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Strength and deformation characteristics of ash and slag mixture

Прочностные и деформационные характеристики золошлаковой смеси

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Abstract. Burning of coal and brown coals at thermal power plants (TPP) is the main method of generating electric and heat energy in the Russian Federation. Inasmuch as a result of coal combustion a considerable amount of waste is produced (up to 50% of the whole mass of base coal) the quantity of the gained ash slag in a landfill is measured with hundreds of millions of tons. Insufficient level of knowledge about strength and deformation properties of these artificially-produced soils for building motor roads' roadbeds and embankments substantially limits the scope of using the ASM in the Russian Federation. In this connection, the purpose of the research is to study a complex of the ASM's engineering properties for evaluating its use as a soil material for building embankments of motor roads' roadbeds and leveling operations. In the frames of the research, there have been tested the ASM samples, obtained from burning Ekibastuz coal in boilers with dry ash removal. Samples were made with different density and humidity. For each density value, there were determined the modulus of deformation and the elastic modulus. The authors have determined the values of the angle of internal friction and specific cohesion of the ASM depending on the moisture and normal pressure. Consolidated and drained tests in triaxial compression devices have allowed to determine the values of the secant elastic modulusand the Poisson's ratio of the ASM's with different density. As a result, it was found that an increase in the ASM's density significantly increases the elastic and deformation modulus, the angle of internal friction, and the cohesion of this artificially-produced soil. However, after a certain degree of compaction, the cohesion value begins to decrease. Increasing the moisture content of the ASM samples decreases the modulus of elasticity and general deformation, but it has an ambiguous effect on the angle of internal friction and cohesion.

Аннотация. Сжигание каменных и бурых углей на тепловых электростанциях (ТЭС, ТЭЦ) является основным способом генерации электрической и тепловой энергии в Российской Федерации. Поскольку в результате сгорания угля, образуется большое количество отходов (до 50% от массы исходного угла), объем накопленных в отвалах золошлаков, измеряется сотнями миллионов тонн. Недостаточный уровень знаний о прочностных и деформационных свойствах золошлаковых смесей (ЗШС) при сооружении земляного полотна автомобильных дорог и планировочных насыпей существенно ограничивает сферу применения ЗШС в РФ. В связи с этим, целью исследования является изучение комплекса инженерных свойств ЗШС для оценки их применения в качестве грунтового материала для возведения насыпей земляного полотна автомобильных дорог и вертикальных планировок. В рамках исследования проведены испытания образцов ЗШС от сжигания Экибастузских каменных углей в котлах с сухим шлакоудалением. Образцы изготавливали с различной плотностью и влажностью. Для каждого значения плотности определен модуль общей деформации на приборе компрессионного сжатия и модуль упругости по адаптированной методике рычажного пресса. Определены значения угла внутреннего трения и удельного сцепления ЗШС в зависимости от влажности и нормального давления с применением метода одноплоскостного прямого (медленного) среза. Консолидированно-дренированные

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испытания в приборах трехосного сжатия позволили определить значения секущего модуля упругости и коэффициента Пуассона при значениях плотности. В результате установлено, что увеличение плотности ЗШС существенно повышает модуль упругости и деформации, угол внутреннего трения и сцепление этого техногенного грунта. Однако после определенной степени уплотнения начинается снижение величины сцепления. Увеличение влажности образцов ЗШС понижает модуль упругости и общей деформации, но имеет неоднозначное влияние на угол внутреннего трения и сцепление.

Introduction

The vast majority of thermal power plants (TPP) in the Siberian and Far Eastern Federal Districts, some TPP in the European part of Russia are coal and brown coal-fired and more over, this tendency will have been sustaining for decades. From 10 % to 50 % of ash and slag wastes (ASW) are formed, including finely dispersed fly ash and ash-and-slag mixture (ASM), when burning each ton of coal. Ash and slag are jointly transported to ash dumps, forming the ASM. Almost 1.6 billion tons of the ASM have been accumulated on the territory of the Russian Federation. Only in the city of Omsk, about 73 million tons of the ASM have been accumulated and this figure increases by an additional 1.6 million tons annually.

But another problem is escalating in cosmopolitan cities: hundreds of millions of cubic meters of soil are required to construct an earth roadbed, a layout road embankment, to correct in arable and highly cost rural lands.

The use of the ASW is possible in many industries. This is production of rare-earth elements, creation of composites using fly ash, soil melioration, production of ceramic products and bricks, catalysis and, of course, in the construction industry [1–3]. Among the listed methods of recycling, the large-tonnage use of the ASM for building embankments is the most prospective since it allows solving both problems mentioned above with low additional cost.

Publications [4–8] reflect studies confirming the possibility of building motor roads’ embankments of the ASM. The main obstacle, hampering the full-scale use of the ASM, is insufficient knowledge base of their physical and mechanical properties, strength and deformation characteristics when changing humidity and density for designing engineering structures.

Studies of the fly ash’s mechanical properties abroad were carried out in 1972 by A.M. DiGioia and W.L. Nuzzo. During experiments, they conducted tests on direct cut and triaxial compression devices at different dry soil densities (from 60 to 80 pounds per cubic foot). The influence of vibrational loads of different frequencies on the ash compactibility was also investigated. However, these studies were typical not for dump ash and slag, but for the fly ash of western Pennsylvania. In addition, the study did not investigate the influence of moisture on the material’s properties [9].

The studies of Gray and Lin (1972) focus on the dependence of the particles’ shape, granulometric and chemical composition on the change of the specific weight of coal ash and its effect on strength characteristics of the material. The results of this researching cannot be fully used widespread because the ash from Michigan state was tasted which has much higher concentration of free lime than in inert ash of Russia [10]. Like Gray and Lin, B. Indraratna et al. (1990) in their paper [11] studied granulometric and mineralogical compositions, pozzolanic properties, compactibility and strength characteristics of C class ashes, selected from the Mae Moh power plant in northern Thailand.

