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ОСОБЕННОСТИ ИНЖЕНЕРНО-ГЕОЛОГИЧЕСКИХ СВОЙСТВ ОТХОДОВ УГЛЕОБОГАЩЕНИЯ В СВЯЗИ С ИХ СКЛАДИРОВАНИЕМ

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Аннотация: Несмотря на успехи развития зеленой энергетики, стратегия большинства стран с большими запасами угля предполагает увеличение объемов его добычи в ближайшие 20 лет, что делает проблему складирования и вторичного использования отходов углеобогащения одной из наиболее актуальных проблем угольной промышленности. В связи с большими перспективами вторичного использования отходов при складировании все чаще используют раздельное размещение отходов в отвалах. Это приводит к формированию сложной неоднородной структуры техногенных массивов, что повышает требования к изученности свойств материалов, складируемых в отвал. Представлены результаты лабораторных исследований физико-механических свойств отходов обогащения угля месторождений Печорского угольного бассейна и их смесей в различных пропорциях, полученных с фабрики, а также образцов отвальной массы существующего породного отвала. Характеристики угла внутреннего трения и сцепления при испытаниях на одноплоскостной срез и трехосное сжатие по консолидированно-дренированной схеме показали близкие значения для различных видов отходов: φ = 29°–32°; C = 27–50 кПа. При этом недрированная прочность кеков значительно ниже, что предопределяет необходимость учета и контроля порового давления при наращивании высоты отвальных сооружений. Даны рекомендации по обеспечению длительной устойчивости отвальных сооружений на описываемом объекте при складировании отходов углеобогащения.

Ключевые слова: складирование отходов, техногенные грунты, углеобогащение, инженерно-геологические факторы, физико-механические свойства, гранулометрический состав, прочность на сдвиг.

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Specificity of properties of coal processing waste regarding their storage

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Abstract: Despite the progress in green energy, the strategy of most coal-rich countries is to increase coal production in the next 20 years, which makes the issue of storage and reuse of coal processing waste one of the most urgent problems in the industry. In connection with the prospects for the secondary use of waste, the technology of separate coal waste disposal in dumps becomes more widespread. Separate disposal of coal-bearing rocks, sludge and slurry, leads to the formation of a heterogeneous soil body, which explains the relevance of studying patterns of waste properties formation and their changes in time. The results of laboratory testing of coal processing waste from the plant in the Pechora coal basin are presented. The mixtures of wastes in various proportions were tested, as well as samples from the already constructed dump. Drained direct shear tests demonstrate similar values of the angle of internal friction and cohesion for various types of waste: φ = 29°–32°, C = 27–50 kPa. Nonetheless, the undrained shear strength of slurry is much lower, which justifies the need to take into account pore pressure when increasing the height of dumps. Based on the results the recommendations concerning ensuring the long-term stability of the dumps are provided.

Key words: waste storage, technogenic soils, coal processing waste, geotechnical factors, mechanical properties, soil particle, shear strength.

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Introduction

Coal industry plays a key role in the fuel and economic balance of coal-rich countries, including Russia. According to Global Energy Transition Statistics, the volume of world coal production for the period from 2010 to 2020 remained at the same level on average, but in most of countries it increased by up to 30% (e.g. Russia and India) (Fig. 1), Russian share in world production increased up to 5.5%. This trend is expected to continue in the near future. Based on the Energy Strategy of Russia until 2035, the volume of coal production will increase to 490 million tons per year by 2035 despite the environmental restrictions. In addition to rising production, there is an increase in coal processing, which is reported by Russian coal mining companies, aimed at better quality and higher market value.

An increase in the volume of processed coal also leads to an increase in the accumulation of coal processing waste. The trend of the accumulation of coal processing waste can be illustrated using the example of Russian Federation, where to date, more than 12 billion tons of waste have been accumulated as a result of mining and processing. According to government reports, coal industry is responsible for 67% of industrial waste in Russia (5.2 billion tons by 2019). Over the past 10 years, the country has seen a gradual increase in both coal production and processing. Over the last 10 years, the volume of waste generated annually has increased by 66% (Fig. 2).

