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Influence of composition and density of slags on their strength and filtration parameters

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The results of complex studies of the physical and mechanical properties of metallurgical slags are presented. The parameters of non-granular (MSNG) and granular (MSG) varieties of metallurgical slags were comprehensively analyzed. It was established that the differences in the technologies of their production determine the difference in the values of both the granulometric composition and the indicators of physical, strength and filtration characteristics. The direct dependence of strength and filtration indicators on the type of slags, in particular, mainly on the degree of their compaction and to a lesser extent on their moisture content, was revealed. It has been proven that an increase in density from loose to extremely dense causes an increase in the specific adhesion three times in non-granulated slags and two times in granulated slags.

Keywords: granulated and non-granular metallurgical slags, granulometric composition, physical indicators, shear test, strength characteristics, filtering parameters.

Вплив складу й щільності шлаків на їх параметри міцності й фільтрації

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Подано результати комплексних досліджень фізичних і механічних властивостей металургійних шлаків. Відзначено, що не гранульовані металургійні шлаки (МШНГ) виходять шляхом простого відсипання у відвали чи вироблені кар'єри, а гранульовані металургійні шлаки (МШГ) зазнають особливого технологічного процесу, пов'язаного з додатковою обробкою форми їх частинок або компонентів. Всебічно проаналізовано параметри не гранульованих і гранульованих різновидів металургійних шлаків. Встановлено, що відмінності у технологіях їх отримання визначають різницю величин як гранулометричного складу, так і показників фізичних, міцнісних та фільтраційних характеристик. Встановлено, що саме неоднорідність частинок і, особливо їх розміри та форма, викликали необхідність розробки, виготовлення і застосування у випробуваннях приладів, що враховують перелічені фактори. При цьому для забезпечення необхідної достовірності результатів випробування проводили з триразовою повторюваністю. Модифікована методика випробувань відповідала вимогам норм. Кількісні результати випробувань представлено у формі таблиць для можливості їх інтерпретації у будь-якій прийнятній параметричній варіації. Виявлено пряму залежність показників міцності та фільтрації від виду шлаків, зокрема, переважно від ступеня їх ущільнення та меншою мірою – від їх вологості. Доведено, що зростання щільності від пухкої до гранично щільної викликає збільшення питомого зчеплення в три рази у не гранульованих і в два рази – у гранульованих шлаків. При цьому кут внутрішнього тертя збільшується, відповідно, на 7% та 30%, а коефіцієнт фільтрації, аналогічно, зменшується у 6,8 та 4,8 разів. Узагальнено результати комплексних досліджень міцнісних і фільтраційних властивостей шлаків, що дозволило обґрунтувати можливість їх широкого застосування як матеріалу для штучних масивів й основ, так і елементів, що фільтрують, на об'єктах промислового та цивільного будівництва.

Ключові слова: гранульовані та не гранульовані металургійні шлаки, гранулометричний склад, фізичні показники, випробування на зрушення, характеристики міцності, фільтраційні параметри.

Introduction

One of the current and promising areas of modern geotechnics is the use of various industrial wastes for the device (most often layer-by-layer dumping with compaction) of bulk massifs for objects of various purposes and artificial foundations (such as sand and soil cushions) of the foundations of buildings and structures [1 - 3].

Thus, the utilizable wastes of metallurgical production are represented with blast-furnace, waste and other types of slags.

Review of the research sources and publications

For the effective use of any type of recyclable industrial waste in the construction of artificial massifs and foundations, geotechnical engineers need experimental data on their physical and mechanical characteristics, by analogy with natural soils [1 - 8].

In a number of Ukraine regions, where sand is a scarce material (in particular, river and sea ports of the Azov Sea), the largest metallurgical plants located nearby continuously "produce" and accumulate waste in the form of slag.

The main volume of laboratory tests of these breeds was carried out in various organizations with the participation and under the direct scientific and technical guidance of prof. A.V. Shkola [9, 10].

Definition of unsolved aspects of the problem

However, in order to expand the regulatory framework for the use of metallurgical slags in geotechnics, it is necessary to improve the experimental assessment of the strength characteristics and filtration properties of such slags in order to justify the possibility of their use in the construction of artificial foundations.