In our experiments we have taken into consideration the researching by J.P. Martin [12] for fly ash of F class (non-cement) for evaluating of their use in a road embankment. The article evaluates the shear strength, compressibility, water-permeability and compactibility of the ASM in comparison with earlier works of other authors.

Singh and Panda (1996), having tested the strength characteristics on freshly compacted samples with different moisture, concluded, that the main part of the shear resistance is due to the angle of shear resistance [13].

The justification of stability for a road embankment which was made from ASM was made by R. Ossowski и K. Gwizdala [14] on the basis of the results of monitoring of an experimental road embankment subject to flooding. And also the parameters for these materials were taken from the results of their coworkers` researchings by Dredg Dikes, L. Balochowski Z. Sikora [15], and the rest – from the work by Ossowski и Sikora[16].

N.S. Pandian did research of ASM, clinker and flue ash under various conditions using three-axis compression. He considers that cohesion in ASM appears only in thick and humid mixture and disappears at water saturation or destruction of compact structure [17]. The results of sample testing with various ash combination and clinker are also displayed in the article by B. Kim et al. [18].

S.K. Pal and A. Ghost investigated the shear strength of the ASM samples, selected from nine TPP. The tests were carried out in triaxial compression devices according to the scheme of unconsolidated-undrained test [19]. The strength characteristics of the ASM in three-axis compression devices were also evaluated by Jakka et al. In these experiments, the ASM from three different sources have been tested in a friable and compacted state, which makes it impossible to predict the roadbed's stability under real operating conditions [20].

The work of S.K. Tiwari reflects the influence of water saturation of samples, designed in a laboratory, on their strength characteristics. The author has stated that the ASM's strength did not decrease to zero as in Pandian's experiments [21].

Studies of the physical and mechanical properties of the ASW and directions of their effective utilization have been intensively developed in Russia in the 1970–80s. Complex studies of ash and slag, conducted in the SouzDorNii, SibADI, Giprodornia, and the scientific centers of Belarus, Ukraine, Kazakhstan and Uzbekistan are reflected in the construction standards VSN 185-75. The requirements for the ASM for building a roadbed in this first document were limited only to the amount of frost heaving. The calculated strength and deformation parameters of the ASM are absent there.

In 1978 the article [22] was published in which V.A. Melentjev and others summarized the considerable amount of information about the properties of ASM of various CHPs. This is review paper which poorly takes into account the problems of using the ASM as artificially-produced soils.

Information on the ASM mechanical properties, depending on the moisture and porosity of this material, is presented in the work of P.Y. Dyakonov [23]. However, as in other authors` works, the limited amount of researching gives no opportunity to draw a conclusion upon the dependency for different conditions of earth roadbed maintenance.

Specialists from TSUAB, M.V. Balyura and V.V. Fursov , have analyzed the physical and mechanical properties of the ASM from the dumps of the Tomsk state district power plant (SDPP)-2, Severskaya TPP, Kemerovskaya TPP, Novokemerovskaya TPP [8,24]. These studies had a dotted character, without an analysis of cause-effect relationships. Therefore, it is impossible to determine reliable calculated parameters for designing embankments of the ASM on their basis.

Some strength properties of the ASM from the dump of the Kashirskaya SDPP - 4, which we used to calculate the stability of high embankments at the traffic junction near Kashira, Moscow Region, were investigated in the laboratory of the geological department of the Moscow State University [6].

The researching of ASM as man-made soils has been conducted in SibADI since 1973. These data and also some results of other researching in the Russian Federation and abroad were reflected in the road construction standard (218.2.031-2013) which is the principal document regulating the use of ASM in road construction of the Russian Federation nowadays. The calculating rates of durability and deformation figures, shown in the road construction standard have been deliberately underestimated because of the limited data during the development of this document. Therefore, when designing the ASM embankments only on the basis of the data from this document, a significant and sometimes unreasonably inflated margin of safety is possible.

Attempts to use foreign and domestic data on the strength and deformation parameters of the ASM during the elaboration of the above mentioned normative and guidance document have failed to give positive results due to a number of reasons:

- the majority of publications do not contain the necessary information on the methods for determining the indicators that interest us;
- methods of the ASM testing are so diverse that they often do not allow to compare the results obtained;
- the majority of publications do not reflect the entire range of the ASM's mechanical properties in the range of possible impact of natural factors, that change during the operation of motor roads in the Russian Federation;
- all mechanical properties of ASM depend on technique of burning coal and his genesis and for coal ash which was formed after combustion Ekibastuz coal similar research was not carried out;

– the authors of some publications do not give specific data on test results.

Therefore, the purpose of the research is to study a complex of the ASM’s engineering properties for assessing their use as a soil material for building embankments of motor roads’ roadbeds and leveling operations.

Methods

In the frames of the research, there was prepared a test program, which included a series of one-factor experiments. The choice of experimental conditions reflected the most probable embankments’ states in the process of their operation throughout the life cycle. The research program is presented in the Table 1.

Table 1. Test program

Series number	Changing parameter of the ASM	Range of change	Value of unchangeable parameter	Purpose of a series of experiments
1	Density of a maximum dry density	90 %–105 %	optimal moisture	to determine the regularities of changing the ASM mechanical properties depending on moisture and compaction degree
2	moisture	12 %–33 % (total saturation)	MDD – 95 %	

Before producing the samples, the value of maximum dry soil’s density and optimal moisture of the ASM were determined. For these purposes, there was used a form of a large device for standard compaction of the SoyuzDorNii design, which is an analogue of the testing form by Proctor’s method.

