expanded by introducing double (triple, etc.) compaction of the material and preheating the charge to 80 °C prior to the compression tests.

The device for compression tests and the experimental procedure are given in [15]. The series consisted of 2–5 experiments. Corresponding compression dependences were obtained for each of them. Analyzing these and other data obtained (the average density of the briquette from each series, coefficient of its elastic expansion, energy consumed for the compaction process) and summarized in Tables 8–16 and presented graphically (Fig. 9–11), the following can be pointed out. Change of binder percentage in the range from 5 to 10 % practically does not affect characteristics of the compression curves under normal conditions of mixture compaction (Tables 8–10, Fig. 9).

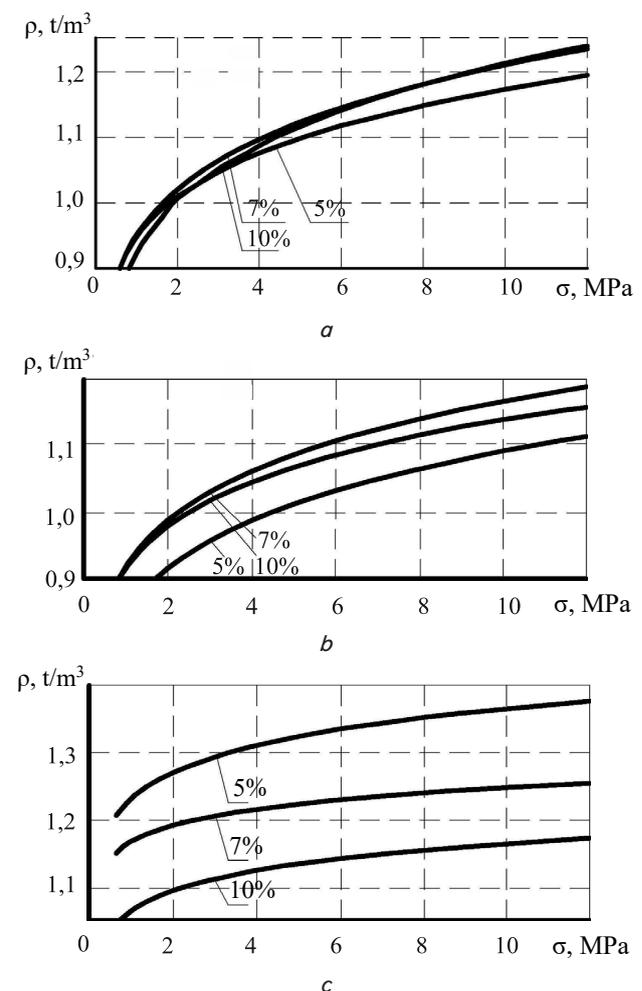


Fig. 9. Compression dependences of mixtures with different binder contents: a – compaction without additional conditions; b – heating up to 80 °C; c – 2-fold compaction

Table 8

Indices of compression curves with different binder contents

Binder content, %	Mixture density, kg/m <sup>3</sup>			$K_t$	$n$	Energy intensity, kJ/kg
	At 1 MPa	At 10 MPa	After unloading			
5	948.5	1189.9	1162.3	1.020	0.112	0.729
7	969.5	1181.3	1150.8	1.023	0.101	0.608
10	964.9	1149.6	1128.7	1.016	0.089	0.542