Problem statement

Therefore, the task of this work is experimental laboratory studies of the strength and filtration parameters of metallurgical slags in order to justify their use as artificial foundations and backfills for delays, as well as the installation of filtration elements when compacting soft soils in the form of wells, cuts and layers.

Basic material and results

The name of the varieties of metallurgical slag (MS) as a waste of the respective industries reflects the technological differences in the process of their production.

So, ordinary metallurgical slags are obtained by simple dumping into dumps or worked out quarries (Fig. 1,a).

Those slags that undergo a special technological process associated with additional processing of the shape of their particles or components are commonly called granular (Fig. 1,b).

The first slags received a clarifying explanation for the common name - non-granulated (MSNG), and the second - granulated (MSG).

a)

b)

Figure 1 – Varieties of metallurgical slags:
a – non-granulated; b – granular

The main qualitative and quantitative, as well as physical difference between these types of metallurgical slags is the range of variability in the forms and size of particles (granules), as elements of their composition in percentage terms.

The determination of the main physical characteristics of the granulometric composition of slags was carried out with a three-fold repeatability in full accordance with the current building codes [11], and their numerical parameters are given in Table 1.

According to the granulometric composition, the corresponding graphical dependencies were built and the degree of heterogeneity of Cu slags was determined by the reference criteria, the final values of which are given in Table. 2.

Qualitative and quantitative analysis of the granulometric composition shows that both types of slag, non-granulated and granulated, have significant heterogeneity and, most importantly, the presence of large particles, as a result of which they are classified as coarse-grained.

Table 1 – The granulometric composition of the studied slags

Non-granular metallurgical slags (SMNG)									
Diameters of grains, mm	< 15	< 10	< 7	< 5	< 3	< 2	< 1	< 0,5	< 0,25
%	100	98.7	96.5	92.7	77.4	53.4	6.6	3.0	0.3

Slags metallurgical granulated (SMG)						
Diameters of grains, mm	< 40	< 20	< 10	< 5	< 2,5	< 1,25
%	100	42.1	12.5	2.5	0.6	0.2

Table 2 – The coefficients of heterogeneity of the studied types of slag

Grain diameters in mm with a probability of 10% and 60%, respectively, d_{10} and d_{60} according to the particle size distribution curves and their inhomogeneity coefficients $C_u = d_{60}/d_{10}$			
Slags/diameter	d_{10}	d_{60}	C_u
SMG	1.3	2.3	1.77
SMNG	9	25	2.78

The previously performed complex of compression tests of the deformation properties of slags in the odometer confirmed the need to use a device that is structurally enlarged compared to the standard device, the dimensions of which allow taking into account and obtaining the adequacy of the experimental conditions and slag parameters.

Therefore, by analogy, shear tests, in view of the same obvious discrepancy between the sizes of typical receiving devices in the form of half rings and the sizes of slag granules, it was decided to carry out in a specially manufactured large-sized installation, structurally enlarged compared to the standard device VSV-25 Hydroproject.

Previously, to select the optimal ratio between the sizes (diameter) of large inclusions and the sizes of shear rings and, accordingly, samples, several series of trial or search tests were performed.

Based on the analysis of their results and taking into account the adequate ratio of the particle size of the slag particles of the essence of single-plane shear tests, the optimal dimensions of the semi-rings (samples) were selected: a diameter of 504 mm and a height of 200 mm, while the cut area was 2000 cm^2.

The maximum vertical and horizontal forces during the tests did not exceed 10 tf.

To determine the required and sufficient gap between the half-ring cages, which would not affect the final test results, several methodological series were carried out with a fixed gap in the intervals of 5...20 mm for SMNG and 10...40 mm for SMG.

A comparative analysis showed that the optimal gap between the half rings, which has practically no effect on the shear parameters and test results, can be taken equal to 20 mm without any special errors.

The mode of testing met the requirements of DSTU [12] as much as possible.

The only difference from the recommended test schedule was an increase of four and five times the shear rate, respectively, of granulated and non-granulated slags.