Research of strength characteristics of the ASM was performed on the direct cut devices PSG-3M in accordance with the technique, similar to the method of ASTM D3080. Samples of the ASM were formed in a large device for standard compaction, varying the degree of compaction by the number of weight impacts. When achieving the required value of density, a ring, with 40 cm^2 cross-section, was pressed into the ASM for the direct cut test in the PSG-3M device.

The tests were carried out according to the scheme of consolidated and drained cut of artificial composition’s samples. The experiments were carried out by successive shearing of the samples at three vertical load stages of 100, 200, 300 kPa. The samples’ manufacture was originally conducted with the moisture of 33 % (maximum water saturation). The prepared sample at the optimum moisture was placed in a direct cut device, a load of 50 kPa was applied to it, after that 10 ml of water was poured into the top part until it appeared from the lower part of the sample.

The determination of the ASM’s deformation modulus was carried out on compression devices KPr-1M. Samples were made in a manner similar to the method of manufacturing samples for direct cut tests. After manufacture, circular samples with a diameter of 87.4 mm and a height of 25 mm were placed in a compression device (not allowing lateral expansion), both sides were interleaved with filter paper, indicators of vertical displacement were installed and pressure stages of 100, 200, 300 kPa were successively applied. After each loading, vertical settling was expected and fixed. Upon reaching the 300 kPa stage and stabilizing the settling, a stepped unloading of the sample was carried out with the control of elastic deformations. After the load was removed, the load was repeated similarly to one at the beginning of the experiment. Abroad, a similar test method is described in ASTM D 2435-04 and is a remote analogue of compression tests.

The dependence of the ASM’s elastic modulus on the degree of moisture and compaction was determined using the method of the lever press. The compaction of the sample in a form was implemented with a weight from a large standard compaction device. The form for testing had a height of 150 mm and internal diameter of 150 mm. Since the diameter of the form was bigger than the diameter of the anvil, the soil was compacted layer by layer, moving the anvil according to the scheme, used in “A” test of Proctor's method.

The soil was compacted into three layers, each layer was compacted with a number of impacts predetermined during pre-compaction. The finished sample was cut up to the brims of the form, a stamp with a diameter of 50 mm was placed on the center of the sample’s surface. Further, a stepwise load application was carried out through a stamp of 0 to 500 kPa at 100 kPa interval. After stabilizing the settlings at each stage, the stamp’s settling was fixed by means of two time-type sensors. Stepwise unloading of the sample was carried out with the interval of 100 kPa with the control of deformation restoration. Then the sample was loaded again. If the branch of the compression curve of unloading and secondary loading coincided, the tests were terminated. The closest analogue of this method in foreign practice is the method for determining CBR, described in ASTM D1883-16 (this standard uses only the primary loading branch and the kinematic loading scheme).

Testing of the ASM for triaxial compression was carried in triaxial compression devices ASIS. The samples production was carried out by forming the soil's monolith in a large device for standard compaction and subsequent plugging of a cylinder into the massif (Fig. 1a). Density and moisture control was carried out by weighing a form, filled with soil, and sampling for determining moisture.

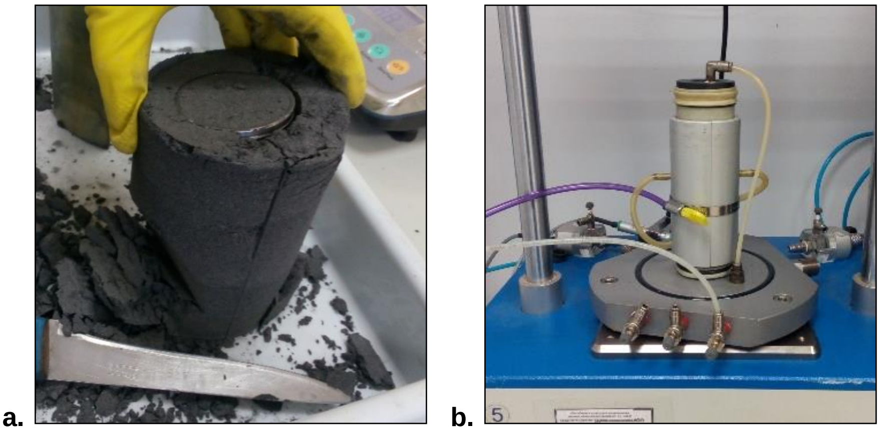

Figure 1. Testing of the ASM in the triaxial compression device:
a – a cylinder plugged into the massif; b – a rubber-covered sample

The extracted sample, with the diameter of 50 mm and the height of 100 mm was covered in a hermetically sealed rubber (Fig. 1b), then there was installed a camera of the device which was filled with distilled deaerated water and lateral pressure was fed. In the frames of the experiment, the tests were carried out only at the lateral pressure of 100 kPa, which was required to determine the Poisson's ratio and the secant elastic modulus, with a relatively low lateral pressure. Determination of characteristics was carried out on a consolidated and drained scheme, which is almost similar to ASTM D7181-11 tests.

Results and Discussion

The peculiarities of the ASM structure. The optimal moisture of the ASM and the maximum dry soil's density were determined before testing the samples (Fig. 2).

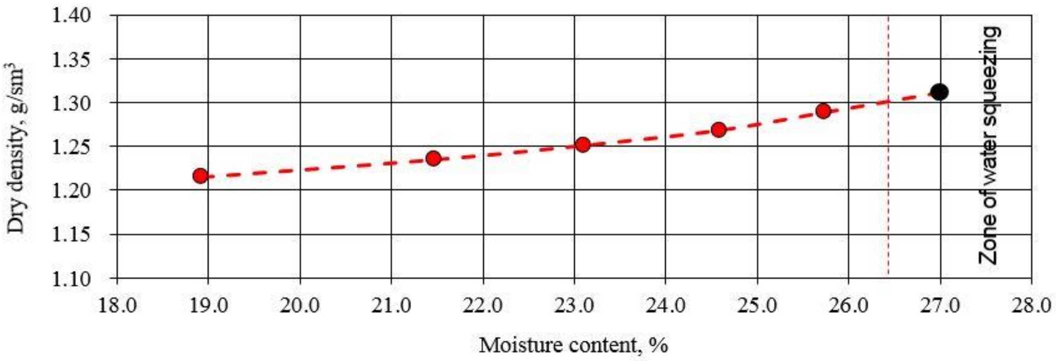

Figure 2. Dependence of the dry soil's density (the ASM) on moisture

The graph of standard compaction of the ASM usually does not have an extremum, characteristic for clay soils (similar data given in the works of Pandian, Jakka, Balachowski, Tiwary [12, 17, 19, 20]). As Singh et al. recommended, the concept of optimum moisture for this artificially-produced soil is assigned by the limiting value of the density to the zone of water squeezing [13].