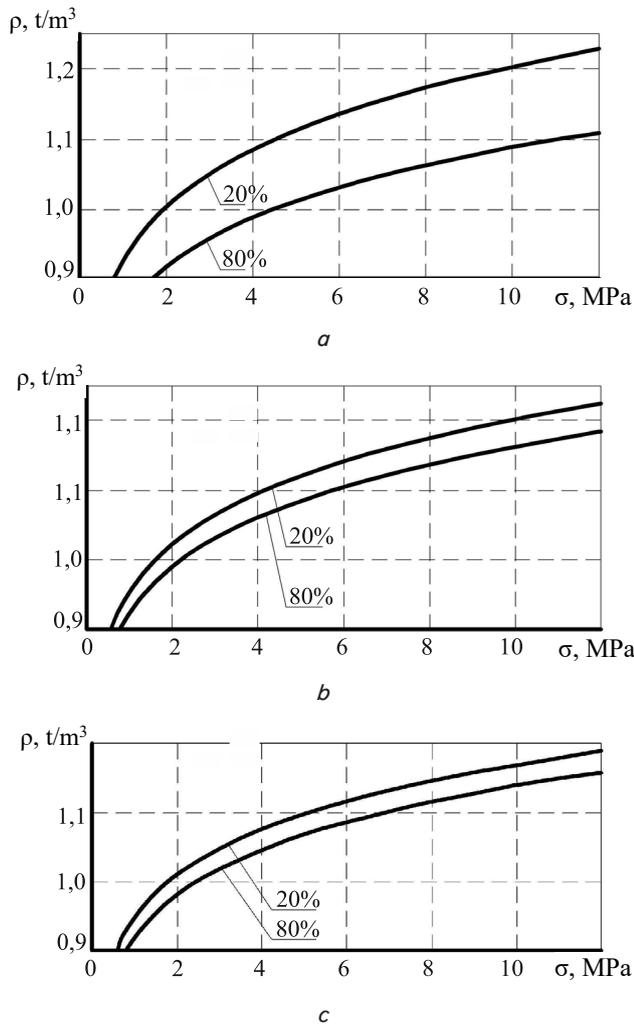


Fig. 10. Compression dependences of mixtures at different temperatures: a – 5 % binder content; b – 7 % binder content; c – 10 % binder content

Table 9

Indices of compression curves with different binder contents; the mixture heated to 80 °C

Binder content, %	Mixture density, kg/m <sup>3</sup>			$K_t$	$n$	Energy intensity, kJ/kg
	At 1 MPa	At 10 MPa	After unloading			
5	871.8	1074.4	1054.7	1.017	0.105	0.728
7	939.9	1161.7	1129.4	1.026	0.100	0.761
10	935.9	1134.5	1102.5	1.025	0.091	0.685

Table 10

Indices of compression curves with different binder contents, 2-fold compaction

Binder content, %	Mixture density, kg/m <sup>3</sup>			$K_t$	$n$	Energy intensity, kJ/kg
	At 1 MPa	At 10 MPa	After unloading			
5	1242.8	1360.7	1320.1	1.027	0.044	0.267
7	1175.2	1246.4	1228.6	1.013	0.028	0.197
10	1075.6	1165.3	1137.6	1.022	0.038	0.298

Under conditions of preheating to 80 °C, no unambiguous dependence was observed either. With 2-fold compac-

tion, the density of the resulting briquettes was inversely related to the binder content in them. A similar result was observed with 1-fold pressing but it was weakly marked (a 2–3 % decrease in density vs. 13–15 % with 2-fold pressing). As the amount of binder increased, compression curves invariably became flatter (the exponent  $n$  decreased by an average of 15 %).