Solving the problem of accumulation, storage and reuse of coal processing waste is a crucial issue for the industry. On average 0.2 — 0.4 tons of waste is formed during the production of 1 ton of coal. The volumes of processing waste generated for the period from now until 2035 are estimated at 240 million tons. Accordingly, the annual in-crease in accumulated waste is approximately 12 million tons, which is

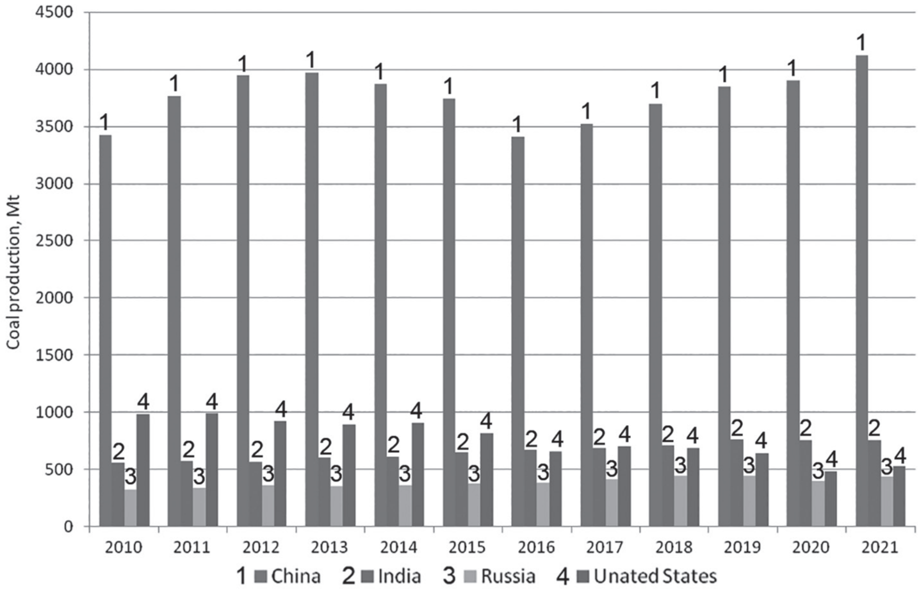

Fig. 1. The dynamics of coal production in important coal producing countries in 2010 – 2020 (according to Global Energy Transition Statistics)

Рис. 1. Динамика добычи угля в некоторых угледобывающих странах в 2010 – 2020 гг. [1]

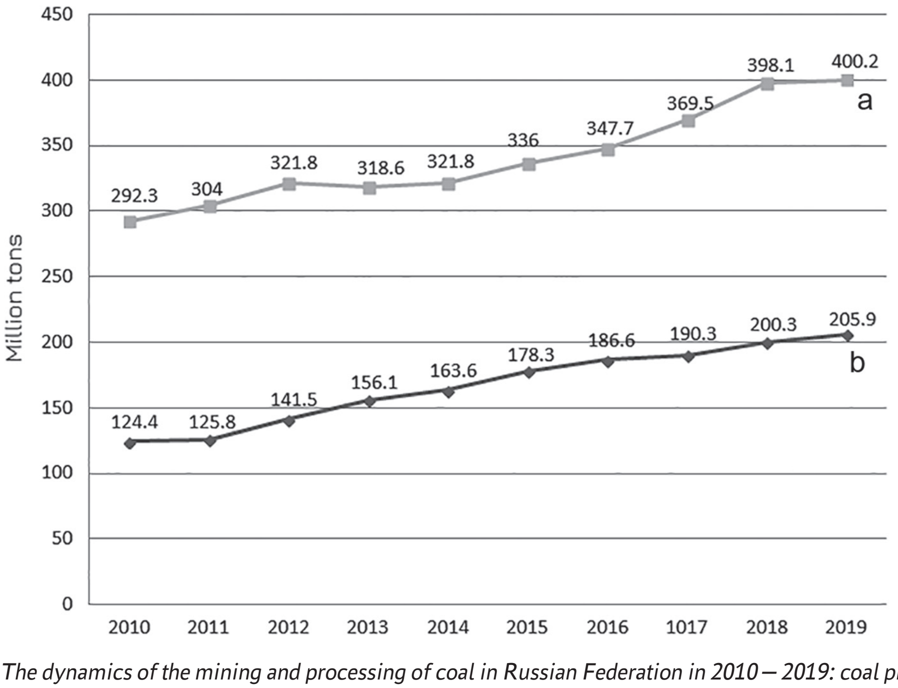

Fig. 2. The dynamics of the mining and processing of coal in Russian Federation in 2010 – 2019: coal production in Russia, million tons (a); coal processing in Russia, million tons (b) (complied according to Government Report «About the state and use of natural resources of Russian Federation in 2020», 2021)

Рис. 2. Динамика добычи и переработки угля в России в 2010 – 2019 гг. [3]: добыча угля, млн т (а); переработка угля, млн т (б)

3% of waste generated in the country per year. This amount is comparable to accumulated waste by entire mining industry of Germany in recent years [1].