The analysis of the curve in Figure 2 indicates that the change in the ASM's density indicator does not exceed 7 % with a change in moisture by 42 %, therefore, this artificially-produced soil has a wide interval of possible moisture for compaction. The value of optimal moisture for the ASM is twice and more times higher than the similar parameter for pulverscent sands and light sandy loams, although the granulometric composition of these natural soils and the ASM has similar features [7, 17]. The abnormally high values of water absorption of the ASM are explained by the peculiarities of their microstructure, that is confirmed by Kim at al [18].

Unlike most natural dispersed soils, the real value of the ASM's specific surface doesn't have direct relation with granulometric composition. Particles of the grinded "barren rock" of the soil (entered in coal) are subjected to the thermal effect, passing through the flame of a boiler unit, having the temperature of 1400-1600 C°. These particles undergo a stage of pyroplastic state with emitting a complex gaseous phase. Therefore, the ash particles have significant microporosity (Fig. 3, microphotographs are made in LLC "Institute of Applied Ecology and Hygiene").

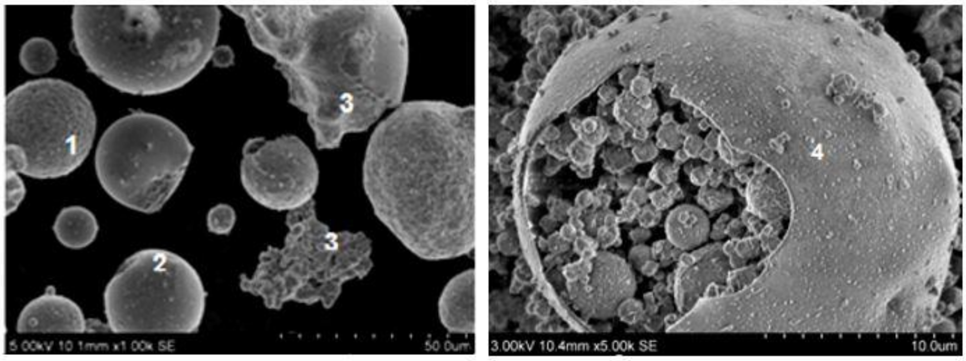

Figure 3. Morphological elements of ash: spheres with a rough and grumous surface (1); with a smooth and vitrified surface (2); fragments of particles and aggregates of irregular shape (3); pleurosphere with a broken shell (4)

According to our data, the specific surface of the ASM, determined by the standard air-permeability method, varies from 0.8 to 2.5 thousand cm^2/g (fly ash – up to 6.0 thousand cm^2/g), depending on the sampling site in ash dump. The presence of open and closed microporosity is the reason that the value of the actual specific surface of ash particles (determined by the method of low-temperature adsorption of nitrogen or desorption of argon) reaches 50,000 cm^2/g and more. In the work [25], Zabielska-Adamska gives a reference to studies that indicate the high adsorption capacity of the ASM, which is related to the value of the specific surface.

A significant value of the specific surface area of highly dispersed ash particles is the main reason for the abnormally high water retentivity of all ash and slag, whichis confirmed at the work of Huang [26]. The same reason explains the comparatively small value of the bulk density of the ASM, which usually varies from 0.8 to 1.3 g / cc. Although, the true density of vitreous substance of ash particles reaches 2.5-3.2 g /cc.

Strength parameters. The forces separation of soils shear strength on the forces of internal friction and cohesion is conditional. In the process of shear, it is impossible to purely separate elements, associated with the deformation of water films, overcoming the forces of molecular interaction, mutual blocking and mechanical engagement of particles. Consequently, it is not always possible to establish the exact mathematical dependencies of changing these parameters.

The generally accepted strength parameters of soils - the angle of internal friction φ and the specific cohesion c are not true in these engineering experiments, but the apparent cohesion and the angle of shear resistance, which have been determined by many researches in their works [11, 12, 17]. Nevertheless, these conditional values are accepted as the main criteria for calculating soil structures. The φ and c values are calculated by plotting a straight line with the best approximation to experimental points by the least squares method. Figure 4 shows the results of determining the angle of internal friction, specific cohesion and general shear resistance in the samples of the ASM, depending on the compaction coefficient.

It follows from the graphs that the density of the ASM has a significant effect on the strength characteristics of this artificially-produced soil. As Huang describes, with increasing density, the particles are increasingly getting closer, the number of contacts, jamming and blocking depth of separate particles is growing [26]. Thus, with increasing density, the angle of friction will be higher because of more jamming and blocking. The cohesion decreases with an increase of the ASM's compaction coefficient from 1.0 to 1.05. The similar effect is considered by Padam in his thesis. In his experiments, when the work on compaction increases the cohesion value also decreases [27]. Presumably, this is explained by the destruction of large porous aggregates of the ASM, occurring during compaction, which has been described earlier by Kim et al. and observed by us (Figure 5).