This condition satisfies the requirement of the standards to limit the total duration of the cut to no more than 10 minutes.

Finally, the optimal values of the displacements of the semi rings when the limiting shear stresses are reached are taken equal to 20 mm for SMNG slags, and 50 mm for SMG.

A total of 108 different tests were performed for SMG and SMNG in both air-dry and water-saturated conditions.

Each series included paired studies of the so-called twin samples at three additional densities D_0 = 0; 0.5; 1.0.

The corresponding values of bulk densities are characterized by the porosity coefficient *e* and were calculated by the expression

$$D_0 = (e_{max} - e_{nat.})/(e_{max} - e_{min}). \qquad (1)$$

The same expression, for the convenience of primary direct control of the density ρ of slags in the same states, can be interpreted as follows

$$D_0 = (1 - \rho^{\ min}{}_{/nat.})/(1 - \rho^{\ min}{}_{/max}), \qquad (2)$$

where $\rho^{\ min}{}_{/nat.} = \rho_{min}/_{nat.}$;
$\rho^{\ min}{}_{/max} = \rho_{min}/_{max}$.

The calculated averaged values ρ_{max} , ρ_{min} , and e_{max}, e_{min} are given in Table 3.

In calculations, during tests for e_{max} and e_{min} the experimental density values for SMNG and SMG were taken to be 2.76 g/sm^3 and 2.89 g/sm^3.

Table 4 and Table 5 show the results of ultimate shear strength τ_{max} and their average values τ_{cp} for both types of slags in air-dry and water-saturated states in the range of vertical sealing pressures of 0.5; 1.0 and 2.0 kg/sm^2 per sample.

Table 3 – Average values of the characteristics of both types of slag

Slags	ρ_{max} , g/sm^3	ρ_{min} , g/sm^3	e_{max}	e_{min}
SMG	1.55	1.20	1.30	0.78
SMNG	1.32	1.02	1.83	1.19

Table 4 – Results of shear tests of SMG slags under different water saturation conditions

ρ, kg/cm^2	D_0	Air dry condition				Water-saturated state			
		τ_{max} , kg/sm^2			$\tau_{cp.\ max}$, kg/sm^2	τ_{max} , kg/sm^2			$\tau_{cp.\ max}$, kg/sm^2
0,5	0	0,31	0,32	0,33	0,32	0,35	0,32	0,34	0,34
	0,5	0,50	0,52	0,54	0,52	0,46	0,38	0,54	0,46
	1,0	0,64	0,66	0,68	0,66	0,77	0,74	0,71	0,72
1,0	0	0,63	0,66	0,69	0,66	0,63	0,60	0,62	0,62
	0,5	0,94	0,83	0,91	0,89	0,80	0,60	0,88	0,81
	1,0	1,31	1,39	1,00	1,10	1,31	1,11	0,91	1,11
2,0	0	1,56	1,33	1,19	1,33	1,11	1,16	1,14	1,14
	0,5	1,76	1,64	1,56	1,64	1,67	1,56	1,42	1,53
	1,0	1,79	2,15	1,62	2,00	2,09	1,81	1,73	1,92

The final processing of the data arrays of the performed experiments made it possible to quantify the values of the normative angles of internal friction ϕ and specific adhesion *c* of slags at different density of addition both for air-dry and water-saturated states, the results of which are given in Table 6 and Table 7.

In addition to the above shear tests, a significant amount of filtration tests of slags were also carried out, which pursued the following goals:

– slags in their composition and structure are an excellent filter material, and due to the heterogeneity of the granulometric composition, they can partially perform or serve as a "return filter";

– at constant water saturation, they form an almost monolithic porous structure with a compressive strength of up to 0.5 ... 1.0 MPa;

– the use of metallurgical slags as a draining material allows solving the important environmental problem of recycling other wastes from metallurgical production.

The specified set of laboratory tests and analysis of the results of their filtration properties showed the prospects and expediency of using metallurgical slags for the installation of vertical filtration drains, as well as a drainage layer on the roof of weak, including silty soils.