Since most of the waste is placed in dumps and piles, large areas are occupied by waste. Accumulated wastes have a large-scale and prolonged impact on the atmosphere, hydrosphere, soils, vegetation cover, and microclimate, and cause deterioration of the public health on the mining enterprises [2] and in mining areas [3, 4]. Even wastes regarded as the least dangerous have toxic properties [5]. For a medium processing plant, approximately 2–3 thousand hectares are required for the storage of waste. Taking into account the geochemical migration, the affected area expands by 10–15 times [5].

Coal processing waste consists of coal as well. Moreover, when the content of the coal fraction is more than 20%, the waste heap is classified as a man-made coal deposit. One of the problems associated with the high content of coal in waste is spontaneous combustion when the content of carbon and sulfide compounds is more than 5% in total [6]. This process leads to the release of large amounts of toxic substances and carbon dioxide. At the same time, in most cases, there are no monitoring surveys on the potentially flammable territories.

The problem of accumulation of mining waste is a burning issue for many countries. However, the problem of disposal of coal processing waste is the most critical due to the largest volumes of accumulation, several times greater than the volume of accumulation, for example, iron stone processing waste. Mining companies tend to re-duce the amount of waste and occupied territories to cut costs. The strategy of coal waste reuse has the greatest prospects for increasing mining efficiency. According to Russian National Standard GOST R 57011-2016 «Wastes from coal mining and processing. Classification» in the case of a relatively high content of carbonaceous particles, coal waste disposal facilities are classified as technogenic coal deposits. Studies show the diverse directions of coal processing waste management:

- In the energy sector as a high-ash raw material [7, 8, 9];
- In metallurgy as a material for the production of refractories [10];
- In construction for production of bricks, expanded clay, reinforced concrete, etc. [11, 12];
- In metallurgy as a material for the production of refractories [13];
- In mining as a material for reclamation [14].

It should be pointed out that nowadays the above-mentioned technologies for the reuse of coal waste are not widely used due to complexity, relatively low demand for final products, and low profitability of the process. The feasibility depends on the composition and properties of wastes, as well as economic indicators, under which the most economically profitable option is selected at a present time for each of the coal-mining enterprises. In this regard, even if for present technical development the reuse of waste is not cost-effective, safe storage of waste should be provided for ensuring the reuse of coal waste in the future.

In the terms of engineering geology, coal processing wastes are considered technogenic soils, which are characterized by specific physical and mechanical properties, that differ significantly from natural soils [15]. As a rule, coal processing wastes are characterized by a high degree of particle dispersion, high moisture content, low permeability and coagulability. Moreover, processing waste soil bodies are characterized by anisotropy [15]. As a result, the use of coal processing waste, for example, as a construction material is currently restricted. To date, the physical and mechanical properties of certain types of coal waste are characterized as poorly known, which is acting as a limiting factor for their use. Therefore, currently, the preferable direction of reducing the anthropogenic load on the environment, which also contributes to resource conservation, is carrying out research aimed at studying the efficient and safe method of the storage of coal processing waste.

Physical and mechanical properties of coal mining and processing waste have been studied by significant number of soil scientists. The main investigations were A.M. Galperin [16, 17], M.Yu. Lychko [18], E.N. Ogorodnikova, S.K. Nikolaeva [19], Yu.I. Kutepov [20], N.A. Kutepova [21], D.O. Glushkov [22]. Among foreign authors, this issue was covered by K.M. Skarzynska [23], M. Golam [24], P. Filipovich, M. Borys [25], and A. Gruchot [26]. Directly Yu.I. Kutepov, N.A. Kutepova, and V.V. Moseikin have developed the engineering rationale for the construction of waste piles of coal waste [27, 28]. An analysis of the published articles in this field allows us to conclude that the topic of forming of coal waste pile has been sufficiently studied. At the same time, the analysis of research problem of forming and changing of the physical and mechanical properties of coal processing waste shows that there is no reasonable methodology for studying the physical and mechanical properties of technogenic soils and the instrumental testing base for these purposes is not regulated. As a rule, a formal approach is used when determining properties: tabular data are used or values are obtained for other research objects. The intensity of the construction rates, parameters of the dump and design features are not taken into account as well. Based on the fastening of coal processing waste accumulation, as well as the lack of a sufficient number of studies in this field, the authors assume that the problem of forming and changing in time the properties of coal processing waste is relevant.