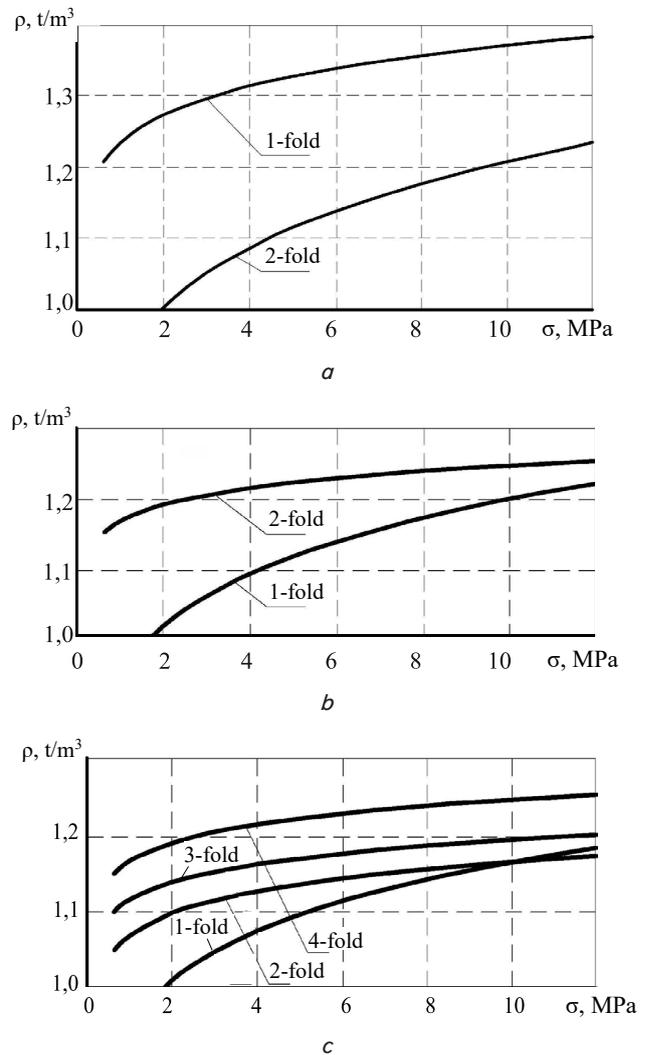


Fig. 11. Compression dependences of mixtures with multiple compaction: a – 5 % binder content; b – 7 % binder content; c – 10 % binder content

In all cases with preheating, the density of the resulting briquettes invariably decreased (on average by 5–6 %). As the binder percentage increased, these differences leveled out (the difference in density approached 2 %, Tables 11–13, Fig. 10).

Table 11

Indices of compression curves; preheating up to 80 °C with 5 % binder content

Compaction conditions	Mixture density, kg/m <sup>3</sup>			$K_t$	$n$	Energy intensity, kJ/kg
	At 1 MPa	At 10 MPa	After unloading			
Normal	948.5	1189.9	1162.3	1.020	0.112	0.729
Preheated	871.8	1074.4	1054.7	1.017	0.105	0.728

Table 12

Indices of compression curves; preheating up to 80 °C with 7 % binder content

Compaction conditions	Mixture density, kg/m <sup>3</sup>			K <sub>t</sub>	n	Energy intensity, kJ/kg
	At 1 MPa	At 10 MPa	After unloading			
Normal	969.5	1181.3	1150.8	1.023	0.101	0.608
Preheated	939.9	1161.7	1129.4	1.026	0.100	0.761

Table 13

Indices of compression curves; preheating up to 80 °C, with 10 % binder content

Compaction conditions	Mixture density, kg/m <sup>3</sup>			K <sub>t</sub>	n	Energy intensity, kJ/kg
	At 1 MPa	At 10 MPa	After unloading			
Normal	964.9	1149.6	1128.7	1.016	0.089	0.542
Preheated	935.9	1134.5	1102.5	1.025	0.091	0.685

With multiple compactions of the mixtures (Tables 14–16, Fig. 11), each subsequent compaction increased the briquette density while indices of the degree of compaction curves fall, especially sharply with the second loading (on average by 60–65 %).

Table 14

Indices of compression curves for multiple compactions with 5 % binder content

Number of compaction cycles	Mixture density, kg/m <sup>3</sup>			K <sub>t</sub>	n	Energy intensity, kJ/kg
	At 1 MPa	At 10 MPa	After unloading			
1	948.5	1189.9	1162.3	1.020	0.112	0.729
2	1242.8	1360.7	1320.1	1.027	0.044	0.267

Table 15

Indices of compression curves for multiple compactions with 7 % binder content

Number of compaction cycles	Mixture density, kg/m <sup>3</sup>			K <sub>t</sub>	n	Energy intensity, kJ/kg
	At 1 MPa	At 10 MPa	After unloading			
1	969.5	1181.3	1150.8	1.023	0.101	0.608
2	1175.2	1246.4	1228.6	1.013	0.028	0.197

Table 16

Indices of compression curves for multiple compactions with 10 % binder content

Number of compaction cycles	Mixture density, kg/m <sup>3</sup>			K <sub>t</sub>	n	Energy intensity, kJ/kg
	At 1 MPa	At 10 MPa	After unloading			
1	964.9	1149.6	1128.7	1.016	0.089	0.542
2	1075.6	1165.3	1137.6	1.022	0.038	0.298
3	1121.2	1195.2	1168.9	1.020	0.030	0.245
4	1172.9	1260.5	1234.0	1.019	0.029	0.231

The device and experimental procedure are described in [19]. The test results are summarized in Table 17. It can be seen that an increase in binder content had a positive effect on the splitting strength of the briquettes (with an increase in binder content from 5 to 10 %, the briquette strength

increased by more than 20 %) while energy intensity decreased.

