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A Study of Water Permeability of Coal Ash and Slag to Assess the Possibility of Their Use as Road Pavement Layers

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Abstract

This paper focuses on problem of the coal combustion waste use. The possibility of using the coal ash and slug as an additional layer of road pavement is considered. Particular attention is paid to water permeability, which along with the mechanical properties determines the possibility of their use as pavement layers. A series of laboratory studies on samples from the two ash dumps were conducted. This made it possible to determine the values of permeability coefficient for various types of waste having different densities. The research was conducted in laboratory on the equipment that allowed us to change the value of hydraulic gradient (for individual experiments). It was found that filtration begins only when the initial filtration gradients are exceeded, which is associated with the features of composition and structure of coal ash and slug. These results can be used to make a final decision on feasibility of using the coal waste as a layer of road pavement.

Key words: Man-made Deposits, Ash and Slug, Road Pavement, Water Permeability, Steady Flow Conditions, Initial Hydraulic Gradient.

1. INTRODUCTION

One of the main tasks solved by engineering geology is the study of soils from the standpoint of their use as building materials. In the current context, the solution of this problem is becoming increasingly important in connection with the intensive formation of man-made deposits due to the growth of urban areas, the development of mining operations and the functioning of industrial enterprises. The operation of industrial enterprises using solid coal fuel leads to the formation of a large amount of stored ash and slag. According to statistics, up to 20 million tons of wastes left after coal burning at thermal power plants are formed annually in Russia. The total area of the territories occupied by ash dumps is about 300 km^2. This circumstance causes serious socio-economic and environmental problems and encourages the search for ways to utilize these wastes [5,6,10,17,19]. One promising application of coal ash and slag is road construction, in which they are used both as a local binder and aggregate of bitumen concrete mixtures or as building material for filling the subgrade [16]. The use of coal waste as additional layers of pavement (for drainage, frost protection, heat insulating) assumes their compliance with a number of requirements. Among them, the most important is the water permeability of the material.

2. METHODS

The study of the water permeability was carried out on the ash and slag samples taken from the two ash dumps. According to the regulatory document ODM 218.2.031-2013 adopted in Russia, the samples taken belong to the low-calcium, highly-acidic ash and slag with the significant content of unburned coal residues (over than 60 %) (Table 1).

The results of the particle size analysis of the studied samples are as follows: the deposits from the ash dump No. 1 are gravel and from the ash dump No. 2 are coarse-grained. Their typical integral particle size distribution curves are shown in Fig. 1. For each type of the ash and slag, the uniformity coefficient was determined as:

$$C_u = \frac{d_{60}}{d_{10}}, \qquad (1)$$

where d_{60} and d_{10} are the diameters corresponding to percents finer than 10 and 60%, respectively. The results of the uniformity coefficient calculation are as follows: No. 1 is uniform (C_u = 1.7) and No. 2 is non-uniform (C_u = 6.7).

Table 1. Chemical composition of the ash and slag wastes from two ash dumps

Sampling location	**Characteristics of the ash and slag**		**Content of elements in terms of oxides,% by weight***			
	Type	**Kind**	***CaO+MgO***	***SiO_2+Al_2O_3***	***Fe_2O_3+FeO+R_2O***	***SO_3***
Ash dump No. 1	Low-calcium	Highly-acidic	7.6	78.3	14.1	-
Ash dump No. 2			8.7	75.5	15.8	

Note: * Losses during calcination of the ash and slag accounted for over than 60%.

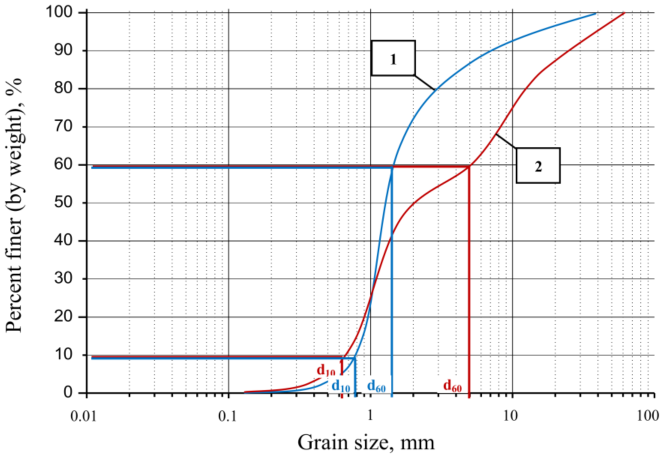

Fig. 1. Typical grain-size distribution curves in semi logarithmic scale for the ash and slag (the numbers "*1*" and "*2*" indicate specimens from the relevant ash dumps)