When the work on compaction increases, the arising contact stresses destroy the mechanical linkages of the ASM's particles, as it happens in sands and is described by Roberts и De Souza [28], and reduce this component of resistance to shear. At the same time, there is maintained the cohesion caused by the interaction of water films around the particles and described by Martin et al. [12].

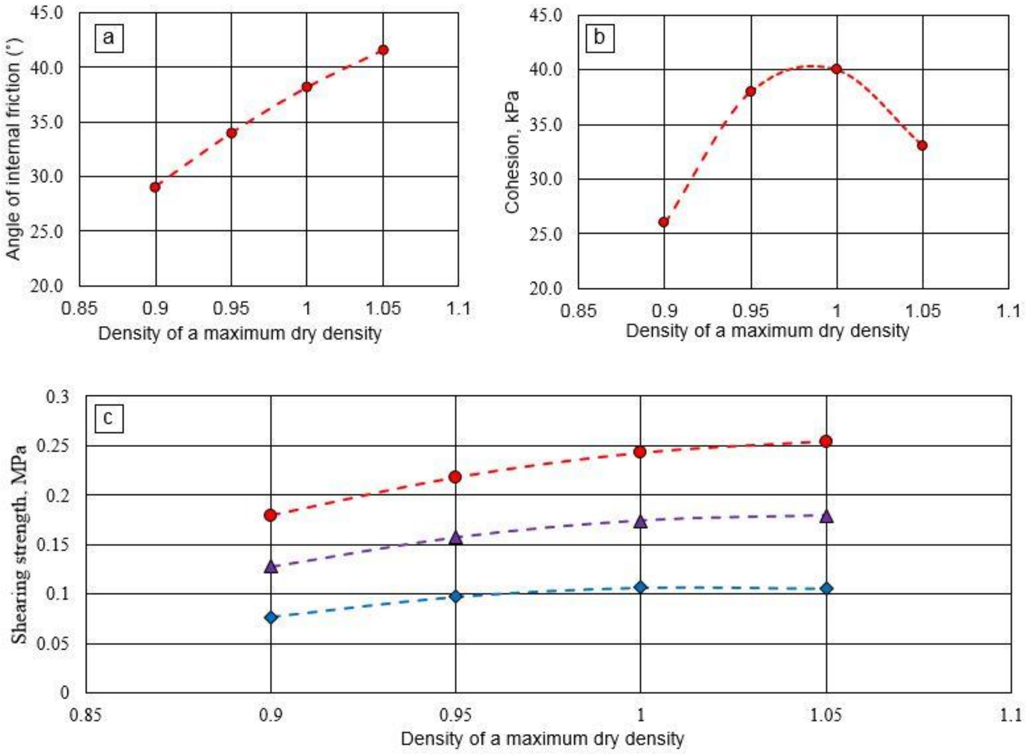

Figure 4. Dependences of the angle of internal friction (a), specific cohesion (b) and shear strength (c) from the compaction coefficient. Shear strength at normal pressure: ◆–100 kPa; ▲– 200 kPa; ■– 300 kPa

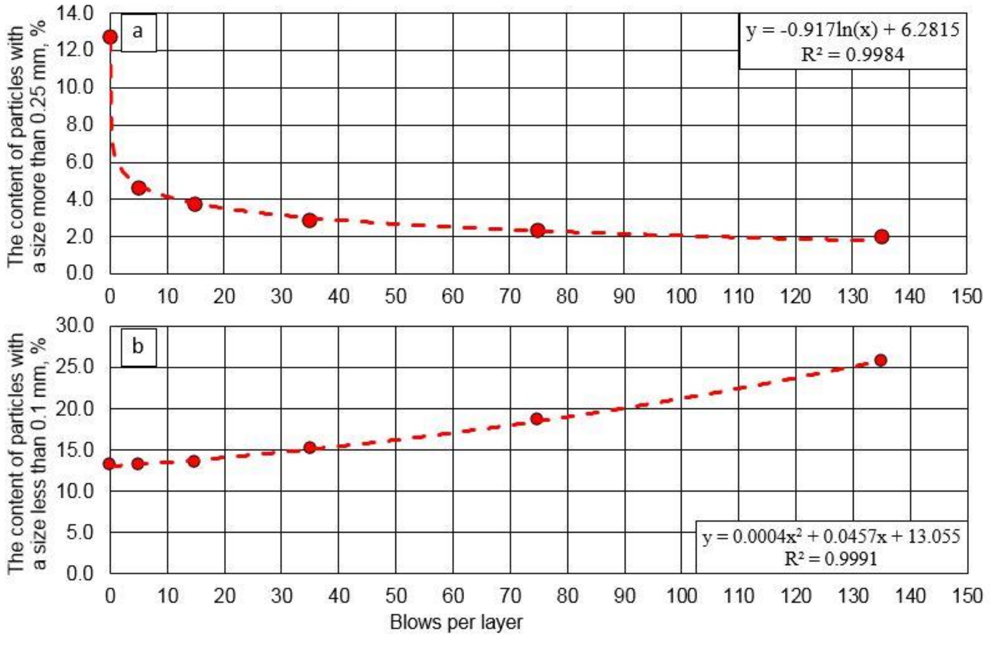

Figure 5. Content change of the fraction with the size over 0.25 mm (a) and less than 0.1 mm (b) during the ASM compaction