Table 17

Splitting test results for raw briquettes

Binder content, %	Compaction conditions for briquettes		
	With no additional conditions	Charge preheating to 80 °C	Multiple compactions
5	0.729/0.158	0.728/0.178	0.996/0.223
7	0.608/0.178	0.761/0.193	0.805/0.222
10	0.542/0.194	0.685/0.199	1.316/0.281

Notes: in the numerator: energy intensity of compaction, kJ/kg; in the denominator: splitting strength, MPa; in the column “Multiple compactions”: the result of 4 compactions is indicated for the last mixture and 2 compactions for the rest

The briquettes obtained from the charge preheated to 80 °C, were usually 5–10 % stronger, all other things being equal. At the same time, energy consumption for their compaction increased (on average, by 15 %, that is with an increase in strength by 1 %, energy consumption increased by 2 %). It is noteworthy that from the point of view of energy consumption, the best characteristics were obtained with re-compaction at which this ratio is better: with an extra 32–36 % of energy consumption, the briquette strength increased by 25–40 %.

To establish the compaction number limit, the load was applied four times to the mixtures of the last series while the total energy intensity of the process increased by almost 2.5 times. Breakage of briquettes has shown that the increase in strength reached 40–50 %. Apparently, a 2-fold load application is sufficient.

### 5. 2. Substantiation of increasing the ecological and economic efficiency of using the studied waste properties

To substantiate and assess the forecast environmental and economic efficiency of the selected options for technological equipment, the known passport characteristics of typical equipment and results of laboratory studies were processed using the Index-E program [16]. Significant average socio-economic indices were taken into consideration, for example, ones adequate for Ukraine (such as the minimum wage, average inflation rate, etc.). Mutually dependent corrections of initial values of performance indices expectable during the predicted period of operation of the study facilities (15 years) were specified which was reflected in the computation task. For example, according to the programmed corrections of initial values of required parameters, a planned improvement of equipment was added to the project (for example, the purchase and installation of additional filters to minimize the volume of emissions and discharge of pollutants). An increase in staff salaries, purchase, and commissioning of additional units of equipment has been specified. Price rise: electricity; rent of the industrial site occupied by the equipment; products obtained after waste processing, purchase of spare parts, and repair work for the selected period of time (Tables 18, 19) were also included in the calculation.

Based on the results of the calculation in the Index-E program and taking into consideration the initial data given in Tables 18, 19, visualized annual and final environmental and economic indices for the facilities under study were formed (Fig. 12, 13).

Table 18

Initial data of the task for calculation in the Index-E program (boiler recycling plant for incineration of briquetted waste (based on Boiler 1 TPS))

Parameter name	Unit of measure	Initial value	Value correction (No. 1)		Value correction (No. 2)		Value correction (No. 3)		Value correction (No. 4)		Value correction (No. 5)	
			%	g	%	g	%	g	%	g	%	g
Power of emission (per unit of equipment)	g/h	6,920	-20	5	-45	11	-55	15	no	no	no	no
Power of discharge (per unit of equipment)	g/h	1,600	-30	5	-50	11	-65	15	no	no	no	no
Cost of functions (per unit of equipment)	USD*/h	291.6	+15	3	+25	7	+30	10	+35	13	+40	15
Total equipment units	unit	10	+10	7	+20	14	no	no	no	no	no	no
Operation time	h/year	3,925	+10	4	no	no	no	no	no	no	no	no
Operation time (3 years)	h/year	10,000	no	no								
Total processed waste	t/year	54,936	+20	7	+40	15	no	no	no	no	no	no
Personnel wages (per unit of equipment)	USD/h	0.01	+5	3	+10	7	+15	11	+18	13	+21	15
Cost of working area (per unit of equipment)	USD/h	5.84	+10	7	+20	14	no	no	no	no	no	no
Cost of energy resources (per unit of equipment)	USD/h	14.85	+7	3	+15	7	+20	10	+25	15	no	no
Repair cost (per unit of equipment)	USD/h	282.41	-80	3	-70	10	no	no	no	no	no	no
Money flow (per unit of equipment)	USD/year	227,459	+10	5	+20	12	no	no	no	no	no	no
Prime cost (per unit of equipment)	USD/year	120,176	-100	4	-85	11	-100	12	-80	14	-100	15