To sum up, the study of coal processing waste properties is required, first of all, for calculating and justification of the optimal storage parameters for the ensuring the long-term slope stability. Hence, in order to minimize the cost of waste disposal, enterprises tend to increase the height of coal waste storage facilities. In this case, a possibility of a loss of slope stability occurs, which leads to significant damage.

The probability of failure occurs most frequently when the hydrogeological conditions are studied insufficiently, the pore pressure is not taken into account, or unreliable values of physical and mechanical properties are used. Among these factors only studying of the properties is possible at the initial stage before the storage starts. Therefore, this data may be used for feasibility study regarding to waste piles parameters design.

Materials and Methods

The choice of the scheme of coal processing depends on the coal properties and its type. Despite a large number of methods, the most widely used methods are gravity separation and flotation. Electrical separation and other methods are rarely used.

The object of study is located in the Pechora coal basin on the Vorkuta coal mine, and is characterized by a traditional scheme of processing (Fig. 3). Processing takes place in a dense separator, a drum separator and hydrocyclones, slurry processing (particles finer than 0.15 mm) is carried out in spiral separators and flotation machines. Since the final products contain a large amount of water, inertial screens and vibrating centrifuges are used to dehydrate products. Disc vacuum filters and filter presses are used for dehydration of flotation concentrate.

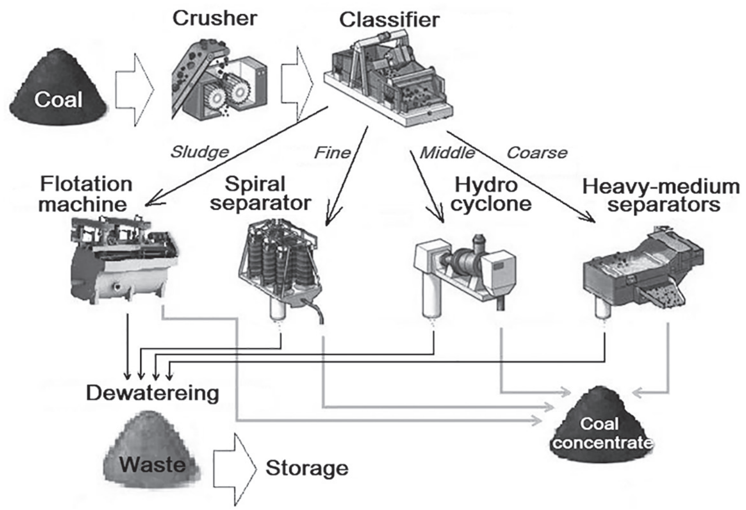

Fig. 3. The scheme of coal processing on the study object (compiled by the authors)
Рис. 3. Схема обогащения угля, применяемая на объекте исследования

Generally, waste from the processing plant includes coarse and fine rock formations, slurry from the filter-press section (the finest fraction of the sludge), slag from the drying bunkers. Waste transported to the waste piles, where the material is stored in tiers. Lithological composition of the storaged wastes are mainly sandstones, siltstones and mudstones. The height of the first tier of considered piles is 30 m and the second is 15 m, it is planned to form the third and subsequent tier.

The waste pile disposal technology includes the following steps:

- Formation of transport paths and sections from the dry coarse rock;
- Filling the section with slurry;
- Backfilling the section with a layer of dry coarse rock.

The material for the research was obtained from one of the largest coal processing plants in Europe, located on the territory of the Pechora coal basin. Samples of coal-bearing rock, sludge and slurry from the existing waste dump were obtained to determine the physical and mechanical properties.

For those samples, where it was possible, the following parameters of physical and mechanical properties were carried out: water content; liquid limit; plastic limit; plasticity index; liquidity index; bulk density; dry soil density; specific gravity; void ratio; saturation ratio; angle of internal friction and cohesion by the direct shear method and triaxial tests, as well as total strain modulus.

For all types of samples, series of six direct shears have been carried out applying a consolidated drained «underwater» scheme (full water saturation, produced during the compaction of samples at the consolidation stage). For the soil and soil mixture, a series of six direct shears have been carried out applying a consolidated drained scheme at natural moisture. The number of tests is determined by the minimum requirements of GOST 20522-2012 «Soils. Methods of statistical treatment of test results», needed for calculation values of the strength parameters. Tests of waste from the plant and samples from the waste dump were carried out on a screening of – 5 mm, the content of which in the source material exceeded 30%. In addition, tests of slurry have been carried out to determine the strength parameters of this type of soil in an unstabilized state by