Assessment of the water permeability of the ash and slag samples was carried out in laboratory conditions using a constant head test (steady flow conditions) [9]. This methodology is widely used in the study of sandy soils, which are similar in particle size distribution to the studied wastes. The value of the coefficient of water permeability was determined using the apparatus *CF-1*, which is the ability to conduct tests with a constant gradient in the range from 0 to 1 (Fig. 2).

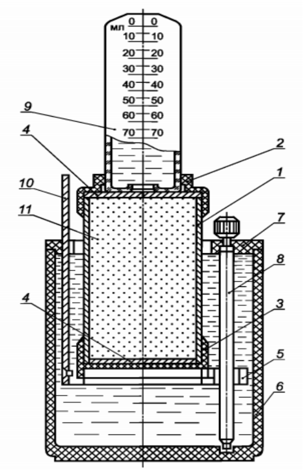

Fig. 2. Schematic view of the apparatus *CF-1*:
1 – filtration tube; 2 – connector; 3 – perforated bottom; 4 – brass net; 5 – holder; 6 – container; 7 – cover; 8 – lifting screw; 9 – measuring cylinder; 10 – hydraulic gradient scale; 11 – specimen [9]

To estimate the coefficient of water permeability, the specimens of the ash and slag were prepared in an extremely loose and extremely dense state (Table 2). Extremely loose state was achieved by filling the samples from a height of 5-10 cm without compaction. Extremely dense state was achieved by filling the filtration tube with layers of 1-2 cm thick, followed by tamping.

Table 2. Density of tested ash and slag specimens

Sampling location	Density	Condition	Average value of density, g/cm^3
Ash dump No.1	Dense	Air dry	0.83
	Loose		0.69
Ash dump No.2	Dense		0.87
	Loose		0.72

Filtration tests were started only after reaching the required ash and slag density and saturating them with distilled water. The value of hydraulic gradient was progressively increased from 0.2 to 1.0 in increments of 0.2 (less often 0.1) from one test to another. During each experiment, the filtration time of a given volume of water was recorded.

3. RESULTS

It were carried out three series of tests for each hydraulic gradient value (more than 120 test in total). The results of these tests (in graphical form) are shown in Fig. 3. The graphs show the dependence of the filtration rate on the hydraulic gradient.

In the process of tests, it was found that water filtration begins only after reaching a certain hydraulic gradient, called the initial filtration gradient. Its value varied within the range of 0.49 to 0.53. The value of the permeability coefficient was determined on the linear sections of the graphs using the well known Darcy's Law. The obtained values were reduced to conditions at a temperature of 10 °*C* (according to average annual groundwater temperature) using the following equation:

$$k_{10} = \frac{\mathrm{k}}{\mathrm{T}}, \qquad (2)$$

where k and k_{10} are the values of permeability coefficient at actual temperature and at temperature of 10 °*C*, respectively, T is the temperature correction calculated as:

$$T = (0{,}7 + 0{,}03T_f), \qquad (3)$$

where T_f is the actual water temperature during the test, ^0C.

The results of determining the permeability coefficients of the studied samples are shown in Table 3.

Table 3. Values of the water permeability coefficient of tested ash and slag wastes

Sampling location	Density, g/cm^3	Coefficient of water permeability, m/day	
		At actual temperature of 18 ^{0}C	Using temperature correction (T = 10 ^{0}C)
Ash dump No.1	0.83	1.4	1.1
	0.69	1.5	1.2
Ash dump No.2	0.87	1.3	1.0
	0.72	1.4	1.1