Note: \* US Dollar

Table 19

Initial data of the task for calculation in the program Index-E (Installation of thermal recycling of unprepared waste (based on Boiler 2 TPP))

Parameter name	Unit of measure	Initial value	Value correction (No. 1)		Value correction (No. 2)		Value correction (No. 3)		Value correction (No. 4)		Value correction (No. 5)	
			%	g	%	g	%	g	%	g	%	g
Power of emission (per unit of equipment)	g/h	7,500	-20	5	-45	11	-55	15	no	no	no	no
Power of discharge (per unit of equipment)	g/h	2,100	-30	5	-50	11	-65	15	no	no	no	no
Cost of functions (per unit of equipment)	USD*/h	289,84	+15	3	+25	7	+30	10	+35	13	+40	15
Total equipment units	unit	10	+10	7	+20	14	no	no	no	no	no	no
Operation time	h/year	7,850	-10	4	no	no	no	no	no	no	no	no
Operation time (3 years)	h/year	10,000	no	no								
Total processed waste	t/year	78,480	+10	8	+25	12	no	no	no	no	no	no
Personnel wages (per unit of equipment)	USD/h	0.01	+5	3	+10	7	+15	11	+18	13	+21	15
Cost of working area (per unit of equipment)	USD/h	5.83	+10	7	+20	15	no	no	no	no	no	no
Cost of energy resources (per unit of equipment)	USD/h	14.85	+7	3	+15	7	+20	10	+25	15	no	no
Repair cost (per unit of equipment)	USD/h	270.4	-80	3	-70	10	no	no	no	no	no	no
Money flow (per unit of equipment)	USD/year	261,583	+10	5	+20	12	no	no	no	no	no	no
Prime cost (per unit of equipment)	USD/year	126,185	-100	4	-85	11	-100	12	-80	14	-100	15

Note: \* US Dollar

The reported original scientific and practical study results are a sufficient basis for a comprehensive substantiation of an optimized choice of specialized technological equip-

ment for industrial production of fuel briquettes from SCW and the formation of practical recommendations to increase its efficiency.

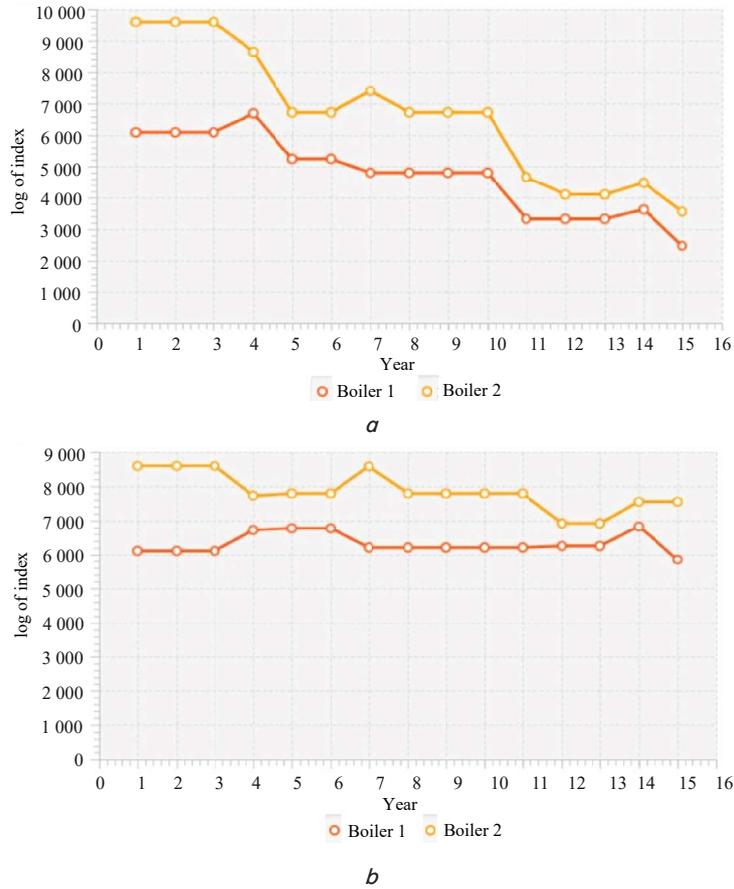


Fig. 12. Dynamics of annual indices: *a* – environmental effect of the facilities studied in the forecast period (coefficients of pollutant emission per 1 ton of processed waste from the total number of equipment units per year) for the project; *b* – economic effect of the facilities studied during the forecast period (profit ratio per 1 ton of processed waste per year)