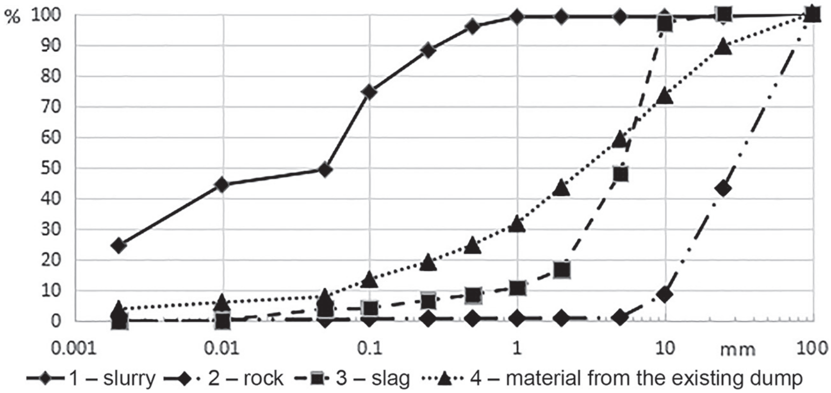

Fig. 4. Grain distribution curves of coal processing waste from the plant (compiled by the authors)
Рис. 4. Кривые гранулометрического состава отходов углеобогащения с фабрики

applying the fast shear scheme. The deformation parameters of the slurry were also determined using compression and triaxial tests.

Results

Grain size of coal processing waste

The average distribution of fractions according to the results of the grain-size analysis of the studied materials by sieve and areometer methods are shown in Fig. 4.

Among the studied soils the slurry stands out by particle diameter d_{50} = 0.05 mm, while for other soils it is more than 2 mm.

It should be noted that the grain size composition of the wastes from the plant and the existing waste dump differ widely, which can be explained by the physical weathering of the soils stored in the dump,

Table 1

Physical properties of wastes
Физические свойства материалов

Parameters	Units	Material			
		Slurry	Coal-bearing rock	Sludge	Waste dump material
Water content, W	unit fraction	0,29	0,04	0,28	0,06
Liquid limit, WL	unit fraction	0,29			0,22
Plastic limit, WP	unit fraction	0,21			0,16
Plasticity index, IP	unit fraction	0,08			0,06
Liquidity index, IL	unit fraction	1,00			1,36
Bulk density, r	$g \cdot cm^{-3}$	1,43			2,06
Dry soil density, rd	$g \cdot cm^{-3}$	1,11			1,90
Specific gravity, rs	$g \cdot cm^{-3}$	1,63	2,30	1,87	2,38
Void ratio, e	unit fraction	0,47			0,27
Saturation ratio, Sr	unit fraction	1,00			0,74
Maximum water-holding capacity	unit fraction	0,29			0,11

Table 2

The results of semiquantitative X-ray phase analysis of clays <0,002 mm from the specimen of slurry according to Yu.S. D'yakonov

Результаты полуколичественного рентгенофазового анализа глинистой фракции <0,002 мм пробы шлама по методике Ю.С. Дьяконова

Mineral	Content (relative %)
Illite	56
Kaolinite	22
Chlorite	20
Quartz	≈2

leading to the disintegration of large fragments, as well as the stress from stored overlying waste during the dump constructing.

Physical properties of coal processing waste

The results of the analysis of physical properties of coal processing waste are presented in Table 1.

For the slurry, the coefficient of permeability was also determined, which averaged 10^{-4} m/day. Such value is explained by the grain-size composition of the material, which is close to loamy soils of natural origin, as well as mineralogical composition of <0,002 mm fraction, which is presented by clay minerals (Table 2). Such coefficient of permeability indicates the probability of excess pore pressure occurring, which may not have time to dissipate in the case of intensive dump construction.

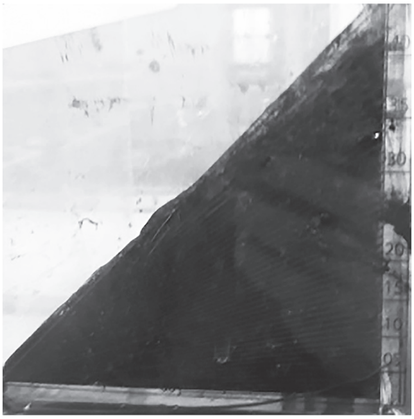

Fig. 5. Determination of the angle of internal friction of the slurry (compiled by the authors)

Рис. 5. Испытание шлама в приборе для определения угла естественного откоса

Mechanical properties of coal processing waste

For an indirect assessment of the mechanical properties in a water-saturated state, a slurry was examined in a device for determining the angle of internal friction. The dried and crushed slurry sample was poured into the device for determining the angle of internal friction, after which the slurry was saturated with water. After the test, the sample was left in the device for a 1 day. As a result, the material formed an angle equal to 44° (Fig. 5). The water content of the slurry after testing was 39.6%. Relatively high values of the angle of internal friction are explained by friction forces and the interaction of angular particles. It should be noted that the water content of the slurry increased by 10% relative to the initial one.