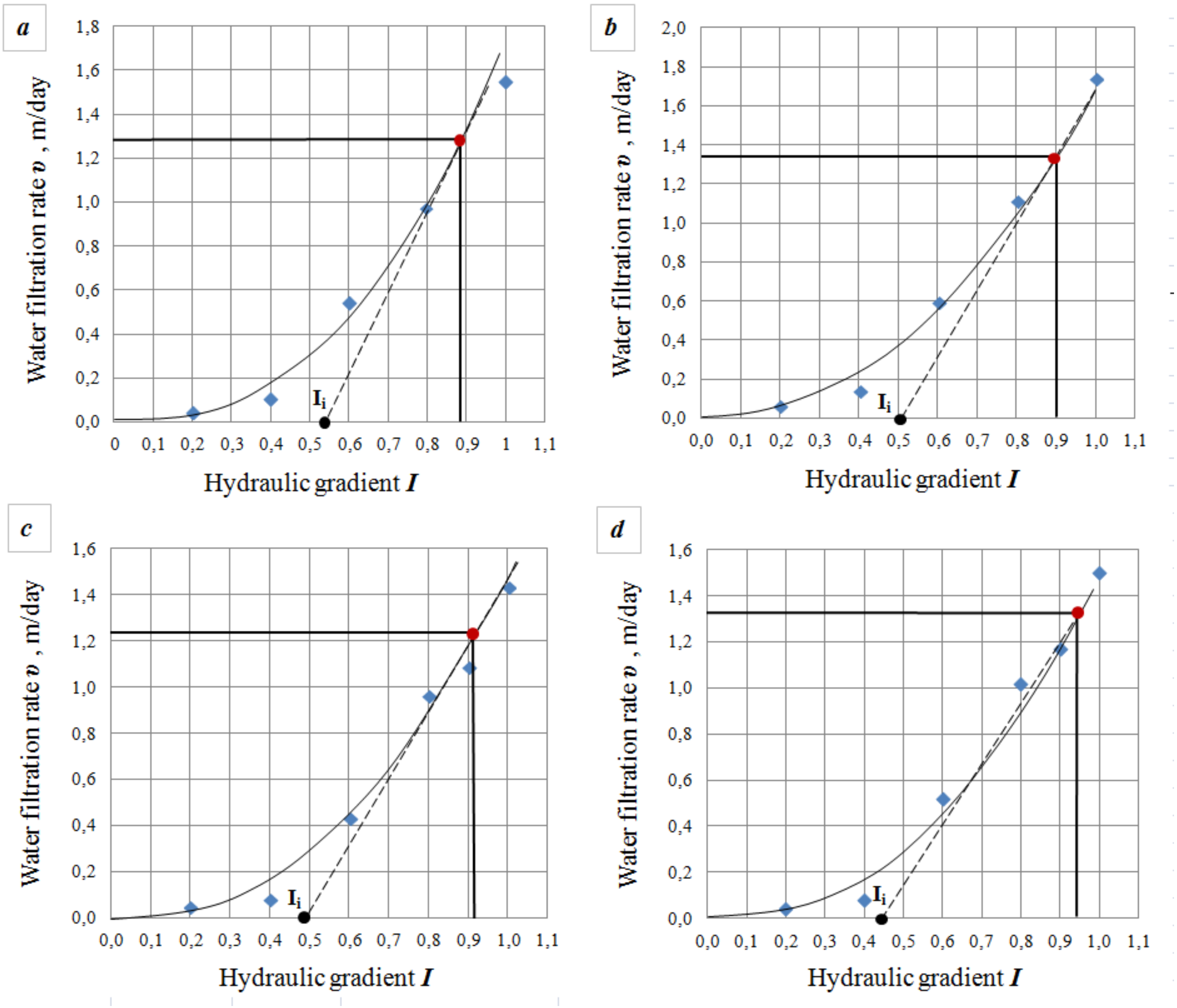

Fig. 3. Change in the water filtration rate (m/s) with increasing the hydraulic gradient: "*a*" and "*b*" represent the samples from the ash dump No.1 in extremely dense and loose state, respectively; "*c*" and "*d*" represent the samples from the ash dump No.2 in extremely dense and loose state, respectively. The point selected for calculating the average value of permeability coefficient is highlighted in red

4. DISCUSSION

According to published data, the permeability coefficient of ash and slag wastes usually varies from 0.08 to 4 m/day [4,12]. As our test results showed, the permeability coefficients of the studied samples correspond to the above values and vary from 1.0 to 1.2 m/day (at 10 ^0C). At the same time, it should be noted that the studied samples, considered as coarse-grained and gravelly deposits, are often characterized by higher coefficients of water permeability exceeding 10 m/day [8]. In addition, filtering through them begins only when a sufficiently high initial hydraulic gradient (from 0.49 to 0.53) is exceeded, which is typical for fine-grained wastes but not for more coarse deposits.