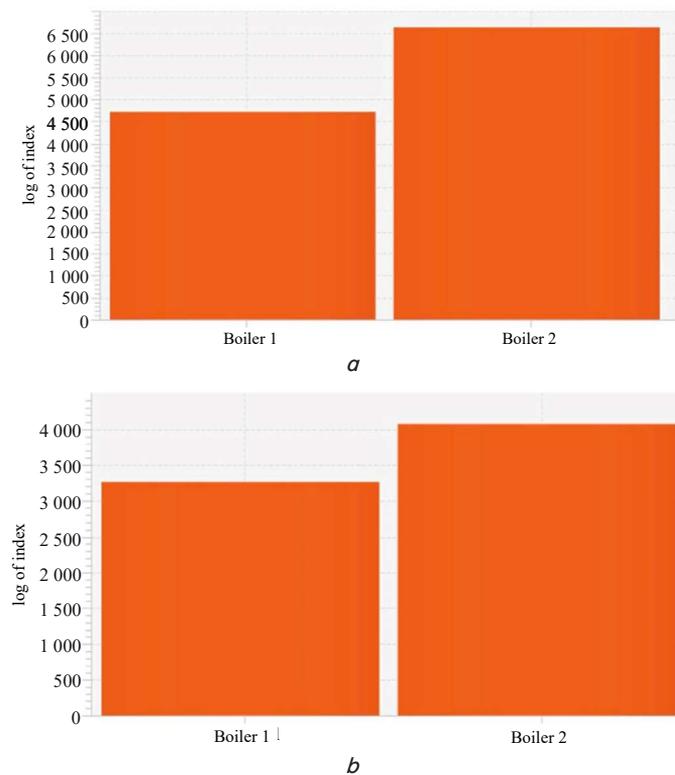


Fig. 13. The results of calculating the final indices of environmental (*a*) and economic (*b*) effect from the facilities under study in the forecast period (average values of the coefficients of profit and impact of equipment on the environment per 1 ton of processed waste): *a* – the results of calculating the final environmental index; *b* – the results of calculating the final economic index

## 6. Discussion of the results obtained in studying the properties of carbon waste as substantiation of recommendations for improving the efficiency of fuel briquette production

### 6.1. Analysis of the results of the experimental study of the SCW properties

The data obtained as a result of experimental study of carbon waste (Tables 1–7, Fig. 3–8) and the results of calculations according to the presented formulas allow us to form the following practically significant conclusions and patterns:

- the considered SCW mixtures are plastic and plasticity increases as the binder content increases;
- the SHW is a material more free-flowing than the SCW mixtures and its behavior is mainly determined by the binder content;
- for all compositions, the binder effect on the coefficient of internal friction is noticeably greater than on the coefficient of external friction;
- when mixing coal-enrichment sludge and solid waste, there is a significant decrease (by 1.5 times) in the internal friction coefficient of the latter and the initial shear resistance  $\tau_0$ ;
- when determining the coefficients of external friction, an inverse dependence of tangential stresses of the adhesive shear  $\tau_0$  on the coefficient of friction  $f_0$  is observed: if the latter has a maximum, the value of  $\tau_0$  has a minimum and vice versa;
- an increase in the binder content from 6 to 9 % reduces energy consumption for compaction and increases material density to  $1,500 \text{ kg/m}^3$ ; the binder content in the charge above 9 % is ineffective;
- mixtures of solid waste with slurries formed in coal preparation are the most plastic in the conditions of compaction at a moisture content of 10–15 %;
- an increase in compaction pressure of more than 10 MPa does not have a significant effect on increasing material density and strength.

The study results show the possibility of stabilizing the properties of processed raw materials which means an increase in stability and reliability of the thermolysis process and the unit productivity.