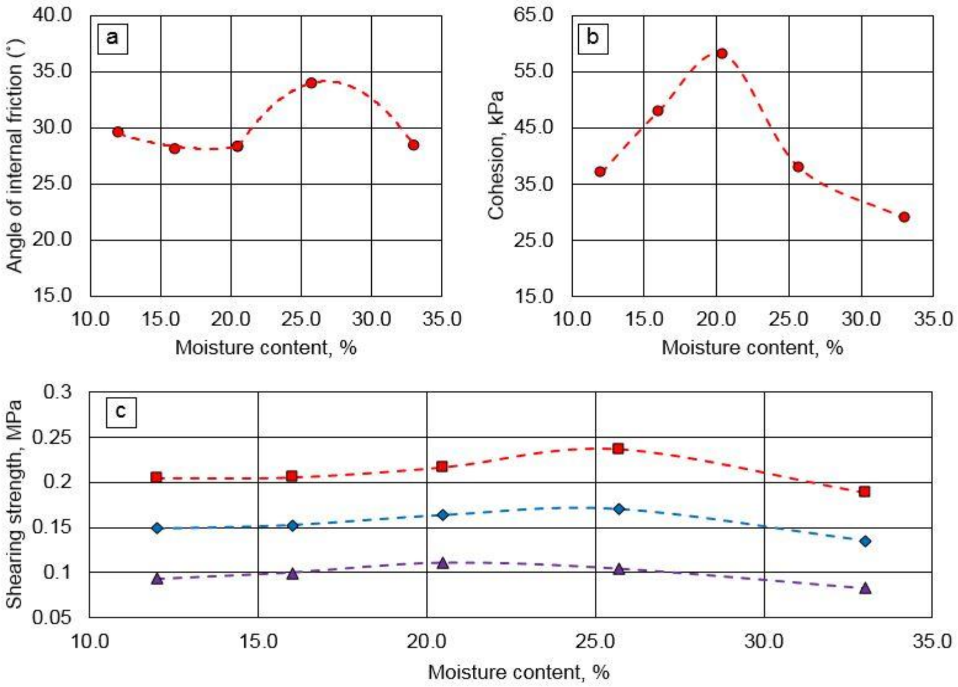

Figure 6. Dependences of the angle of internal friction (a), cohesion (b) and shear strength (c) on moisture. Shear strength at normal pressure: ▲–100 kPa, ◆ – 200 kPa, ■– 300 kPa

The tests of the ASM with different moisture were carried out at 0.95 compaction coefficient, which usually corresponds to the so-called common soil density. At the same time, the moisture of a roadbed can vary over a life cycle within a wide range. The maximum moisture value of 33 % corresponds to the total water saturation of the ASM at a normal pressure of 100 kPa. Figure 6 shows the results of determining the ASM strength characteristics depending on its moisture.

During multiple testing of samples with different moisture, there have been obtained non-standard dependences of changing the angle of internal friction on moisture. As in the experiments of Lamb et al. the maximum shear strength was obtained at optimal moisture of the ASM [29]. On the whole, it has been determined that shearing stresses, necessary for the destruction of the sample, increase with a rise of moisture up to the optimal value.

It is known from the work of DiGioia and Nuzzo that the most part of shear strength the ASM has in wet condition [9]. Strengthening of water films' confining force when the moisture increases is apparently explains the increase of cohesion with the same degree of compaction. After the appearance of redundant moisture (20.5 %), the cohesion decreases. At total saturation the value of cohesion and general shear resistance was minimal, as in Pandian's experiments [17]. The values' intervalsof the angle of internal friction and cohesion do not fall outside the limits, obtained by Pal et al. [19].

Besides two strength parameters in calculations using software complexes for modeling, based on finite elements method (Mohr-Coulomb, Drucker-Prager, Herdering soil), an additional parameter, the dilatancy angle (ψ) [30-33], is introduced. For the approximate dilatancy angle determination there is used an empirical dependence which links this parameter to the angle of internal friction: ψ ≈ φ – 30°. At a value of φ less than 30°, the dilatancy angle is equated to zero [34].

Strength parameters of the ASM, determined by the results of the research, are presented in the Table 2.

Table 2. Strength parameters of the ASM

Parameters	Influencing factors and their values								
	Density of a maximum dry density				Moisture, % by mass				
	0.90	0.95	1.00	1.05	12.0	16.0	20.5	25.7	33.0
Angle of internal friction, degree	29.1 26.4	34.0 29.8	38.2 35.8	41.6 40.4	29.6 27.7	28.2 26.5	28.3 26.1	34.0 29.8	28.4 24.9
Specific cohesion, kPa	26 24	38 33	40 37	33 32	37 35	48 45	58 54	38 33	29 26
Dilatancy angle, degree	0	4	8.2	10.2	0	0	0	4	0
Note: standard value of the parameter is above the line, calculated value of the parameter is under the line, considering processing by methods of mathematical statistics.									

The strength parameters of the ASM, determined by us, have been compared with natural soils prevailing in the SFD (numerical values of the natural soil parameters are not presented due to limitations in the volume of publication). A comparison has showed that the ASM is an artificially-produced soil, which is not inferior in strength parameters to natural soils. Moreover, the ASM is superior to the most part of natural sediments on shear strength.

Deformation parameters. The main characteristics of the soils compressibility are the general deformation modulus $E_{general}$, the elastic modulus E and the coefficient of lateral expansion (Poisson's ratio) *v*. Both moduli are parameters of the stress diagram – deformation, and as a rough approximation, represent the proportionality coefficient of this dependence at the required stress level. The differences are that the elastic modulus describes only elastic (restoring) deformations, and the general deformation modulus – both elastic and plastic.

Figure 7 shows the results of determining deformation modulus of the ASM samples in the compression device, depending on the compaction coefficient and moisture content of this material.