A series of determinations of the value of the filtration coefficient were made at five values of the relative density D_0: – 0; 0.25; 0.50; 0.75 and 1.00.

The quantitative results of these tests are given in table 8.

Table 5 – Results of shear tests of SGMNG slags under different water saturation conditions

ρ, kg/cm^2	D_0	Air dry state				Water-saturated state			
		τ_{max}, kg/sm^2			$\tau_{cp.\ max}$, kg/sm^2	τ_{max}, kg/sm^2			$\tau_{cp.\ max}$, kg/sm^2
0.5	0	0.72	0.68	0.62	0.67	0.71	0.65	0.72	0.71
	0.5	0.91	0.97	0.93	0.93	0.78	0.75	0.83	0.80
	1.0	0.97	1.23	1.14	1.13	1.13	1,02	1.07	1.09
1.0	0	1.20	1.20	–	1.20	1.04	1.19	1.15	1.13
	0.5	1.44	1.49	1.47	1.46	1.28	1.33	1.30	1.30
	1.0	2.19	1.51	1.64	1.65	1.60	1,62	1.50	1.57
2.0	0	2.13	2.04	1.99	2.06	1.94	1.86	1.81	1.90
	0.5	2.25	2.33	2.48	2.40	2.20	2.20	–	2.20
	1.0	2.83	2.77	2.60	2.70	2.47	2.51	2.58	2.52

Table 6 – Normative values of the angle of internal friction of SMG and SMNG slags at different states of water saturation and density of composition

Slags	State	The angle of internal friction ϕ, with a relative density coefficient D_0 equal to				
		0	0.25	0.5	0.75	1.0
SMG	Air dry	33.0	35.0	38.0	40.5	43.0
	Water-saturated	28.5	31.0	34.0	36.5	39.0
SMNG	Air dry	42.5	43.5	44.5	45.5	46.5
	Water-saturated	40.0	41.0	42.0	43.0	44.0

Table 7 – Normative fractions of cohesion of slags SMG and SMNG at different states of water saturation and increase in values

Slags	State	Specific cohesion c, MPa, with a relative density coefficient D_0 equal to				
		0	0.25	0.5	0.75	1.0
SMG	Air dry	0	0.005	0.01	0.015	0.02
	Water-saturated	0.01	0.015	0.02	0.025	0.03
SMNG	Air dry	0.02	0.030	0.04	0.050	0.06
	Water-saturated	0.03	0.040	0.05	0.060	0.07

Table 8 – Values of filtration coefficients at fixed values of relative density of metallurgical slags

Slags	State	Filtration coefficient of slag κ_ϕ, m/day at a relative density coefficient D_0 equal to				
		0	0.25	0.5	0.75	1.0
SMG	Water-saturated	68.2	30.3	25.3	12.5	10.0
SMNG	Water-saturated	72.3	38.7	35.2	18.2	15.1

Conclusions

Thus, the analysis of the results of the performed studies allows us to formulate the following generalizations.

1. The strength characteristics of both types of metallurgical slags, both non-granulated and granulated, functionally depend mainly on their bulk density and, to a lesser extent, on their moisture content.

2. In the transition from extremely loose composition ($D_0 = 0$) to extremely dense ($D_0 = 1$), the angle of internal friction ϕ increases by 30% for granular slags, and by 7% for non-granulated slags.

3. The value of specific adhesion c for granulated slags, respectively, increases almost twofold, and for non-granulated slags, it increases threefold.

4. A close correlation has been established between the values of the filtration coefficient and the relative density of slags. Thus, an increase in the relative density from zero to one reduces the value of the filtration coefficient for both types of slags from 4.8 to 6.8 times.

5. The generalized results of the above comprehensive studies of the strength and filtration properties of slags make it possible to substantiate the possibility of their wide application as a material for artificial arrays and foundations, as well as filter elements at industrial and civil construction sites.

6. To verify the reliability, reliability, and efficiency of such use of metallurgical slags, it is necessary and necessary to perform both model laboratory and field full-scale studies of their long-term operation during the construction of real objects for typical operating conditions and loads.

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