The study has revealed a tendency to a 5–6 % decrease in density of the resulting briquettes upon preheating of recyclable materials. As a percentage of the binder increases, these differences leveled up (the density difference approached 2 %, see Table 11–13, Fig. 10). This can be explained by the fact that before the tests, it was the temperature of the charge and not moisture content that determined its readiness. When heated to  $80^\circ\text{C}$  for an equal time, the briquetted mixtures of recyclables with different binder contents did not have time to reach the same moisture content. The conclusion about the inexpediency of preheating the charge is confirmed by some more observations. First, heated briquettes tend to have a higher coefficient of elastic expansion which is undesirable. Secondly, the energy consumption for compacting such briquettes (inferior in density to their “cold” counterparts) increases on average by 15–20 %. That is, from the point of view of compression properties of the raw material, preheating the charge to  $80^\circ\text{C}$  before compaction is undesirable.

Final analysis of the conducted experimental study (Tables 1–17, Fig. 3–11) that summarizes the described laboratory studies shows that with an increase in moisture content or binder content, solid carbon waste becomes more plastic and viscous: the coefficient of internal friction decreases from

0.6 to 0.4. The effect of moisture on the coefficient of external friction is less noticeable (reduction to 25 %). Preheating the charge to  $80^\circ\text{C}$  helps reduce the density of the resulting briquettes (on average by 5–6 %) and leads to an increase in the coefficient of elastic expansion. Briquettes, all other things being equal, are 5–10 % stronger but a 1 % increase in strength means a 2 % increase in energy costs. Upon re-compaction, a noticeable change in the compression properties occurs. The briquette density increases by an average of 7 %. With a lower binder content, an increase in density of 14 % was obtained. In this case, the increase in strength is directly proportional to energy consumption. Based on the results obtained, in order to increase the briquette strength, it is recommended to increase the binder content in them and use their re-compaction. All this, depending on the specific production conditions, by means of justified corrections, will help to improve characteristics of the product of preliminary waste preparation when optimizing energy consumption for implementation of the technological process.

The complexity and versatility of the studied properties of recyclable materials favorably distinguish this study from alternative studies [5, 17–22] making its results more indicative and practically significant for implementation into real process flowsheets of waste processing. Thus, practical application of the information obtained about the above conclusions and the regularities of changes in technical properties of recyclables solves the identified scientific and practical problem of expanding the base of theoretical and practical data on technical parameters of various compositions of industrial and household SCW with an increase in efficiency of the process of fuel briquette manufacture. Thus, the issue of experimental substantiation of the recommendations formulated in the study was solved.

### 6.2. Analysis of the results of justifying the ecological and economic efficiency of the optimized choice of specialized equipment

Analyzing the obtained indices of predicted efficiency of applying these technological processes and the equipment for their implementation given in Tables 18, 19 and Fig. 12, 13, it is important to note the following:

- the coefficient of expenditure of funds per year (per 1 ton of processed waste) when burning briquetted waste (in the task for calculation with the help of the Index-E, Boiler 1 program), is on average 32.9 % less than the value of this index when recovering unprepared waste (Boiler 2);
- the coefficient of influence of the Boiler 1 facility on the environment over a 15-year period is 28.89 % less than the value of this index during operation of the Boiler 2 facility;
- the coefficient of profit from equipment per year (per 1 ton of processed waste) when using the Boiler 1 facility is 18.29 % less than the same index when operating the equipment corresponding to the Boiler 2 facility.

Analysis of the data obtained using the Index-E program (Fig. 12, 13) based on the experimental results taking into consideration the initial data (Tables 18, 19), allows us to make a scientifically substantiated conclusion that the facilities under consideration (Boiler 1 and Boiler 2) are relatively cost-effective. However, the Boiler 1 facility has a more pronounced level of environmental and economic efficiency in comparison with the Boiler 2 facility (even with a slight decrease in the average economic effect). Taking into consideration peculiarities of the specified parameters of equipment operation, this is clearly seen from the set of indices charac-

teristic of its medium-term operation provided longer use and necessary corrections for parameters of economic operation. Based on this, the Boiler 1 facility can be recommended for implementation, subject to the technical optimization, a reasonably relevant increase in the economic efficiency of waste briquetting through the practical use of the described characteristics of the SCW and SHW compositions.