The studied wastes were tested by the method of direct shears at full water saturation under drained conditions: slurry was tested in the initial state, and for the rest of the soils fraction < 5 mm was tested. The test results are presented in Table 3. The materials, except for the slurry, were studied at a normal load of 200–1600 kPa, and the slurry at a normal load of 200–800 kPa. At a higher load, the slurry squeezed out of

Table 3

Strength parameters of wastes in a water-saturated condition

Прочностные параметры шлама, породы и шлака в водонасыщенном состоянии по результатам испытаний на одноплоскостной срез

Parameter	Material			
	Slurry	**Coal-bearing rock**	**Sludge**	**Waste dump material**
Cohesion, kPa	28	47	51	60
Angle of internal friction,°	31	30	32	30

the shear box. Results of direct shear tests are presented in Fig. 6.

In addition, direct shear tests were carried out for the slurry under undrained conditions. The slurry strength parameters are: cohesion — 4 kPa, angle of internal friction — 23°. The strength diagram of the slurry is shown in Fig. 7. The tests were carried out at vertical loads up to 150 kPa since at high pressures the material was squeezed out of the shear box.

For verification of the above mentioned results consolidated drained and consolidated undrained triaxial tests were carried out for the slurry. Tests show that strength parameters are almost identical according to both schemes in actual stress (Fig. 7): according to consolidated drained scheme cohesion is 33 kPa, angle of internal friction is 31°; according to consolidated undrained scheme cohesion is 22 kPa, angle of internal friction is 32°. According to consolidated undrained scheme in total stress cohesion is 0 kPa, angle of internal friction is 15°.

The lower strength values for consolidated undrained triaxial tests are explained by the fact that in case of drained direct shear tests, even at high test speeds, there is a possibility of squeezing out of the water along the shear surface. Therefore, in triaxial tests, the pore pressure effect on material behaviour is more substantial.

Furthermore, strength properties of waste mixtures were carried out in order to compare properties of mixture and properties of unmixtured materials. The mixing was conducted by the following scheme: coal-bearing rock and sludge were mixed in equal proportion and then the slurry

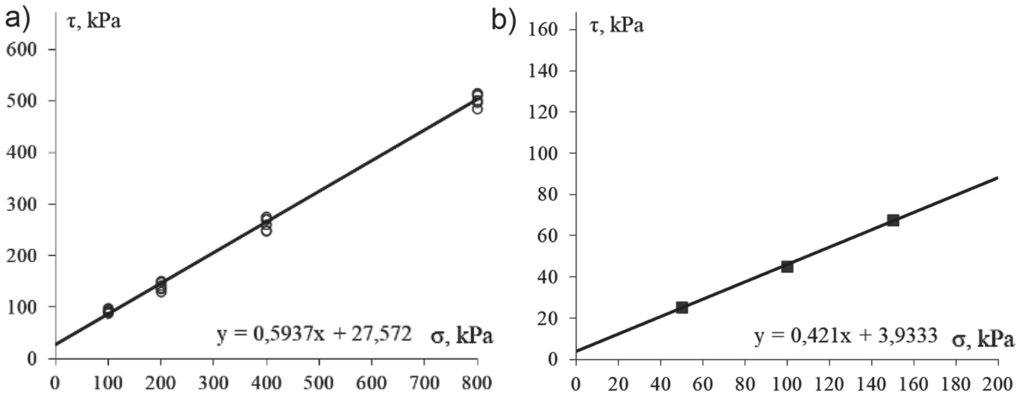

Fig. 6. The results of slurry testing for direct shear under drained conditions: drained conditions (a); undrained conditions (b) (compiled by the authors)

Рис. 6. Результаты испытаний шлама на одноплоскостной срез при дренированных условиях: при дренированных условиях (а); при недренированных условиях (б)