Such a discrepancy in the particle size and the values of the permeability coefficient is most likely due to the chemical composition of the studied samples. As noted earlier, the solid ash and slag residue is mainly represented by unburned coal particles (more than 60%), as well as compounds of silicon, aluminum, iron, calcium and magnesium (see in Table 1). This is consistent with data provided in published sources [18]. The composition of the coal portion of the solid residue is almost identical to the composition of the coal burned that determines its properties [11].

It is known that coal is a porous material penetrated by a system of pores and fissures with dimensions of 10^{-8} to 10^{-10} m. The presence of a developed system of micro- and macropores in the coals determines a specific surface area of up to 200 m^2/g, which contributes to their high hydration capacity [1,14,20,21]. According to studies using the BET method, the specific surface area of the selected samples was more than 8.0 m^2/g. This is due to the presence of polar functional groups (acid sorption centers) on the surface of coal particles [13]. The interaction of sorption centers with water molecules due to hydrogen and Van der Waals bonds leads to the formation of strongly retained adsorption water on the surface of coal particles (Fig. 4) [7].

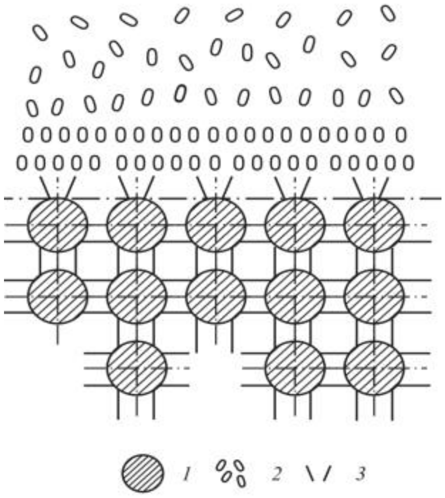

Fig. 4. Formation of adsorption water on the surface of coal particles [3]: 1 – molecules of coal particles; 2 – water molecules; 3 – polar functional groups

It follows that the formation of a hydration shell, the thickness of which can reach $(0.3 \div 4.0) \cdot 10^{-9}$ m, leads to a decrease in the pore space and is accompanied by a process of slowing down the filtration of free water or its absence under conditions of low hydraulic gradient. The consequence of this is the low water permeability of the studied ash and slag and the presence of an initial gradient of filtration, which should be the subject of a separate study.

According to current recommendations on the use of the ash and slag waste as additional layers of the road pavement, the studied samples must satisfy the requirements presented in Table 4.

Table 4. Recommended requirements for the permeability of the ash and slag when using them as additional layers of the road pavement [15]

Possible area of use	Coefficient of water permeability *k*, m/day
Drainage, frost-protective, heat-insulating layer	≥ 1.0
Frost-protective and heat-insulating layer	≥ 0.2
Frost-protective and heat-insulating layers of pavement with the use of technical reclamation (strengthening with binders, waterproofing, etc.)	less than 0.2

Note: In addition, the criteria for the applicability of ash and slag are the weight loss during calcination and the amount of frost heaving

According to the above permeability guidelines, the ash and slag wastes of both ash dumps can be used as additional layers of the road pavement. However, their application can be limited due to the existing hydraulic gradient, which may be lower than the initial one, that will lead to the formation of a stagnant filtration mode and excludes the use of the ash and slag as a drainage layer.

5. CONCLUSIONS

Laboratory studies of the water permeability of the low-calcium, highly-acid ash and slag under the steady flow conditions allowed us to draw the following conclusions.

The value of permeability coefficient of the studied samples, despite the gravel and coarse-grained composition, varies from 1.0÷1.1 m/day to 1.1÷1.2 m/day (at 10 ^0C) in dense and loose state, respectively.

For the studied ash and slag, the presence of an initial hydraulic gradient varying in the range of 0.49 to 0.53 was found.

The low values of the permeability coefficients, as well as the presence of initial hydraulic gradient, are explained by the chemical composition of the ash and slag containing a large amount of unburned coal particles. Their presence increases the sorption activity of deposits (the specific surface area is 8.0 m^2/g), accompanied by the formation of hydration shells on the surface of coal particles and the deceleration of free water filtration.

In accordance with current recommendations on the permeability, the studied ash and slag wastes can be used as additional layers of pavement. In this case, special attention should be paid to the current hydraulic gradient, the small values of which can limit the area of their use.

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