Unlike the previously considered alternative studies, for example [13, 14], the present study substantiates the effectiveness of choice of technical support for waste management processes by analyzing technical, economic, environmental, social, and even political factors of external influence on mode of operation of the equipment line under consideration. This makes its practical implementation much more flexible and stable in conditions of present-day geopolitical instability in most countries.

Thus, the task of comprehensive substantiation of optimal choice of specialized equipment, correction of its operating parameters subject to the long-term operation was solved. Thanks to an expanded set of criteria for forecasting and evaluating the effectiveness of equipment using a large-scale computer modeling tool based on empirical indices, the corresponding component of the problems identified in the study was resolved.

### 6. 3. Prospective directions of study development

The following should be noted as the main perspective directions of expanding and deepening the study:

1. Expansion of the set of shear tests of raw materials by increasing the number of tested surfaces when measuring the coefficient of external friction was considered. In addition to metal and concrete presented in the studies, it may be preferable to study the coefficient of external friction on surfaces made of materials from which the working space of briquetting and processing equipment is made (various alloy steels of certain surface cleanliness classes). This will make it possible to more accurately forecast material behavior in equipment.

2. In order to improve the potential of using the study results, it seems preferable to expand the raw material base, analyze the SHW mixtures differing in morphological and fractional composition specific for concrete territories. Optimized studies will make it possible to more accurately describe material behavior for each specific case and, accordingly, contribute to more efficient waste processing.

3. Optimization of the methodological basis and software implementation of the computer modeling tool (Index-E program):

- correction of the set of criteria (parameters characterizing the equipment under study) both to increase objectivity and accuracy of the calculated efficiency forecast by introducing more informative indices and simplify work with the program by eliminating secondary parameters;

- development and implementation of a software algorithm of prompt non-confidential user data acquisition about individual real projects of forecasting and evaluating the effectiveness of specialized equipment in the context of various external social, technical and environmental-economic features of national and world regions in order to create an

open, public (through the program update) common databases on various types of equipment and technological processes of waste management which will enable experience exchange between individual practicing users of the Index-E program.

## 7. Conclusions

1. The experimental study of properties of carbon waste has established that with an increase in moisture or binder content, solid carbon waste becomes more plastic and viscous (on the contrary, dry household waste behaves like a bulk material). At the same time, the coefficient of internal friction decreases significantly (from 0.6 to 0.4). The effect of moisture content on the coefficient of external friction is less noticeable (reduction by 2–5 %). The change in the binder content in the mixture from 5 to 10 % practically does not affect the compaction characteristics. As the moisture content increases, the density of the resulting briquettes decreases slightly (by 2–3 %). An increase in the binder content has a positive effect on the briquette strength determined by splitting while specific energy consumption for compacting reduces. Preheating the charge to 80 °C helps reduce the density of the resulting briquettes (on average by 5–6 %) and leads to an increase in the coefficient of elastic expansion. Briquettes, other things being equal, are 5–10 % stronger but a 1 % increase in strength causes a 2 % growth in energy costs. Upon re-compaction, a noticeable change in the compression properties occurs. The density of briquettes increases by an average of 7 %. The best results were obtained with a lower binder content (a 14 % increase in density). In this case, the increase in strength is directly proportional to energy consumption. According to the results of the experimental study, to increase the efficiency of the briquetting process, it was reasonably recommended to increase the strength of briquettes as their determining characteristics by increasing the binder content in briquettes and, as an extreme measure, their re-compaction can also be applied. A further increase in the number of loading cycles and preheating of the charge do not seem to be feasible because of energy consumption and, therefore, from an economic point of view.

2. It has been reasonably established that with the optimized operation of boiler houses of the recycling plants that incinerate the briquetted waste, the coefficient of funds expenditure per year (per 1 ton of processed waste) is on average 32.9 % less than the value of this index when operating the equipment for recycling unprepared waste. At the same time, the coefficient of environmental impact over a 15-year period was 28.89 % less than the value of this index when operating similar equipment. This gives grounds to assert that even against the background of a decrease in the profit ratio from equipment per year on average by 18.29 % in comparison with the analog, the optimized technology of producing waste briquets followed by their incineration, according to the totality of signs, is characterized by a significant increase in the environmental and economic efficiency of the waste recovery process.

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