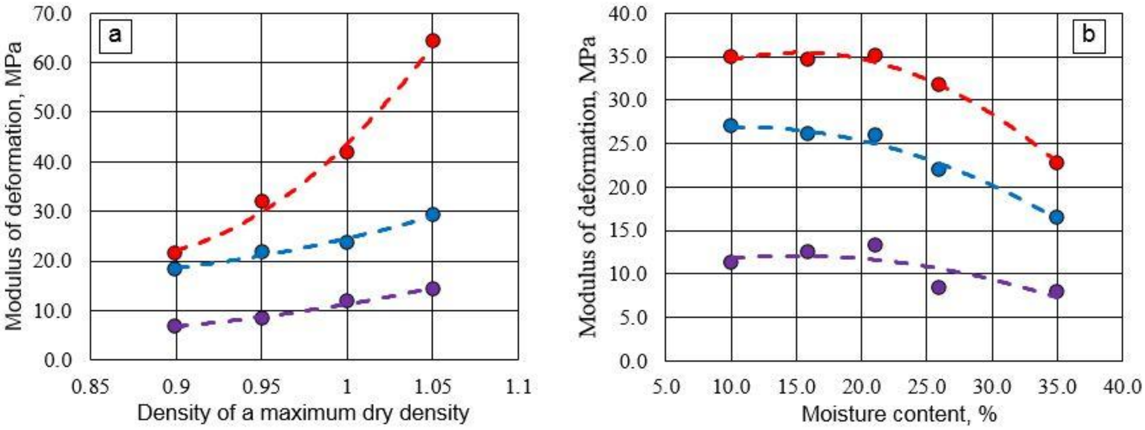

Figure 7. Dependence of the deformation modulus of the ASM on the compaction coefficient (a) and moisture (b), at normal pressure: ▲–100 kPa; ◆ – 200 kPa; ■– 300 kPA

The graph (Fig. 7a) shows a significant growth of the deformation modulus at increase of the density of a soil skeleton. A quick increase of the modulus under the conditions of the compression device at the pressure of 300 kPa is connected with a state of soil in which there is no particles repacking due to slip of aggregates, and the settling can be explained by the destruction of particles tightly clamped in their positions. Such changes in the ASM's structure have been described earlier by Kim at al. [18].

The results of the research (Fig. 7b) indicate a decrease of the constrained modulus of deformation with an increase of the ASM moisture. When increasing the moisture, the water expands the particles, which weakens the structure of the ASM. The results of testing the ASM, considering the statistical processing, are shown in the Table 3.

Table 3. The modulus of the ASM deformation

The deformation modulus at normal pressure	Influencing factors and their values								
	Density of a maximum dry density				Moisture, % by mass				
	0.90	0.95	1.00	1.05	10.0	16.0	20.5	25.7	33.0
100 kPa	6.79 5.93	8.46 7.16	11.86 8.30	14.25 13.74	11.35 10.95	12.52 11.99	13.28 12.33	8.46 7.16	7.81 6.22
200 kPa	18.30 17.50	20.92 17.89	23.75 18.93	29.22 27.64	26.86 25.14	26.10 25.13	25.91 24.94	20.92 17.89	16.44 15.88
300 kPA	21.53 19.76	31.66 27.14	41.81 38.24	64.11 63.84	34.92 32.85	34.55 32.53	35.04 33.30	31.66 26.15	22.73 22.05
Note: standard value of the parameter is above the line, calculated value of the parameter is under the line, considering processing using the methods of mathematical statistics.									

Determination of the elastic modulus was carried out with the replacement of the lever press for the universal machine AL-7000LA10, which makes it possible to apply a stepped static load to the deformable sample. The regularities of changing values of the elastic modulus of the ASM depending on the compaction coefficient are shown in Figure 8a, and on the moisture – in Figure 8b.

The method of testing stipulated the soil behavior under normal compaction. In the process of compaction, a more compact packing of particles occurred due to local shears and slipping of smaller particles into the soil pores, which further has strengthened its skeleton. In the compacted state the soil works in the stage of reversible deformations and the shears are practically attenuated. The higher the compaction coefficient, the more compact structure of the soil skeleton is formed in the sample, which means that the load distributes to a bigger number of contact points. Besides the increase the structural strength, it reduces the overall deformability of the material; this has determined the growth of the elastic modulus [20].

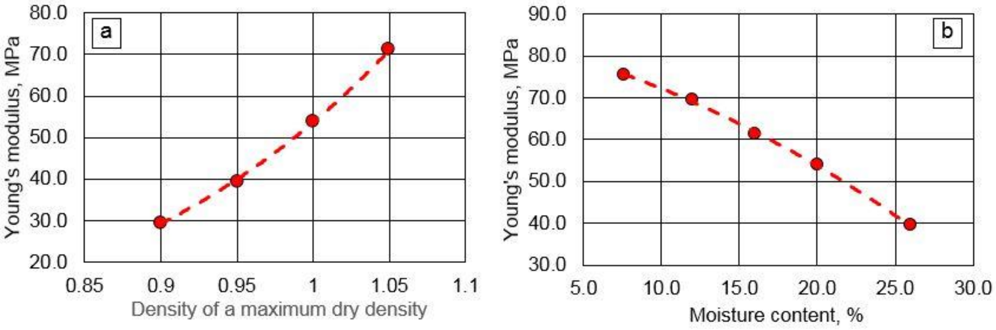

Figure 8. Dependence of the elastic modulus of the ASM on the compaction coefficient (a) and moisture (b)

In contrast to compaction, an increase of soil moisture causes decompression of the skeleton. The higher the moisture, the stronger the negative effect, up to the full moisture capacity at which the effect of particles weighing is created. The direct contacts of the ASM particles decrease, and the existing neutral stress finally decompresses the soil.

It is difficult to compare the results of studies on determining the compression and elastic moduli due to the absence of this method in foreign studies of the ASM. However, there are studies in which the elastic modulus is related to the Californiabearing ratio (CBR) [35]. It is known, that the elastic and deformation moduli can be related by means of the linear dependence [36].

Toth et al. [37] writes that the CBR value of water-saturated samples varies from 6.8 % to 13.5 %, while unsaturated - from 10.8 % to 15.4 %. This indicates a significant decrease in the bearing capacity for the water saturation of ash and slag, which we see in our experiments. Pandian investigated the CBR of waste slag, fly ash and fuel slag with water saturation and without saturation. In his experiments, there is also noted a decrease in the bearing capacity up to two times of waste slag with water saturation, which agrees with our experiments at different moisture content of the ASM [17].