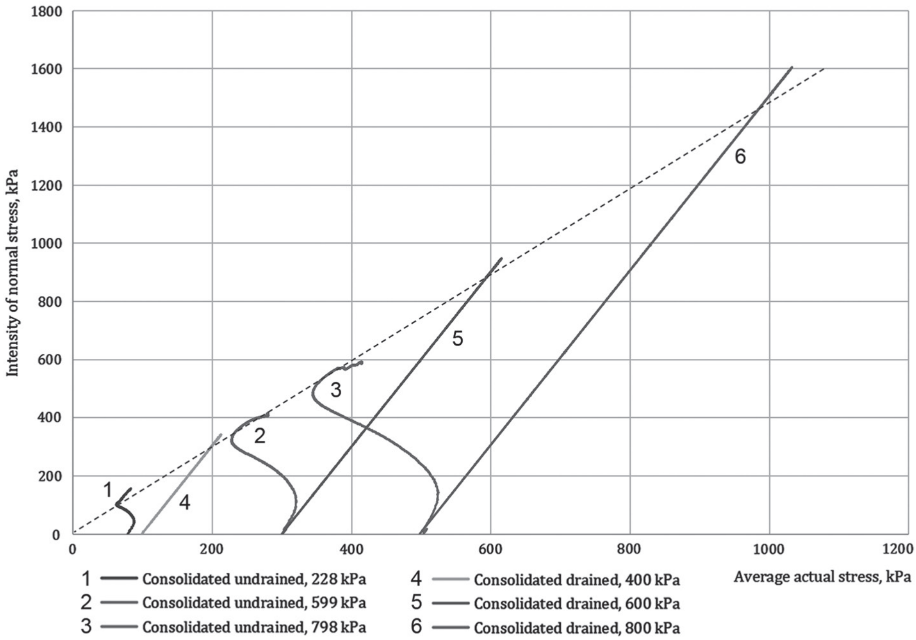

Fig. 7. The dependance of the intensity of normal stress on average actual stress according to consolidated drained and consolidated undrained triaxial tests of slurry

Рис. 7. Зависимость интенсивности нормальных напряжений от средних эффективных напряжений по результатам испытаний шлама методом трехосного сжатия по КН и КД схемам

Table 4

Strength parameters of mixtures of waste in a water-saturated state
Прочностные свойства смесей отходов

Parameter	Mixture	
	70/30	**50/50**
Cohesion, kPa	49	57
Angle of internal friction, degree	29	29

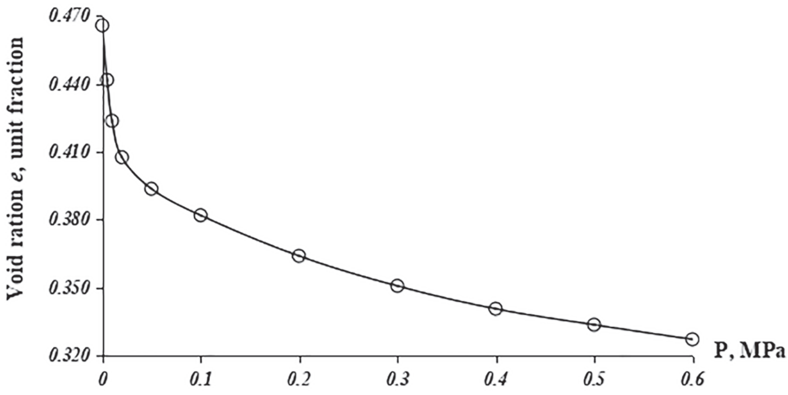

Fig. 8. Compression curve from slurry testing (compiled by the authors)

Рис. 8. Компрессионная кривая по результатам испытаний шлама was added. As a result, strength properties were obtained for two mixtures:

1. rocks + sludge – 70%, slurry – 30%;
2. rocks + sludge – 50%, slurry – 50%.

The results of the tests are presented in Table 4.

Deformation properties of the slurry were studied using compression and triaxial tests. The consolidation coefficient for compression tests in the range of 0.1...0.3 MPa was 0.07...0.08 m^2/day. Compression tests to measure the deformation characteristics of the slurry showed the following scattering of values: the normal stress — 0.1...0.2 MPa: coefficient of compressibility — 0.180...0.194 MPa^{-1}; odometric modulus of deformation — 7.5...8.2 MPa; bulk modulus — 4.5...4.9 MPa. These values allow considering the slurry as a highly compressible material. An example of a typical compression curve for a slurry is shown in Fig. 8. According to consolidated drained triaxial tests for 400, 600 and 800 kPa strain modulus was 4,1; 19,7 and 24,0 MPa respectively.

Discussion

Based on the results of laboratory testing, it was shown that coal processing wastes stored in a dump are technogenic soils with specific properties. Properties are formed and depend on the technology of processing used on a plant. The change in the properties of coal processing waste occurs throughout the entire period of formation of the dump structure and continues after the cessation of the waste storage process. Therefore, for such soils, it is of great importance to control the state of soil bodies that they form.