In the framework of the study, we compared the basic deformation parameter - deformation modulus of the ASM with characteristics of natural soils. A comparison showed that the ASM also is not inferior to most natural clay soils in the deformation modulus’s value, competing with sandy soils.

The results of our researching show that ASM complies to the medium-formed soils (according to the Russian classification), whereas the results of Martin et al`s experiments display that it was classified as low-compressible (with high stiffness) soil [12].

Tests on triaxial compression devices were carried out on a consolidated and drained scheme, in the "A" type stabilometer at the lateral pressure of 100 kPa. Deformations, chamber pressure and pore pressure were fixed by sensors of the ASIS complex. The vertical pressure stages and the deformation stabilization’s time were chosen as for pulverscent sands.

In the frames of stabilometric tests, there was determined a secant modulus of deformation which is necessary indicator for soils modeling using the Hardening Soil model. This indicator is a modulus of soil deformation at half of value of the stress deviator at the moment of destruction [34]. The test results are shown in the Table 4.

Table 4. Results of determining a secant elastic modulus of the ASM

Compaction coefficient	0.90	0.95	1.00
The secant elastic modulus, E_{50}, MPa	11.26	13.23	13.89

Besides the secant modulus of deformation, there was determined the deformation modulus at different value of the vertical pressure (Fig. 9).

In contrast to the method for determining the compression modulus of deformation in the triaxial compression device, the reaction pressure from the lateral surfaces does not increase with a growth of normal pressure, as the soil sample can be expanded. Therefore, with the increase of pressure on the sample, the soil structure is rebuilt, new local shears occur, until there is reached a state of soil's fluidity and its subsequent destruction.

The character of the samples destruction with different compaction also differs. When the compaction coefficient is less than 1.0, the deformation occurs with destruction in the form of a "barrel", and more compact samples are destroyed otherwise - in the form of a shear plane. This indicates a stronger, but brittle structure whose properties are determined, apparently, by the mechanical contacts of the particles [38]. Despite the brittle nature of the destruction, the lateral expansion of the sample to the stage of destruction occurs more intensively. Probably, this is due to the large pore sizes in the structure of the less compacted ASM. These pores are filled at local shears above all, which prevents intensive lateral expansion.

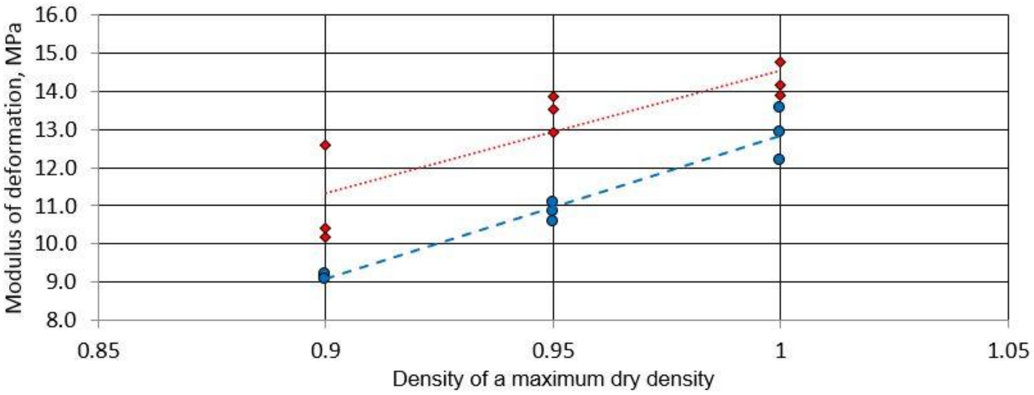

Figure 9. Dependences of the deformation modulus of the ASM on the compaction coefficient at the pressure of: ◆–100 kPa; ●– 200 kPa

The value of the Poisson's ratio for the ASM is determined experimentally and is presented in the Table 5.

Table 5. Results of determining Poisson's ratio

Compaction coefficient	0.90	0.95	1.00
Poisson's ratio	0.094	0.133	0.167

Conclusions

The conducted studies have shown that the ASM is an artificially-produced soil with specific mechanical properties. Thus, the graph of the standard ASM’s compaction shows the absence of clear maxima on the curve, which is typical for sandy soils. At the same time, according to the parameters of mechanical properties and regularities of their variation, the ASM does not refer to non-cohesive soils, as it has been previously thought, but more corresponds to sandy loams or pulverscent sands.

The growth of the ASM skeleton’s density causes an increase of the massif’s strength only until the maximum density of the dry soil is reached and almost does not increase in future. Therefore, the overconsolidation of the ASM for the majority of geotechnical tasks is not advisable.

This artificially-produced soil is resistant to moisture. The shear strength of the ASM is maximal at the moisture close to the optimal, and even at the moisture, corresponding to the maximum moisture capacity, remains at a high level. The deformation parameters of the ASM depend on the density of this soil, and an increase in density by 1 % from MDD gives an increase in the elastic modulus from 2.7 %, and in the deformation modulus from 0.5 MPa to 2.8 MPa, depending on the vertical load. The ASM’s moisture influences the deformation parameters a bit less than the density, with an increase in moisture by 1 % the elastic modulus decreases by an average of 1.9 MPa and the deformation modulus by 0.5 MPa. At the moisture of total saturation, the elastic and deformation moduli have the smallest values.

Comparison of the deformation moduli of natural soils and the ASM shows, that this artificially-produced soil is not inferior on this parameter to natural clay andpulverescent soils and competes with sandy soils.

As a result of the tests it has been found that the ASM after Ekibastuz coal combustion is a ground building material with deformation and strength characteristics that are quite suitable for building a roadbed of motor roads, as well as installing foundations of buildings and structures of any importance class.

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