There is a relationship between the properties of the parent material, which includes coal itself, and secondary material, which is formed as a result of the transformation of the parent material. A generalized characteristic of the mechanical properties of coals of the Vorkuta coal deposit according to VNIIGIS and PechorNIIproject showed that the angle of internal friction of coals is 37°, and the cohesion is 4.5 MPa [29]). Therefore, for technogenic soils formed during the destruction of coals, the angle of internal friction should be close to the values of the parent material, and cohesion should be practically absent. This is confirmed by the results of the present research, in particular, according to drained test schemes by methods of single-plane shear and triaxial compression, as well as by characterization of the properties of coal slurry, given by Yu.M. Lychko, who provides data that the angle of internal friction in such soils can be up to 30—34° [18].

At the same time, the undrained strength of coal slurry is two times lower: the abgle of internal friction is 15°. In the case of storage of coal processing wastes as unmixed soils, when selecting the optimal parameters of dumps, the probability of excess pore pressure occurring in the slurry should be taken into account. Therefore, it is necessary to calculate the intensity of the dump construction, taking into account the pore pressure dissipation rate, as one of the main factors affecting stability [30]. To control this process, it is essential to install automized systems with pore pressure sensors [31—33]. It is also required to store slurry not only by covering them with coal-bearing rock and sludge but also by disposing of coal-bearing rock and sludge at the base of the depositing site as a drainage layer.

Conclusion

The analysis of trends in coal mining industry has shown the relevance of technogenic soils studies, which are presented by coal processing waste. Since physical and mechanical properties of soils are the core data for calculating of waste dump design, during studies it is important to point out that this material can't be investigated in a similar way to natural soils, without the specifity of their production.

Using the example of Pechora processing plant it was shown that properties of coal processing wastes are determined by features of technological scheme. Moreover, the key point of physical and mechanical properties studies is coal slurry testing. It should be taken into account that nowadays the «dry» storage of coal slurry obtained after dehydration of the flotation concentrate is becoming more widespread.

In actual stresses for technogenic soils formed as a result of coal processing, the values of the angle of internal friction are close to those of parent rock, and cohesion is next to none. At the same time, the undrained strength of coal slurry is two times lower. Based on this, for separate storage waste piles design, it is recommended to use the strength characteristics for coal slurry obtained from the results of consolidated undrained tests.

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РУКОПИСИ, ДЕПОНИРОВАННЫЕ В ИЗДАТЕЛЬСТВЕ «ГОРНАЯ КНИГА»

МОДЕЛИРОВАНИЕ НАГРУЗОК В ПРИВОДЕ КОНУСНОЙ ДРОБИЛКИ

(№ 1261/12-22 от 17.10.2022; 9 с.)

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Проведено моделирование нагрузок в приводе конусной дробилки (КД) с целью разработки математических моделей работы предохранительных устройств, предназначенных для защиты привода и элементов КД от динамических высокоинтенсивных нагрузок, возникающих при дроблении материалов и перегрузок, вызванных, в основном, попаданием недробимого предмета в зону дробления. Использованы статистические данные изменения мощности двигателей КД в процессе работы, собранные на Стойленском ГОКе. Анализ полученных данных позволил определить характерные изменения нагрузки на привод КД на разных этапах ее работы: холостом ходе, загрузке материала и дроблении материала. На базе собранных данных и их анализа построены математические модели изменения нагрузок в аналитическом виде и в программном модуле Matlab Simulink.

Ключевые слова: конусная дробилка, привод, математическое моделирование, приведенный момент инерции, динамические нагрузки, измельчение горной породы, зона дробления, предохранительные устройства, модернизация дробилок.

SIMULATION OF LOADS IN THE DRIVE OF A CONE CRUSHER

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The purpose of the work is to simulate loads in the cone crusher drive. This will allow the development of mathematical models of the operation of safety devices designed to protect the drive and elements of the cone crusher from dynamic high-intensity loads that occur during crushing of materials and overloads caused mainly by the ingress of a non-crushable object into the crushing zone. The paper uses statistical data on changes in the power of cone crusher engines during operation, collected at the Stoilensky mining and processing plant. The analysis of the obtained data made it possible to determine the characteristic changes in the load on the drive of the cone crusher at different stages of its operation: idling, loading the material and crushing the material. On the basis of the collected data and their analysis, mathematical models of load changes were built in an analytical form and in the Matlab Simulink software module.

Key words: cone crusher, drive unit, math modeling, reduced moment of inertia, dynamic loads, crushing of rock, crushing zone, safety devices, crusher upgrades.